Remembered Odors and Mental Mixtures: Tapping Reservoirs of Olfactory Knowledge

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Five experiments explored how (a) perceived and remembered odor intensities relate to concentration; (b) odor intensities integrate in perceptual, memorial, and mentally constructed mixtures; and (c) components vary in intensity in physical versus mental mixtures. Ss estimated the magnitude of unmixed stimuli presented physically (perceptual estimation) or represented symbolically (memorial estimation). Ss also judged mixtures and their components in combinations of perceptual and memorial presentation. Power functions with similar exponents described the relations between both perceived and remembered intensity and concentration. Perceptual, memorial, and mental mixtures all followed much the same interactive rule of integration. Correspondingly, the intensities of components varied similarly in mentally constructed and physical mixtures. The results imply intensive invariance across odor perception and odor memory.

Two decades of research on memory for odor (see Cain, 1988, for a review) has uncovered various basic properties and some unique features (e.g., Engen, 1987) of chemosensory memory. Beyond merely laying the foundations for the study of smell recollection, these investigations have enhanced our understanding of the gamut of olfactory phenomena from basic processes such as masking (e.g., Cain & Drexler, 1974) to conditions affecting the endurance of odor recognition (e.g., Engen, 1987; Lawless & Engen, 1977). Much of this research has established the role of cognition in chemosensory experience. The present experiments also study the perception and memory for odor and odor mixtures. Whereas earlier studies have mainly been concerned with qualitative aspects of memory for odor, the present study is concerned with characterizing memory for odor intensity. Despite the strictly quantitative nature of our measurements of remembered odor, however, the following experiments entail procedures that probe underlying processes and representations of olfactory stimuli. A major point is to argue and demonstrate further the inherently cognitive underpinnings of any olfactory behavior. To anticipate, the present results imply the existence of considerable covert knowledge about the varieties of chemosensory experience.

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Qualitative Versus Quantitative Aspects of Memory for Odor

Starting with a study by Engen and Ross (1973), investigators documented the influence of cognitive variables such as labeling, codability, and familiarity in odor perception and memory (e.g., Cain, 1980, 1982; Davis, 1975, 1977; Lawless, 1978; Lawless & Cain, 1975; Lawless & Engen, 1977; Lyman & McDaniel, 1986; Rabin & Cain, 1984; Schepner, Voss, & Cain, 1981; see also Engen, Kuismia, & Eimas, 1973; Engen & Pfaffmann, 1960). Research to date on chemosensory memory, however prolific and important, has been limited to qualitative aspects of memory. Virtually nothing is known about the rules that govern memory for intensity. The present study addresses questions related to memory for intensity of odors and odor mixtures by applying techniques of memory psychophysics (cf. Algom, Wolf, & Bergman, 1985).

Memory psychophysics, or mnemophysics (cf. Algom & Marks, 1989), is the branch of psychophysics that explicates the functional relations between physical stimuli and their remembered sensory responses. Although some preliminary data have been reported on both taste (Algom & Marks, 1989; Moyer, Sklarew, & Whiting, 1982) and smell (Osaka, 1987), virtually all mnemophysical research to date has applied to the visual modality. The present research uses a range of mnemophysical methods to explore fundamental issues relating to odor memory and odor representation. We addressed three classes of questions, which, in turn, form the three parts of the present investigation.

Present Study

The first part of our study (Experiment 1) was concerned with unidimensional mnemophysics; it compared perceptual and memorial psychophysical functions referring to a common set of concentrations of a single odorant. The lawful dependence of perceptual magnitude on odor intensity (concentration) has already been documented (cf. Engen, 1982).
Typically, the psychophysical relation for odors conforms to a power function with an exponent well below unity. Perceived intensity of odorants increases, then, at a much slower rate than does stimulus intensity. Several questions need to be addressed. How do remembered odor magnitudes depend on referent physical intensity (concentrations)? Do memory scale values map onto their physical referents by means of the same functional relation (power transform) as do perceptual scale values? If so, do the parameters that govern the psychophysical functions (i.e., the exponents) remain the same? Standard psychophysical methods can be used with both perceptual and memorial types of judgment; the only procedural difference is that odors are physically presented in the one case (perception) and symbolically represented (retrieved from memory) in the other.

The second part of the study (Experiments 2–4) sought to expand olfactory mnemophysics by testing multidimensional stimuli, in particular, odor mixtures. The methods of mnemophysics become perhaps most powerful when applied to multidimensional stimuli where they allow examination of a whole new class of questions. These relate to rules of organization and synthesis in perception and memory. Judgments of physically presented odor mixtures vis-à-vis judgments of their components have been studied, and some underlying models have been suggested (e.g., Berglund, Berglund, Lindvall, & Svensson, 1973; Jones & Woskow, 1964). The second part of our study attempted to uncover the rules that underlie judgments of subjectively constructed mixtures. We wished to evaluate the processes that occur when people judge the intensity of mixtures not presented for smelling, but whose components only are symbolically represented. (Subjects had smelled the respective components separately but never in combination.) We sought to elucidate how remembered representations of the components interact (or fail to interact) to produce a representation of their mixed intensity. The experimental conditions included judgments of such “mental mixtures” based on different combinations of perceptual and memorial information referring to their components. Of particular interest was a comparison of such (presumably tacit) rules of concatenation with the rules of integration that operate when people actually smell the mixtures as well as their components.

The third and last part of our study (Experiment 5) focused on analysis rather than synthesis. It probed people’s knowledge of the behavior of individual odorants in mixed versus unmixed preparations. Perceptually, an odorant smells stronger when presented alone than when presented as a constituent in a mixture, in which case it is subject to the (usually) suppressive processes of masking or counteraction. Here we asked, “would processes analogous to masking surface for constituents of mental mixtures as well (i.e., for mixtures constructed wholly subjectively)?” Appearance of “masking” for mental mixtures would attest to how humans possess considerable latent knowledge regarding olfactory ecology.

Note the comprehensive nature of the questions tested, blurring the boundaries between the qualitative versus quantitative aspects of chemosensation. The method used throughout called on observers to make judgments of intensity, yet, beneath those judgments, general properties of olfactory functioning surfaced, permitting us to answer some unaddressed questions relating to people’s implicit knowledge of odors and the rules governing their composition. The results converged on a common conclusion: People display far deeper olfactory knowledge than they either are aware of or can intelligently articulate.

Experiment 1. Unidimensional Mnemophysics: Perceptual and Memorial Psychophysical Functions for Odor

As mentioned earlier, mnemophysical research has been largely confined to the visual modality. Bjorkman, Lundberg, and Tarnblom (1960) were probably the first investigators to try to derive psychophysical functions for remembered visual stimuli and to contrast those with regular perceptual functions. Unfortunately, their memory condition actually comprised a mixture of perception and memory that precludes drawing a firm conclusion. In a recent typical study, Moyer, Bradley, Sorensen, Whiting, and Mansfield (1978) had separate groups of subjects estimate the size of perceived and of remembered one-, two-, and three-dimensional objects. Subjects in the memory conditions were told to imagine (rather than view) each stimulus as its prelearned name was called out and then to assign a number in accord with standard magnitude estimation instructions (e.g., Stevens, 1975). Perceptual and memorial estimates were well fit by power functions, but the exponent for memory-based judgments was reliably smaller. For example, perceptual area related to physical area by a power function with an exponent of 0.64, whereas remembered area related to physical area by a power function with an exponent of 0.46. Similar results—namely, adequate power fits accompanied by an attenuated memory exponent—have been reported by several investigators (Algom et al., 1985; Chew & Richardson, 1980; Da Silva, Marques, & Ruiz, 1987; Da Silva, Ruiz, & Marques, 1987; Kemp, 1988; Kerst & Howard, 1978; Wolf & Algom, 1987; see also Wiest & Bell, 1985). The reappearance of the power function for remembered magnitudes is just as important as the values of the exponents or their relation. It implies that remembered stimuli map onto physical values the same way as do perceived stimuli, supporting the view that internal processes—of memory or imagery—mirror processes of perception given the same task and stimulus characteristics (e.g., Algom, 1988; Finke, 1980, 1985; Kosslyn, 1975, 1980; see also Algom & Lewin, 1982; Algom & Singer, 1985, for demonstrations of quasiperceptual processes in mental imagery). On a more general level, the results may be interpreted as displaying lawful and long-enduring constraints on internal representation of perceptual knowledge (Shepard, 1984; Wolf & Algom, 1987).

