The sensory psychology of odor mixture: Changes in odor strength and odor hedonics

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For decades, researchers have been intrigued by man's ability to integrate sensory information from a large number of chemicals into a single smell perception. The aroma of a strawberry or an apple, the fragrance of an exotic perfume, or the horrendous stench which emanates from a sewer, all of which seem singularly unique, in reality comprise many dozens, hundreds, or even thousands of different chemicals. Their interaction, and the instantaneous registration of these components in our conscious perception produce the unitary impression.

What is even more remarkable about this world of odor mixture is the continuing integrity of quality perception in the face of changes in the chemical constitution of the substances from which the smell emanates. An assortment of different apple varieties (e.g., Cortland, Winesap, and Delicious) will exhibit a set of entirely different gas chromatographic tracings showing varying chemicals at varying concentrations. Somehow, the brain manages to register all of these mixtures of chemicals as apples, albeit apples of different varieties.

This report is concerned with research efforts on odor-mixture perception. In most of the studies reported here investigators systematically mixed together two (or perhaps a larger but still manageable number of) chemicals in a limited range of concentrations, rather than trying to imitate nature in her mélange of ingredients. Two major aspects of odor mixture, the perception of odor intensity in these mixtures and the perception of odor hedonics, are discussed.

Odor Intensity

At the turn of the twentieth century, the Dutch physiologist and odor scientist, Hendrik Zwaardemaker, reported the outcome of a series of studies in which he mixed together pairs of chemicals. Zwaardemaker was ingenious in his experimental arrangement. In order to guard against the possibility of chemical interaction, he separated the two odor streams by presenting one odorant to the left nostril, and the other to the right nostril.

Some combinations of odors counteracted each other. Zwaardemaker never precisely specified the exact nature of this counteraction. From later studies, however, we can probably assume that the mixture exhibited some vague and undefinable residual smell.

It remained for subsequent, and more rigorous investigations, to assess the exact nature of odor intensity suppression in mixtures. From a series of experiments described below, virtually all experimenters have found suppression in mixtures—that is, in the mixture the total odor intensity (however measured) is less than, or equal to, the sum of the odor intensities of the components, rarely, if ever, greater than the sum of the component intensities.

Some preliminary studies

More than a decade ago, Jones and Woskow (1964) reported on the subjective assessment of mixture odor intensity (for various chemicals (e.g., cyclohexane, ethyl acetate, toluene). In binary odor combinations, these compounds usually smelled weaker than the sum intensity of the components evaluated separately. The authors instructed their panelists to assign magnitude estimates (Moskowitz, 1976) to reflect odor intensity. Since the panelists evaluated both the components alone, as well as in combination, it then was relatively simple to develop a mathematical equation to relate the total odor intensity of the mixture (${}^{I}\mathrm{mix}$) to the sensory intensities of the components (${}^{I}a$, ${}^{I}b$). The very simplest equation is written:

$$ {}^{I}\mathrm{mix} = {}^{k}1\,{}^{I}a + {}^{k}2\,{}^{I}b + {}^{k}3 \qquad (1) $$

where the coefficients, ${}^{k}1$, ${}^{k}2$, and the additive constant, ${}^{k}3$ are estimated from the magnitude estimates given to a mixture ${}^{I}\mathrm{mix}$, and to its separate components, ${}^{I}a$, ${}^{I}b$.

One important finding was that the coefficients ${}^{k}1$ and ${}^{k}2$ were not 1.0. Had they been, one could conclude that the olfactory system of man simply adds together the sensory intensities of the components. Because ${}^{k}1$ and ${}^{k}2$ were empirically less than 1.0, Jones and Woskow concluded that the nose does not behave like a simple adding machine of intensities. Rather, some of the intensity of the mixture is lost and the nose does not "average" the component intensities giving equal weight to both components.

Beginning in the late 1960s and early 1970s, there was a marked resurgence of research interest in the perception of odor mixtures. Köster (1969) reported the results of a series of studies in which panelists evaluated the odor intensity of components in a two-component mixture by matching the intensity of each component in the mixture to a pure concentration of that same component. This method of equal-intensity matching showed that time and time again the odor intensity of each component in the mixture was lower than when it was smelled alone. A 10 ppm component in the mixture could often be matched by a 5 ppm component (or even a lower level) of the same chemical, evaluated without another competing smell as a background.