Theories of Memory-Based Magnitude Judgments

Two main hypotheses have been suggested to account for the smaller exponent for the memorial judgments. According to the reperception hypothesis (Kerst & Howard, 1978; Moyer
et al., 1978), perception and memory perform identical transformations on the input data. Therefore, two transformations intervene between the memorial estimate and the physical stimulus. For perception, a simple two-parameter power function described how psychological magnitude increases with physical magnitude (Stevens, 1975). Thus,

\[ R = aS^b, \]  

where \( R \) is perceived magnitude, \( S \) is physical magnitude, and \( a \) and \( b \) are constants. The exponent is given by \( b \), whereas \( a \) is a scale modulus determined by the choice of units. For memory, judgment is again a power function of the input with the same value of exponent. However, the proper input for memory-based estimates is not the original stimulus magnitudes \( S \), but rather their perceptually transformed scale values \( R \). Therefore,

\[ M = a'R^a, \]

where \( M \) is remembered magnitude, and \( a \) is an arbitrarily determined measurement modulus as \( a \) in Equation (1). Substituting for \( R \) yields

\[ M = AS^{\frac{v}{c}}, \]

where \( A \) is the new scaling factor. The reperceptual hypothesis predicts perform a square relation between a given pair of perceptual and memorial exponents.

The alternative uncertainty hypothesis attributes the lower exponent in memory to the greater vagueness inherent in such tasks. According to one version (Kerst & Howard, 1978), subjects confound their range of responses as a result of increased uncertainty. A second version (Algom et al., 1985) holds that it is the stimulus dimension (rather than the response continuum) that undergoes changes under the rather fuzzy memory-based judgment condition. In either case, the effect of uncertainty is to lower the value of the memorial exponent.

For compressive sensory continua (i.e., perceptual dimensions characterized by exponents smaller than unity), both theories predict an even more compressive memory exponent. For expansive continua (dimensions characterized by exponents greater than unity), however, different predictions exist. The reperceptual hypothesis predicts a steeper memory function in this case because the memory exponent should equal the square of a perceptual exponent greater than 1. The uncertainty hypothesis, alternatively, still predicts an attenuated memory exponent regardless of the value of the corresponding perceptual exponent. Unfortunately in this respect, most data to date have been garnered on continua belonging to the nondiagnostic compressive class. These data (virtually all applying to visual continua), to be sure, bear out the predictions of either of the previously listed formulations.

Algom and Marks (1989) recently suggested a two-stage model, modifying the reperception hypothesis, that can account for some discordant data too (e.g., Kemp, 1988; Moyer et al., 1982; Osaka, 1987). According to their two-stage model of judgment (e.g., Algom & Marks, 1984, 1990), the sizes of the measured exponents \( b_p \) (perception) and \( b_m \) (memory) vary because of response transformations imposed by nonlinear judgmental processes (transformations by a power function with exponent \( c \)). Mathematically, for perception, Equation (1) then can be specified as

\[ R = aS^{v\times c}, \]

where \( v \) is the underlying unbiased exponent, and the measured perceptual exponent becomes

\[ b_p = v \times c. \]

For memory, Equation (3) similarly changes to

\[ M = AS^{v\times c}, \]

where the measured memorial exponent is

\[ b_m = v \times v \times c. \]

The ratio of the measured exponents,

\[ \frac{b_m}{b_p} = (v \times v \times c)/(v \times c) = v, \]

yields the "true" perceptual exponent. This exponent \( v \) should be distinguished from the observed exponent \( b \), which is confounded by nonlinear biases.

**Memory Psychophysics for Odor**

Not only are available data limited with respect to a decision among alternative classes of explanations, but they derive largely from a highly selective class of continua. Although some preliminary data have been reported on loudness (Kerst & Howard, 1978), electrocutaneous discomfort (Algom et al., 1985), roughness and heaviness (Moyer et al., 1982), taste (Algom & Marks, 1989; Moyer et al., 1982), and smell (Osaka, 1987), to our knowledge no definitive studies have been conducted beyond the visual domain. In the present experiment, we derived psychophysical functions for perceived and remembered odor to determine how intensity changes under the two modes of response generation.

**Method**

**Subjects.** Nineteen men and 15 women, paid volunteers from the Yale University community, served in the experiment. The mean age of participants was 25 years (\( SD = 5.87 \) years). Most (82%) were between 20 and 27 years of age; only 1 was older than 40. Two were smokers.

**Stimuli and procedure.** Five liquid concentrations of amyl acetate were prepared by dilution in odorless mineral oil. Consecutive concentrations differed by factors of 3, 3, 9, and 9, respectively, from highest to lowest. The strongest concentration was 4% (vol/vol). Chromex Interflo P 375 polypropylene pellets were soaked in each of these solutions and then placed into 250-ml polyethylene bottles (four pellets per bottle) equipped with flip-up spouts. Squeezing the bottles below the nose delivers odorous vapor to the nostrils.

The experiment comprised two sessions. In the first, subjects learned to associate colors (displayed on 28.0 x 21.5-cm cardboard cutouts) with each of the five concentrations of amyl acetate. The five colors—blue, green, brown, yellow, and red—were randomly assigned to concentrations across subjects. Stimuli were presented at room temperature (approximately 22°C). Intertrial intervals were at least 1 min to minimize adaptation.
On the first two presentations of the stimulus series (first series of concentrations in ascending order, second in descending order), the experimenter both showed the color and spelled out its name (e.g., RED) as each odor solution was presented. On subsequent trials, subjects had to supply the color name as they sniffed each bottle. After subjects' response, the correct color and its name were displayed regardless of the response. Order of presentation was random and different for each subject. Trials continued until one of the following criteria was reached: (a) three errorless series out of five or (b) four consecutive series with no more than one error in each series. These learning sessions took about 50–60 min per subject.

Four of the 34 subjects failed to reach the criterion by a substantial margin, so their data were excluded from the final analyses. Of the remaining subjects, 9 also failed to reach the criterion, but fell short by no more than one erroneous identification. In fact, because of their near misses, these subjects usually underwent longer training sessions than did the great majority of the subjects who did reach the criterion. (Training was discontinued after 14 successive presentations of the stimulus series or after 75 min, whichever came first.) Therefore, results are based on the data from 30 subjects.

After an interval of 24 hr, subjects returned for a second session. Each subject was randomly assigned to either a perceptual or a memorial condition. In the perceptual condition, actual concentrations of amyl acetate were presented one at a time for judgment. In the memory condition, subjects also made judgments of odor intensity, but no actual odor stimuli were presented; instead intensities were presented by their previously learned colors. As the colors were shown and named in a random order, subjects tried to imagine each stimulus concentration and then estimate its intensity.

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, and then to assign to succeeding stimuli numbers proportional to their intensities, using whole numbers, decimals, and fractions as needed.

Results and Discussion

Perceptual and memorial psychophysical functions. The magnitude estimates of odor given to each stimulus were averaged geometrically, and these means are plotted in the leftmost panel of Figure 1 as a function of concentration level (% by volume). A separate function is drawn for each condition of judgment. The most striking feature of each set of points is the good fit by a power relation (both sets approximate straight lines in the double logarithmic coordinates). Pearson r²'s equal .97 and .99 for perceptual and memorial conditions, respectively. The slopes (exponents of the power functions) are 0.26 for perception and 0.35 for memory. If individual subjects' exponents are pooled, the means are 0.33 and 0.36, respectively; this difference is not significant, t(28) = -0.33, p > .10.

If we consider only those subjects who passed the learning criterion, the constancy of exponent across odor perception and memory becomes even more apparent. The exponents then change to 0.32 for perception and 0.33 for memory. Again, the fits to the power transforms are excellent (r²'s = .99). The corresponding means from pooling the individual subjects' exponents are 0.28 and 0.31, respectively, for perception and memory. The difference, again, is insignificant, t(19) = -0.713, p > .10. Consequently, a single function suffices to describe the growth of olfactory sensation for both perception and memory (middle panel of Figure 1).

This study provides the first rigorous demonstration of a lawful connection between remembered odor intensity and referent physical concentration. Moreover, the data suggest that the psychophysical and mnemophysical power functions are governed by roughly the same exponent. This constancy contrasts sharply with mnemophysical findings from other modalities. The finding cannot be dismissed as mere floor effect because much smaller exponents than the 0.3 values found here have been reported (e.g., Patte, Etcheto, & Laffort, 1975). For visual area, as we have seen, memory exponents are significantly smaller than their perceptual counterparts (e.g., Algom et al., 1985; Kemp, 1988; Kerst & Howard, 1978; Moyer et al., 1978; Wolf & Algom, 1987). This is typical. As indicated, memorial exponents have been smaller than corresponding perceptual exponents when the perceptual exponent is smaller than unity. Therefore, the uniformity of exponents in odor perception and memory may pinpoint a distinctly chemosensory property limited only to remembered odor and, possibly, taste.

The last point is notable. In a recent study conducted in this laboratory, Algom and Marks (1989) reported similar results for taste. In that study, subjects made quantitative judgments of various concentrations of sucrose that were either presented physically (perceptual estimation) or represented symbolically (memorial estimation after 24 hr). As in the present case, perceived and remembered intensities related to referent concentrations by power functions with similar exponents. In fact, the memorial exponent was slightly greater than the perceptual exponent (0.87 vs. 0.70), although not reliably so. The surprising similarity between the two sets of chemosensory data can be gleaned from the rightmost panel of Figure 1, which reproduces the results on taste mnemophysics. Again, these results contrast with those usually reported for visual mnemophysics.

Table 1 gives the individual results of the present experiment. Subjects in both groups were consistent in conforming to a power relation, demonstrating no appreciable differences across mode of response generation. Even the variability is comparable in the two groups (SDs = 0.22 and 0.15, respectively, for perception and memory).

A final important feature of the present results deserves mention. Even though different groups of subjects partici-
pated in the perceptual and the memorial conditions, they produced no significant differences in the absolute magnitude of judgments in any of the experimental values. Interestingly, though, the means from the memory condition always fell below the corresponding means from the perceptual condition (see Algom & Marks, 1989; Barker & Weaver, 1983, for similar results).

**Theoretical implications.** How do the present results help decide between the alternative theories of memory-based magnitude judgments? Both the reperception and the uncertainty hypotheses predict a more compressive memory function for perceptual dimensions that are characterized by an exponent smaller than unity like the one found here. The present findings of virtually identical exponents governing corresponding perceptual and memorial data clearly are incompatible with either formulation. Therefore, we must reject these traditional formulations as a general account of memorial judgment (even if either of them proves adequate for vision). By contrast, the two-stage model can, in principle, account for the present results. It has been successfully applied to the taste mnemophysics data (Algom & Marks, 1989). There the theoretically derived exponent of 1.26 fared well with exponents for sweetness of sucrose reported in the literature (often in the vicinity of 1.3; e.g., Stevens, 1969). The model, however, seems less conclusive in the present case. Although exponents greater than unity have been reported for smell (Laing, Panhuber, & Baxter, 1978), the predicted exponent of 1.09 for odor of amyl acetate certainly is not typical. Earlier studies using direct scaling (e.g., Berglund, Berglund, Ekman, & Engen, 1971; Cain & Engen, 1969; Engen, 1961, 1965; Engen & Lindstrom, 1963) reported exponents between 0.2 and 0.52 (with a mode of approximately 0.32) for this odorant. These values agree with our observed exponent, but they are incompatible with the exponent predicted on the basis of the two-stage model.

**Conclusions.** The present results demonstrate that (a) memory for odor intensity is lawfully related to the referent concentrations; (b) the mnemophysical law is of the same mathematical class as the corresponding perceptual law; (c) roughly the same parameters govern the two psychophysical relations; and (d) memorial judgments of odor intensity are practically indistinguishable from immediate judgments given to the same odorants, at least for the 1-day delays used here. A succinct summary of the present results might simply say that memory for odor intensity is good.

**Table 1**

<table>
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<tr>
<th>Subject</th>
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<th>Memory</th>
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<tr>
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<td>r²</td>
<td>b</td>
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<tr>
<td>2*</td>
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<tr>
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<td>29*</td>
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*Note. b = power function exponent.

*Subject did not pass learning criterion.

**Experiment 2. Multidimensional Mnemophysic:**

Response Patterns for Perceived and Remembered Odor Mixtures

Naturally occurring olfactory stimuli invariably comprise many constituents. Although in a few cases a natural product may derive its odor primarily from only one constituent, for the vast majority of products odor is the integrated resultant of scores of constituents. Hence, olfaction offers unmatched opportunities for the study of genuine integration and synthesis. The complexity of natural stimuli, perforce, makes the perception of mixtures central to olfactory psychophysics. Consequently, studies of odor mixtures have focused on the
rules that govern the combination of components onto a single judgment of intensity. Several different, indeed contradictory, models have been suggested of the ways that components in a mixture interact (e.g., Berglund, Berglund, & Lindvall, 1971; Berglund et al., 1973; Cain & Drexler, 1974) or fail to interact (e.g., McBride, 1989) to produce a psychological representation of their overall intensity. Despite the abundance of perceptual data, no consensus has emerged yet on a general model that describes compositional dependencies in mixtures. There is much we do not know about either perceptual or cognitive processes operating in olfactory mixtures. The present experiment attempts to compare the two classes of processes by applying techniques of memory psychophysics to such multicomponent stimuli. The general question is, "Do the rules of memory-based judgments of mixtures mirror the rules governing mixture perception?"

Similar questions were pursued by Algom and associates in two related studies in vision. In the first study (Algom et al., 1985), different groups of subjects estimated the areas of perceived, remembered, or imagined rectangles. Algom et al. 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 changes in the same way as development progressed (Wolf & Algom, 1987). Will the rule of integration of components also remain invariant across perception and memory for odor mixtures?

**Method**

**Subjects.** Twenty subjects (13 women and 7 men) between the ages of 20 and 36 years participated. As before, all were paid volunteers associated in various ways with the Yale University community. Most had some experience with psychophysical scaling, although not necessarily in olfaction. None had taken part in the previous experiment.