The Vector Model Approach

It remained, however, for other researchers (Berglund and coworkers, 1973) to develop adequate mathematical models of what actually occurs in odor mixtures. The Berglund experimental arrangement was simple, but elegant. An olfactometer was constructed which allowed mixing of different odorous vapors in known concentrations. Their panelists assigned magnitude estimates of overall odor intensity both to components and to mixtures using the same magnitude estimation scale. Since magnitude estimates provide ratio-value information about odor intensity (i.e., a magnitude estimate of 20 for an odor means it smells five times stronger than an odor estimated to be 4), they could develop equations to predict odor mixture intensity, just as Jones and Woskow had done.

The equation that Berglund finally selected was the equation used by physicists to reflect vector addition. The underlying theory was that odorants could be likened to vectors, with the angular separation between the vectors similar to a measure of overall odor dissimilarity, and the magnitude of the odor intensity corresponding to the length of the vector. This analogy implies that odorants which are identical should be separated by an angle of 0°, whereas odorants that are totally sensorially dissimilar (if they could be found) would be separated by an angle of 180°. The mathematical expression for this vector addition is:

$$A^2 + B^2 + 2AB(\cos\alpha) = (\text{Mixture}^2) \qquad (2)$$

where A, B are the magnitude estimates of the odor intensities of the components alone (A and B) and Mixture is the odor intensity of the mixture of A and B on the same scale. Cos α is the cosine of the angular separation between odorants A and B.

In the initial experimental work, Berglund successfully applied this theoretical framework to the analysis of malodors caused by dimethyl sulfide and dimethyl disulfide. Magnitude estimates for a series of concentrations of both components evaluated alone, and then in binary mixture, were obtained. Based upon one set of experimental data, the values A, B, and Mixture were used to compute cos α. Cos α turned out to be around –0.26°, meaning that angular separation between the odorants was approximately 105°. Applying that same cosine value to other mixtures which had not been used to compute α, allowed an excellent prediction of malodor mixture intensity.

Subsequent work has borne out the vector model. In his series of studies on odor mixtures and masking, Cain (1975) evaluated the masking effects of amyl butyrate on propanol. Cain and Drexler (1974) explained the masking by linalool linalyl acetate and lavandin on pyridine.

In most instances, the vector model successfully described in quantitative terms the reduction of overall odor intensity in the mixture, with the possible exception of changes that were observed when one of the components was extremely strong and the other was very weak. In those regions, the model often could not predict what the odor intensity was likely to be. Moskowitz and coworkers (1976) explored a wide range of mixtures for two pleasant smelling components, ethyl salicylate and heptyl acetate. They confirmed the foregoing finding, both in terms of the general conformity of the data to the vector law, and the significant departures from the model when the two odors were quite different in strength.

More complex mixtures and mixture intensity

When one considers three component and higher order mixtures, such as those which nature presents, and which comprise many dozens or hundreds of constituents at varying concentrations, other phenomena emerge. One of these might be "constancy" of total odor intensity. When many odorous components, each having the same odor intensity, are added together the overall odor mixture grows only slightly in total overall intensity as more and more components are added. The mathematical model of vector summation would eventually predict a larger odor intensity than actually occurs.

This constancy in total odor strength occurs because the odors suppress each other. As increasing numbers of components are combined, more and more sensory inputs arrive at the nose. Suppressive effects occur—each odorant suppresses and is suppressed by every other one. The mixture mélange sets up its own sensory dynamic equilibrium. Each new odorant disturbs the equilibrium, but soon the equilibrium re-establishes itself.

Experimenters have found this constancy of total odor intensity in a number of studies. Berglund (1974) investigated the relation between odor intensity and component intensities for malodors in smoke. She used the vector model, discussed above, as a starting point (the vector model can be generalized to account for vector addition when three or more vectors are added together). For mixtures of 3, 4, and 5 components, the vector model predicted a mixture intensity that was consistently different by a multiplicative factor from the actual empirical estimates of mixture intensity. Moskowitz and Barbe (1977) also investigated multicomponent mixtures. They found that the vector model systematically overpredicts sensory additivity. Constancy in higher order mixtures (3, 4, or 5 components) tends to be the rule.