**Stimuli and procedure.** Three intensities of the banana-scented amyl acetate (concentrations of 1.2%, 0.2%, and 0% vol/vol) were combined factorially with three subjectively matched levels of the crushed-grass-scented leaf alcohol (0.5%, 0.08%, and 0% vol/vol) to yield nine mixtures of the two. Note that of the nine solutions only four are true mixtures in that both constituents appear in nonzero suprathreshold levels of intensity. The remaining five stimuli are mixtures only in the nominal sense; they represent intensity levels of amyl acetate alone and leaf alcohol alone as well as the zero-zero odorless stimulus. In addition, nine colored 28.0 x 21.5-cm cardboard cutouts, similar to those used in Experiment 1, were prepared (the additional colors were black, white, orange, and purple).

Stimuli were prepared the same way as in Experiment 1. The mixtures were made in the vapor phase by the use of appropriate combinations of Chromex Interflo pellets, each containing only one odorant. Hence, the bottles with the binary mixtures contained two different types of pellets; the marginal stimuli also comprised two types of pellets, one of which had been soaked in odorless mineral oil. The bottle with the zero-zero stimulus similarly contained an equal number (four) of oil-soaked-only pellets. These preparations excluded many nonodor clues (e.g., bottle's weight) as possible determinants of judgment. Again, subjects had to squeeze the bottles below the nose to deliver the odorous vapor to the nostrils.

The experiment contained two conditions: equal numbers of subjects (10) participated in each. In the perceptual condition, the mixture stimuli were presented one at a time for judgment. Order of presentation was irregular and different for each individual. Each subject went through only a single overall intensity judgment (for each stimulus) to make the perceptual results fully comparable to data collected in the memory condition.

In the memorial condition, the procedure followed that of Experiment 1. Thus, this condition again comprised two sessions. In the first, subjects learned to associate colors with each of the nine smell stimuli. Methods of stimulus presentation, response evocation, and feedback were the same as in Experiment 1.

We had planned acquisition trials to continue until the learning criterion set up in the first experiment was reached. However, none of the subjects passed this criterion in the present experiment. This outcome attests to the extreme difficulty of learning with olfactory stimuli, even in the case where target stimuli vary along more than one dimension. Then, despite a variety of countermeasures, adaptation claimed an ever increasing toll on learning performance. Recall, too, that given the number of stimuli, the time required for a single presentation of the stimulus series in this experiment allowed for almost two full presentations in Experiment 1. To facilitate the associations of colors to smells, we omitted the zero-zero stimulus from the learning battery for some of the subjects (but the null stimulus was always judged for intensity, yielding the veridical zero-intensity response in virtually all cases). Yet subjects were no more successful learning the truncated series to the prescribed (probably unrealistic) criterion.

Despite the tedious experience, subjects did accomplish a considerable amount of associative learning. In fact, a great majority came quite close—within two erroneous responses—to meeting the original criterion. All, however, went through at least six full stimulus presentations over a period of approximately 75 min. Therefore, if for analytical purposes one wishes to establish a less stringent learning criterion, allowing, for example, for no more than two errors in three consecutive series, then certainly all of the present subjects acquired the task at hand.

After a 15-min break, the subject returned to make free-magnitude estimations of the odorant mixtures. However, no actual olfactory stimuli were presented. Referent mixtures were represented instead by their colors. Subjects were told to imagine each odor stimulus as a color was shown and named in irregular order and then to estimate its intensity. Each subject gave a single magnitude judgment per stimulus.

**Results and Discussion**

Figure 2 gives the results from the perceptual and the memory conditions. In each condition, the magnitude estimates of odor intensity assigned to each stimulus were brought to a common modulus (Lane, Catania, & Stevens, 1961) for all subjects and were then averaged geometrically. These means are plotted, on a linear axis, as a function of the concentration of leaf alcohol. The parameter is level of amyl acetate; each contour represents mixtures with a different constant concentration of amyl acetate.

First, consider the perceptual data depicted in the left panel of Figure 2. A salient feature of this family of functions is their tendency to converge at the upper right corner. Adding a low level of one stimulus component to a low level of the other augments odor sensation notably, but adding a low level
to a high one effects virtually no change in smell intensity. These characteristics suggest that an interactive model holds for the present data, with the approximately linear contours converging at the upper right corner. Convergence is the typical, indeed ubiquitous, result obtained when humans judge the intensity of odor mixtures (Cain, 1988).

An analysis of variance (ANOVA) of the intensity judgments confirmed the conclusions drawn from the visual inspection of the graphic display. Both main effects were highly significant, $F(2, 18) = 34.74$ and $37.2, MS_e = 14.61$ and $14.40$, respectively, for amyl acetate and leaf alcohol ($p < .0001$ for each constituent). The critical term to assess, however, is their interaction because it bears directly on the model of the integration of odorants. Results showed a significant overall interaction, $F(4, 36) = 23.17, MS_e = 7.81, p < .0001$, thereby substantiating statistically what is evident from the visual inspection of the perceptual functions: convergent interaction that is approximately bilinear.

Next, consider the memorial results in the right panel of Figure 2. The most striking feature of the memory pattern is its close correspondence to the respective perceptual pattern. For remembered mixtures too, both amyl acetate concentration and leaf alcohol concentration had highly significant effects, $F(2, 18) = 27.3, MS_e = 19.16, p < .0001$, and $F(2, 18) = 7.5, MS_e = 60.76, p < .01$, respectively. Importantly, their interaction was also highly significant, $F(4, 36) = 15.26, MS_e = 25.83, p < .0001$, mirroring the same effect in the perceptual data. Given the different modes of cognitive generation—perception versus memory—the stability evident in the shapes of these families of functions is impressive.

Figure 3 plots the judgments of memorized mixtures against those of the corresponding perceptual mixtures for the common referent set of olfactory stimuli.

Note the linear spacing of the axes in Figure 3. A least squares solution yields the following functional relation: memorial response $= -0.61 + 1.05 \times$ (perceptual response). This defines a best fitting line that starts roughly at the origin and proceeds at about unit slope (i.e., a fully linear relation). The product–moment correlation between the two sets of judgments is .94. The close correspondence of memory and perception is striking, for it was obtained with independent groups of observers participating in the two conditions. Patently, for odors, the mapping of the memorial representations onto their physical referents closely matches that of perceptual representations.

Despite the demonstrated isomorphism, subjects do reap a slight gain as a result of actually smelling the stimuli at the time of judgment. Although the small difference can be gleaned from Figure 2 (compare the strong grass-scented mixtures at the upper right in the two panels), it is best captured by applying the vector addition model (Berglund, Berglund, & Lindvall, 1971; Berglund et al., 1973) to both the perceptual and memorial sets of data. In binary (two-component) mixtures, intensity has proved describable by vector addition of psychological quantities,

$$P_{ab} = (P_a + P_b + 2P_aP_b \cos \theta)^{1/2}, \quad (9)$$

in which $P_a$ and $P_b$ equal the perceived intensities of the unmixed components, $P_{ab}$ equals the intensity of the mixture,
and $c$ is a parameter to be estimated. The parameter $c$ commonly has a value of greater than 90° (i.e., $\cos c < 0$), typically between 100° and 130° (Berglund et al., 1973; Cain, 1978; Laing, Panhuber, Willcox, & Pittman, 1984; see also Cain, 1988, for an overview).

The model yields an average value for $c$ of 114° when applied to the perceptual results. However, on the average, $c$ changes to 141° (if we exclude an anomalously high result at one data point the mean reduces to 129°) for the memorial data. This difference between perception and memory implies greater amounts of suppression for remembered than for perceived mixtures.

What substantive processes underlie the response pattern that surfaced in both the perceptual and memorial factorial plots? Three alternative descriptions can be offered as first-order approximations to the present data. The first is a multiplicative—total odor intensity = grass $\times$ banana—model of the form

$$R_{ab} = (R_a - A) \times (R_b - B) + C,$$

(10)

where $Rs$ are the psychological values for amyl acetate, leaf alcohol, and their mixture, respectively, and $A$, $B$, and $C$ are constants. The additive constants can be construed as reflecting an upper-bound set on the intensities of the component odorants once they are in a mixture. Multiplicativity serves a simple (first-order) description of the interaction between components. Evidence for this model comes from decomposing orthogonally the interaction terms in the respective ANOVAs for perception and memory. Substantial amounts of the interaction variance—84% and 41% for perception and memory, respectively—rested in the Linear $\times$ Linear components. In both conditions, the bilinear component was highly significant, $F(1, 36) = 78.26$ and 24.84, respectively, $p < .001$, but so were the remainders of the interactions, $F(3, 36) = 4.82$ and 12.1, $p < .01$ and $p < .001$, respectively. Hence, the simple multiplicative model can serve at best as a succinct but preliminary summary of odor interactions in mixtures.

A second description of the present results, as was just shown, comes from the application of the vector addition model to the perceptual and memorial sets of data. Similar to the previous algebraic model, the vector model presupposes interactive processes of compensation, counteraction (or masking), and compromise (e.g., Schiet & Frijters, 1988) to underlie the observed convergence.

Finally, the present results are also compatible with a dominant component model suggested by McBride (e.g., 1989; see also McBride & Anderson, in press; McBride & Finley, 1990): The subjectively dominant component by itself determines the total intensity of the mixture. Hence, there is no need to assume integration (interaction or masking) of components at all.

The present experiment cannot diagnostically distinguish among these alternatives, nor was it designed to do so. A significantly larger matrix of stimuli is needed for that purpose; one, however, that would preclude the vital comparisons between perception and memory—the major thrust of this study. Here we had to keep the number of stimuli within a reasonably small limit to allow them to serve in the focal memory-based judgment condition. (Even so, learning to associate colors to odors proved quite difficult.) The $3 \times 3$ designs used lack statistical power for a unique delineation of the integration model.

In sum, regardless of the exact nature of the combinational operations involved, the present experiment suggests that the pattern underlying memory-based judgments of mixtures is the same one used in perception.

**Experiment 3: Mental Mixtures**

The demonstration that information about odors is represented in memory by systems similar descriptively to those used in perception led to the present experiment. In the previous experiment (as well as in the memory condition of Experiment 1), subjects were asked to retrieve odors from memory, odors that had been presented directly (i.e., perceptually) in their entirety. Judgments of intensity in the present experiment are based instead on exposure to two separate unmixed odorants that the subjects were to consider as the respective constituents of an appropriate mixture. The pure concentrations of each odorant alone were, as before, represented symbolically by their prelearned colors. The question posed by this study is, "What rules underlie judgments of mixture intensity when the judged mixtures are all constructed indirectly in memory, without a previous direct physical referent?" Therefore, in this experiment, the combination of components clearly is a discretionary process, coming under cognitive control. Integration here is optional, not automatic, for it is induced by directing the subjects to mix mentally the referent individual odors. How does the rule of composition compare when subjects are asked to judge the integrated intensity of separately presented constituents of such mental mixtures? To anticipate, the present results suggest that when subjects must integrate the two components consciously (not sensorily), the pattern of responses does not change materially from that surfacing with the perception of physical mixtures.

**Method**

**Subjects.** Twelve subjects (6 men and 6 women) aged 20 to 47 years were paid to participate. None had taken part in any of the previous experiments, although nearly all had had some experience with psychophysical judgments.

**Stimuli and procedure.** Odorants comprised two unmixed suprathreshold concentrations of leaf alcohol alone and two unmixed suprathreshold concentrations of amyl acetate alone. (For a small minority of the subjects, the zero-zero stimulus was also presented.) Concentration levels were those used in Experiment 2. Four of the colored cardboards prepared in Experiment 1 were also used.

The experiment contained two phases: (a) a learning session during which the subject was trained to associate a different color with each of the unmixed leaf alcohol and amyl acetate stimuli, and (b) a psychophysical judgment session involving magnitude estimates of the imagery mixtures made up of the previously presented chemicals as their constituents.

The learning session strictly duplicated the conditions of the acquisition phase from Experiment 1. The same learning criteria were used as well. All of the subjects met these criteria with ease. These learning sessions took about 25 min per subject.
After a 15-min break, subjects returned for the second session. The subjects were instructed to form mentally an imagery mixture whose constituents were one of the grass-like (leaf alcohol) stimuli and one of the banana-like (amyl acetate) stimuli from the first session. Then they were asked to estimate the intensity of the mental mixture. No actual chemicals from the learning session were presented. Rather, grass-like and banana-like odors were represented only by their pre-learned colors. The experimenter covaried the colors for the grass and banana constituents factorially to produce four grass-banana pairs for mental mixture. Relative viewing positions (left-right) of the color displays were varied across random halves of the subjects. Presented with a given pair of colors, each subject 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 judgment as well.

Results and Discussion

The magnitude estimates given to each mental mixture—no physical ones were presented—were averaged geometrically (after being brought to a common modulus across subjects), and these means are plotted in Figure 4 as a function of leaf alcohol concentration.

This family of functions is, again, characterized by linear convergence (although some deviation from the pattern is evident in the upper right corner). Thus, even for the intensity of imagery mixtures—stimuli constructed wholly subjectively—the integration rule is similar, if not identical, to that used with physical and remembered mixtures. An ANOVA revealed highly significant main effects for concentration of both chemicals, for amyl acetate and leaf alcohol, respectively, $F(2, 11) = 50.23$ and 103.85, $MSe = 28.0$ and 11.28, $p < .0001$. Of consequence for the model of integration, the banana x Grass interaction was also highly significant, $F(4, 44) = 5.92$, $MSe = 10.28$, $p < .001$. Incidentally, approximately one third of this interaction (30%) is concentrated in the bilinear component. Again, although this component was significant, $F(1, 44) = 7.18$, $p < .02$, the remainder of the interaction was also significant, $F(3, 44) = 5.49$, $p < .01$. A simple multiplicative rule holds less firmly for these data than for some of the other sets collected in this study.

The results are intriguing. In the past, it has been argued whether suppression occurs peripherally (possibly within individual receptor cells or even at receptor sites) or at somewhat more central loci (at the olfactory bulbs or beyond). However, the present results demonstrate suppression even for symbolically represented nonsmelled constituents. Cognitive, centrally controlled mechanisms of integration must be assumed to operate to account for the present results.

The dominant component model (McBride, 1989), of course, does not imply a central cognitive mechanism or, for that matter, any suppression or interaction. However, the upward slope of the uppermost curve in Figure 4 makes that model a less likely candidate to account for these data.

Applying the vector addition model to the present data yields an average result of $93^\circ$ for $c$. This value implies considerable suppression even for mentally constructed mixtures. Interestingly, however, although the absolute amount of suppression is large—$c$ would be $0^\circ$ if there were no suppression—it is less than those observed for actual mixtures or for remembered mixtures (Experiment 2). Recall that $c$ assumed a value of $114^\circ$ for physical mixtures, but assumed a value of $141^\circ$ for remembered ones. Hence, subjects “experienced” more suppression in the latter condition. The present value of $93^\circ$ is about at equal distance from the physical anchor of $114^\circ$, but lies in the other, less suppressive, direction. It is likely that the highly analytic nature of the present task did exert some modest influence on the respective responses.

The only comparable experiment in the mnemophysical literature is a study on visual area by Algom et al. (1985). In one condition of that study (Experiment 3), subjects were trained to name, by 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 the previously presented pairs of lines represented by a pair of appropriate nonsense syllables. Results showed the veridical Height × Width rule to underlie judgments of area for mental rectangles much the way it does for real rectangles. Algom et al. considered such results a subspecies of a general-purpose composition strategy: Integration rules are invariant across various processing states of a given stimulus. The present olfactory results can perhaps be interpreted the same way, attesting the considerable latent (i.e., not overtly articulated) knowledge on the part of the subjects about olfactory interactions.

Experiment 4: Semimental Mixtures

The patterns of responses—indeed the pattern of response, for they tap the same rule—demonstrated in the previous three experiments apply to at least two processes: integration of odorants in a mixture and integration of odorants presented separately in unmixed concentrations. Despite the vast phenomenal differences, the ways in which the olfactory system transforms multiple signals onto a single intensive output are similar. Given separately presented stimulus constituents, the
mental mixtures nevertheless mirrored the metric used when the global stimulus was presented physically. Although this integration clearly is analytic, the process nevertheless seems to be based on tacit knowledge and, hence, may prove to be cognitively impenetrable. Subjects perceive the constituent odors; yet in thinking of them as a mixture, they act on their values in ways comparable to those operative when smelling real mixtures.

Surely, as is clear prima facie from everyday experience, perceptual mixing and mental mixing operate in wholly different systems. What the present results imply is that the two share some common or functionally similar algorithms for at least certain kinds of olfactory responses.

This experiment aims to test the implications further from the existence of a fairly invariant olfactory “deep structure.” Suppose you are familiar with two smells, only one of which is physically present at the time of testing. Suppose further that you combine them together—mix them—in your own world of fantasy. To be sure, such experiences are all but unfamiliar, as when you ponder how the flavor of your soup would have changed had you added chili pepper to it. What rules underlie the concatenation of the respective subjective values in these semimental mixtures? This particular mix of perceptual and memorial information is examined in this experiment.

Method

Subjects. Eleven subjects (6 women and 5 men) aged 21 to 55 years took part. None had participated in any of the previous experiments.

Stimuli and procedure. The same odorants from Experiments 2 and 3 were used at the same concentrations. Two of the colored cards prepared in Experiment 1 were also used. (For a few subjects, the zero stimuli were also cued by additional colors.)

Subjects came to an initial learning session during which they were trained to associate colors with each of the two amyl acetate (or, for a randomly selected part of the subjects, leaf alcohol) concentrations. Methods of stimulus presentation, response evocation, and feedback were the same as in Experiment 3. These sessions took about 10–15 min per subject.

The second session followed a 15-min break. In a trial, subjects were presented with a color from those learned in the first session in conjunction with a squeezable bottle containing leaf alcohol (or amyl acetate). Subjects smelled the odorant while viewing the colored cardboard. They were asked to imagine a mixture whose one constituent was the smelled odorant and whose other constituent was a second odorant symbolized by its color. Then they gave an estimate of its intensity.

The experimenter factorially covaried the colors (representing the different levels of amyl acetate) and the two physical concentrations of leaf alcohol, thereby producing four imagery—semimental—mixtures in all. Again, about half of the subjects received a memorial leaf alcohol and a perceptual amyl acetate. Unmixed stimuli, too, were presented by smelling pure odorants and viewing single colors. The method, again, was magnitude estimation.

Results and Discussion

Data were reduced the same way as in the previous experiments. Figure 5 presents the factorial plot. A preliminary interactive structure surfaces again in the observed convergence of the curves. Classifying the results according to physical versus cued presentations and casting them onto plots analogous to that in Figure 5 does not reveal any appreciable changes. In addition, we found absolutely no difference between a perceptual grass-like smell and a memorial banana-like smell or the reverse arrangement. Hence, for sake of convenience, we adhered to a presentation of data similar to that used in Experiments 2 and 3.

The pattern of performance with the semimental mixtures obtained here is strikingly similar to that obtained in Experiment 3 with fully mental mixtures. The data are also consistent with the patterns derived in Experiment 2 for actual and remembered mixtures. Both main effects for concentration were significant, $F(2, 20) = 31.442$ and $9.0$, $MSe = 48.36$ and $93.94$, for amyl acetate and leaf alcohol, respectively, $p < .01$. The interaction was also significant, though only at the .03 level, $F(4, 40) = 2.98$, $MSe = 55.18$. Interestingly, 80% of this variance was concentrated in the linear x linear component. The bilinear component was significant, $F(1, 40) = 9.56$, $p < .01$, but the residual was not ($F < 1$).

Applying the vector addition model to the present data yields an average value of 111° for $c$. This result is roughly the same as that obtained in Experiment 2 with physically smelled mixtures. Therefore, mentally adding a symbolically represented smell to an actual one exerts as much suppressing influence on the resulting mixture as actually smelling that mixture.

Experiment 5: Mental Analysis

Experiments 2–4 probed the psychological counterparts of the chemical processes of integration and synthesis germane to odoriferous mixtures. Results revealed the same invariance across mode of cognitive generation (perceptual, memorial, or mental) as the one found in vision (e.g., Algom et al., 1985; Wolf & Algom, 1987). This experiment sought to tap the psychological parallels not of chemical combination and syn-
thesis, but rather of the complementary process of chemical analysis. The major question related to people's knowledge of the behavior of individual chemicals in mixtures compared with that of the same chemicals in pure unmixed preparations. How well can people analyze mixtures psychologically? Can they predict with any accuracy the fate of a familiar odorant once it is mixed with another familiar odorant?

With physical mixtures, a salient characteristic is mutual masking of components or mixture compression (Cain, 1988; Jones & Woskow, 1964). Hence, in general, a constituent in a mixture feels less intense than the same constituent smelled alone. Two questions need to be addressed. Will masking or suppression characterize constituents of mental mixtures—mixtures constructed wholly subjectively and that lack any chemical or sensory counteraction of components? In general, how do judgments of a given constituent, as it appears in an imagined binary mixture, depend on the intensity of the other constituent (the masker) as well as on its own?

Method

Subjects. Twenty-one subjects (17 women and 4 men) from the Yale University community, aged 17 to 37 years, were paid to participate.

Stimuli and procedure. The same two odorants from Experiments 2–4 were used. B3–Go, denotes four consecutive concentrations of amyl acetate differing by a factor of 3. The strongest concentration, B3, was 4%. Go and G2 denote two concentrations of leaf alcohol differing by a factor of 6; the stronger concentration, Go, was 4%. Four of the colored cards (yellow, green, blue, and red) prepared in Experiment 1 were also used. Stimuli were presented by having the subjects squeeze the bottles below the nose to deliver odorous vapor to the nostrils.

The experiment comprised two conditions with approximately equal numbers of subjects participating in each condition. In the perceptual condition (n = 10), the four concentrations of amyl acetate were combined factorially with the two concentrations of leaf alcohol to yield eight mixtures of the two. These were presented one at a time to the subjects for judgments of intensity of the banana-like amyl acetate constituent. Preceding each mixture presentation, the subjects judged the intensity of an unmixed amyl acetate stimulus presented alone at the same concentration as it was to appear subsequently in a mixture. Thus, banana-alone and banana–grass mixture presentations proceeded in strict alternation, with subjects always judging the intensity of the banana stimulus. In mixtures, the subjects' task was to smell out the target odorant and, again, judge its intensity (as it feels in the mixture).

The order of presentation of the concentrations of amyl acetate was random within a session, but for a given level the two mixtures containing the strong and weak concentrations of the masker leaf alcohol were presented in the same series of trials. Thus, a block of trials at a given level, say B3 of amyl acetate contained the following sequence: (a) Subjects judged the intensity of B3 alone; (b) then they judged the intensity of the banana constituent in the mixture B3Go; (c) B3 again was presented by itself and judged alone; and (d) the banana component was smelled out and judged for its intensity in the mixture B3Go. The same sequence was repeated for all other levels of amyl acetate.

The procedure used in the memory condition (n = 11) strictly followed that in the perceptual condition except that, when in a "mixture," the target banana odorant was represented symbolically by a corresponding, prelearned color. Subjects smelled the masker grass only while viewing the color standing for the target banana and imagined the two mixed together. Then they assessed the intensity of the banana constituent as it would smell in the appropriate semimental mixture. On banana-only trials, the subjects actually smelled the stimulus as did the subjects participating in the perceptual condition. In fact, these trials also served to associate the colors with the corresponding amyl acetate concentrations. Note, again, that throughout the experiment, under both conditions, the subjects judged only the target substance as it appeared, on alternate trials, alone and as a constituent of a binary mixture. Of course, the binary mixtures were physically presented in the perceptual condition, but only mentally constructed in the memory condition.

The method again was free-magnitude estimation. Subjects were instructed to assign numbers to stand for the intensity of the banana-smelling amyl acetate stimulus.

Results and Discussion

Table 2 gives the results of Experiment 5. In each condition, the magnitude estimates given to each stimulus by each subject were averaged geometrically, and these means are listed in Table 2 separately for the two groups.

First, consider the results for the perceptual condition given in Table 2. Perceived intensity of amyl acetate (the target) increased with concentration (from B3 to B0) regardless of whether it was presented alone or in a binary mixture containing either the strong (Go) or the weak (G2) concentration of leaf alcohol (the masker). In a mixture, at any given concentration, the target felt stronger when accompanied by the low concentration of the masker than by the high concentration of the masker. On the average, the singularity gain for amyl acetate—namely, the ratio by which the perceived intensity of a constituent in a mixture has to be multiplied to feel equally intense to the same constituent presented alone—was 1.8. For mixture presentations at a given concentration, the banana constituent felt an average of 1.5 times stronger when the masker was weak than when the masker was strong. This outcome, of course, is hardly surprising given earlier findings on odor counteraction and masking (e.g., Cain, 1975; Cain & Drexler, 1974).

Next consider the results for the memory condition listed in Table 2. For these subjects too, the intensity of amyl acetate, either presented alone or represented symbolically in a mental mixture with leaf alcohol, increased lawfully with concentration. What is striking in these data is that the subjects in the memory condition also seemed to "experience" masking! Although these subjects have never smelled the relevant mixtures, they did assess the target correctly, its intensity depending functionally on the concentration of the masker. The singularity gain for amyl acetate averaged 1.8, which is exactly the same value as that obtained in the perceptual group where subjects did actually smell the banana–grass mixtures. Moreover, even for semimental mixtures, the banana constituents, symbolized as they were by appropriate colors, were judged an average of 1.2 times stronger when accompanied by a low concentration of the masker grass than by a high concentration of the smelled grass constituent. Hence, the subjects demonstrated considerable adeptness in judging the fate of a known odorant in a mixture with another known odorant, a mixture that they have never experienced, however. Apparently, people are capable of analyzing mixtures mentally vis-
Alone and in Physical and Mental Mixtures

Note.

Mean Intensity Estimates of Amyl Acetate (B) Presented Be considered as replications, with different subjects, of the analysis of mental mixtures is fundamentally sound, ~vis concentrations of their components and, remarkably, their analysis of mental mixtures is fundamentally sound, using actual smelling as a yardstick.

Additional features of the data deserve mention. The results from the banana-alone trials in both the perceptual and memory conditions can yield to standard psychophysical analysis. The psychophysical functions for amyl acetate approximated power functions in both conditions (r^2 = .978 and .989, respectively), with exponents of 0.21 and 0.24. Recall that the unmixed amyl acetate stimuli were presented physically in both conditions; hence, the two functions can be considered as replications, with different subjects, of the same olfactory contingency. The proximity of exponents as well as their compatibility with the respective perceptual value from Experiment 1 confer support on the reliability of a compressive psychophysical relation for amyl acetate. The intensity of its smell grows approximately as the cube root of concentration.

Consider next the psychophysical functions for the smell of amyl acetate as a constituent of a binary mixture with leaf alcohol. The psychophysical functions in the perceptual condition again approximated power functions (r^2 = .978 and .964), but were characterized by greater exponents of 0.26 and 0.32, respectively, for high and low concentrations of the masker leaf alcohol. These results indicate that the intensity of a constituent in a mixture grows at a faster rate as a function of concentration than does the intensity of the same stimulus presented alone in unmixed preparations. This phenomenon may be dubbed olfactory recruitment after similar phenomena that have been documented for a long time in hearing. Intriguingly, the data for the memorial group also indicate some recruitment for remembered amyl acetate constituents of semimental mixtures. The memorial psychophysical functions for the banana constituents—no physical ones were presented in the mixtures—again approximated power functions (r^2 = .989 and .998) with exponents of 0.34 and 0.24, respectively, for high and low concentrations of the marker. Hence, at least the function at the high concentration of leaf alcohol exhibits considerable recruitment (compared with the banana-only function characterized by an exponent of 0.24 for the same subjects). Incidentally, the present neomphysical functions further demonstrate the quasiperceptual nature of remembered odors, reinforcing the general conclusion drawn in Experiment 1: Memorized odors map onto their physical referents the same way as perceived odors. The present results expand this principle to include constituents of binary mixtures.

Plotting the judgments of the memory group against those of the perceptual group (means) results in a product–moment correlation of .94. The correspondence is remarkably high considering that it was obtained with independent groups of observers participating in the two conditions. Moreover, a correlation of this magnitude is sustained only by subjects in the memory group exhibiting phenomena analogous to those of sensory masking and interaction. Had people not possessed a large core of knowledge about olfactory experience, the present results would not have been conceivable.

Finally, it is of some interest to note that subjects in the memory condition assigned somewhat smaller numbers to their stimuli, either physical or mental, than those in the perceptual condition assigned to their parallel physical stimuli. One should not, of course, attach too much importance to intergroup comparisons in number magnitude; of consequence is the metric and nonmetric properties of the numerical estimates. These proved remarkably similar in the two groups regardless of differences in absolute magnitude or other vagaries associated with numerical estimates.

General Discussion

Mental Synthesis

The reappearance of the original perceptual pattern in memory-based and mental estimates of mixture intensity constitutes one central finding. The same pattern applied to judgments of memorized mixtures as well as to imagery mixtures constructed mentally on the basis of information referring only to their constituents. The way in which the relevant information was conveyed—perceptually versus memorially, directly versus indirectly—mattered little to olfactory composition. Thus, regardless of the exact form assumed by the rule of concatenation of components, most important is the fact that, in each case, the pattern mirrors that used in the perception of physical mixtures.

The results of an ANOVA performed on the collective data from the four conditions of Experiments 2–4 (Table 3) support the observed invariance in the pattern of response. Despite the use of independent groups of observers, no significant differences in the absolute magnitude of judgments occurred as revealed by the insignificant group factor. The two other factors, for both chemicals, had large and significant effects. More important, the Chemical × Group interactions were nonsignificant (although the Leaf Alcohol × Group term carried an exact alpha probability of .05 because of some
Modest deviation in one of the conditions. By contrast, the Amyl Acetate × Leaf Alcohol interaction was highly significant, again documenting the visual convergence of the odor contours. Most significant, however, is the lack of interaction between the Amyl Acetate × Leaf Alcohol effect and group (note the F value of 1 for the Amyl Acetate × Leaf Alcohol × Group interaction). This means that regardless of the form of the sustaining process (i.e., selective, multiplicative, vector additive), the interactive patterns observed throughout the factorial plots of this study do not differ materially across mode of response generation.

In displaying an invariance in the principles of multidimensional integration, olfaction joins several visual continua (Algarm et al., 1985; Wolf & Algarm, 1987). In vision, memorial data and mental data obeyed the same rule that operated in perception, and the correspondence was demonstrated for several completely different combination models. This point is noteworthy. Virtually all extant studies of memory psychophysics involved extensive sensory continua, such as linear extent, area, and volume. Certainly, memory–percept invariances have been derived using only these continua. Olfaction provides the first example of an intensive continuum on which this principle is being tested. Prima facie, as the present results show, it would appear that the observed congruence in the results of the perception, memory, and mental tasks lies in a common cognitive algebra (cf. Anderson, 1981, 1982) of olfactory integration.

We do not think that these artifactual explanations are valid. A mental calculation explanation (e.g., Butler & Overshiner, 1983), for example, would predict an additive or at best a subtractive structure. The subjects, on the other hand, used a selectively subtractive, that is, an overall interactive, form of concatenation. In addition, subjects’ spontaneous remarks revealed no explicit conscious theory on their part that could serve as the basis for mental calculations. Their performance, of course, betrayed at once the existence of ample implicit knowledge on olfaction that fortunately turns out to be ecologically valid.

Virtually all homomodal smell or taste mixtures tested in the literature (Bartoshuk, 1988; Cain, 1988) yielded the same converging pattern observed here, but judgments of heteromodal smell–taste mixtures invariably resulted in a parallel, additive pattern (e.g., Murphy & Cain, 1980; Murphy, Cain, & Bartoshuk, 1977). The interactive patterns for olfactory mixtures have been obtained using a wide variety of methods including rating, direct matching, and graphic pointing applied across different populations. Hence, it is highly unlikely that the present commensurate results are but the outcome of nonlinear response biases that, at times, do beset magnitude estimates, especially as magnitude estimates yield, as a rule, another (additive) structure for heteromodal mixtures. Neither can the observed congruence of the present tasks be attributed to the consistent use of small numbers on the part of the subjects; a substantial minority of our subjects used large numbers, and about half of them gave judgments in the double-digit range. Incidentally, nothing in the nature of small numbers (not generally given here) dictates a converging interaction that looks approximately bilinear. Most likely, the source of the observed congruence in the results of the perceptual and mental tasks lies in a common cognitive algebra (cf. Anderson, 1981, 1982) of olfactory integration.

However, the best avenue to counter such arguments is to consider the results on mental analysis. Here a mental calculation-based explanation collapses naturally simply because there is virtually nothing to calculate. Neither does a numerical basis alternative carry much weight, because the ordinal properties of the numerical estimates themselves suffice to produce the main result. The results on mental analysis imply, in tandem with those on synthesis, the existence of a valuable reservoir of olfactory knowledge about sensory experience on the part of human subjects.

Mental Analysis

The constancy across perception, memory, and mental imagery in the psychophysical processing of mixtures is remarkable because it prevails in the face of and in spite of ineluctable phenomenal differences. A similar constancy appears for mixture analysis, when people judge the intensity of a constituent in a mixture (rather than overall mixture intensity) vis-à-vis the intensity of the same chemical in unmixed preparation. That the patterns of analysis remain invariant reinforces the notion that people carry an underlying core of ecologically valid chemosensory knowledge.

Memory–percept isomorphism in mixture processing is open, however, to alternative, artifactual interpretations such as response bias in numerical estimates or mental calculation.

Perceptual and Memorial Psychophysical Functions

The main finding of this study suggests an invariance of the integration rule across perceptual and memorial judgments of the same odor stimuli. However, the results of Experiments 1 and 5 suggest that, for olfaction, there is additional invariance of the valuation function mapping physical magnitudes onto perceived and remembered magnitudes. Unlike in vision, perceived and remembered smell intensity related to referent amyl acetate concentrations by power functions with roughly the same exponents. For olfaction, then, perceptual and memorial composition processes both act on practically equivalent sets of implicit values.
Additional Cases of Chemosensory Interaction

The present results may parallel analogous findings in several chemosensory phenomena including bilateral interaction in olfaction (Cain, 1977), bilateral interaction in the common chemical sense (Garcia-Medina & Cain, 1982), interaction between odor and irritation (Cain & Murphy, 1980), and interaction in dichorhionic mixtures (Cain, 1975). Common to all these interactions is the observation that they cannot occur at the periphery. In dichorhnic stimulation, for example, different odorants are presented separately (but simultaneously) to each nostril. Yet such dichorhionic mixtures were shown to display the same behavioral properties (e.g., suppression as the corresponding binary mixtures presented in the usual manner to both nostrils. Moreover, the smell image produced by dichorhnic stimulation of an odorant to one nostril but an irritant to the other was essentially indistinguishable from that produced by the corresponding physical mixture. Cain and Murphy (1980) concluded that “the interaction occurs in the brain” (p. 255; see also Laing et al., 1984). It should be recognized that, in a strict sense, dichorhionic mixtures constitute a special case of mental mixtures. Given the present results, the dichorhnic–physical invariance observed in earlier research should hardly be surprising. The same reasoning applies to additional constancies observed with various modes of odor delivery. People may well have learned some ecologically useful rules pertaining to olfactory experience.

Olfactory Cognition

The present results suggest that olfactory imagery (at least that large part called memory images; e.g., Algom & Lewin, 1976, 1979; Horowitz, 1970; Richardson, 1969; Singer, 1966, 1973; see also Algom & Lewin, 1982; Algom & Singer, 1985) is lawfully related to the chemophysical properties of the odoriferous environment. We use the term imagery judicially because the data imply more than merely accurate olfactory memory. Recall that no physical mixtures were presented to the subjects in Experiments 3–5. Judgments of intensity were based instead on exposures to separate, unmixed preparations of odorants. Hence, the judged mixtures were all constructed mentally and thus indirectly, without a previous, direct physical referent. We distinguished such mental mixtures from remembered mixtures (Experiment 2) or remembered odorants (Experiment 1) where the direct physical referents had been presented previously, although they were absent at the time of judgment, being represented only symbolically. Whether olfactory mental imagery is based on underlying propositional networks or on analog representations is yet to be determined. Be that as it may, perceptual organization and capacities pose tight constraints on the inner world of odor memory and imagery. In a strict sense, there are not two worlds available for humans: one perceptual and physically oriented, the other imaginal and detached from reality. Far from being detached, people’s olfactory world of make-believe obeys the rules used in constructing their physically bound perceptual world.

References


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