The experimental results discussed above leave researchers with several problems, as well as at least one potential model, the vector model, as a starting point for predicting odor intensity of mixtures. Two important problems are:

Are all of the sensory characteristics equally affected, or is the suppression of one odorant by another asymmetric? For instance, the vector model may predict, quite adequately, the total sensory intensity of a mixture of two odors (e.g., ethyl salicylate and heptyl acetate, both of which smell pleasant). Yet, if the observer partitions his perception and sensory intensity judgment into that portion due to the minty smell of ethyl salicylate, and that fruity pear-like portion due to heptyl acetate, then does the vector model predict how each sensory component (minty, fruit pear-like) changes in the mixture?

Can there ever be synergism, where the mixture smells stronger than the sum of the components? Salo (1973) reported that in multi-component mixtures, there were some (rare) synergistic ones, so that the odor mixture smelled stronger than one would expect. The vector model can only predict suppression, or, at best, simple arithmetic additivity. It cannot, as presently constructed, predict odor synergism, since the sum of two vectors A+B separated by 0° (the most favorable separation for additivity) will never be more than A+B.

Hedonics and Quality of Odor Mixtures

Some four decades ago, two psychologists, Spence and Guilford (1933) reported the results of their studies on pleasantness/unpleasantness of odor mixtures, and the relation of mixtures to the hedonics of the components smelled alone. As might be expected, mixtures oftentimes smelled more pleasant than the least pleasing component, but less pleasant than the more pleasing one. Intermediacy of hedonics was, thus, the general rule. They also noted that occasionally one component of a binary mixture may so dominate the mixture that it forces its quality, and also its hedonic tone, onto that mixture. In such instances, the hedonic tone of the mixture could be approximated by a simple proportional rule, whereby 80% of the mixture hedonics was due to the dominating component and 20% was due to the dominated component.

These observations have since been replicated, using other scaling techniques, such as magnitude estimation. The usual finding has been one of intermediacy as well. Unfortunately, however, researchers have not been able to derive a general model for hedonic additivity or intermediacy in the same way that they have derived the vector model for summation of odor intensities. Some models suggest themselves, such as the model for linear combination:

$$H_M = k_1H_A + k_2H_B + k_3 \qquad (3)$$

The hedonic tone of a mixture H_M is the weight-ed linear sum of the component hedonic tones. If the coefficients are both 1.0, then the hedonic tone is the linear sum of the component hedonics. More often, however, k_1 and k_2 are not equal to each other for some mixture sets (see Table). This means that the individual differentially weights the two components. The criteria for the weights are, as yet, unknown, save that from evidence that is accruing, it appears that the more unpleasant component contributes more weight.

Table I
Additive relations in odor hedonics

(1) $M_{HD} = -0.08\ (E_{HD}) - 1.01\ (H_{HD}) + 14.24\ R = 0.48$

(E = ethyl salicylate, H = heptyl acetate, M = mixture, HD = hedonic tone)

Source: Moskowitz, Dubose and Reuben, 1976

(2) $M_H = -163.2 + 0.72\ (H_A) + 0.26\ (H_B) + 0.00\ (H_C) + 1.63\ (H_D) + 3.18\ (H_E)$ (Pairs)

$M_H = 311.5 + 0.02\ (H_A) = 2.79\ (H_B) + 0.00\ (H_C) + 1.11\ (H_D) - 3.13\ (H_E)$ (Triples)

(A = methyl salicylate, B = caproic acid, C = isobutyl isobutyrate, D = methyl disulfide, E = camphor)

Source: Moskowitz and Barbe, in press

Part of the shift in hedonic quality in the mixture must also be traced back to shifts in odor intensity, in addition to the summation of positive and negative hedonic tones. Thus, in mixtures, a more complex situation is set up, whereby two things occur simultaneously.

1. Each odorant masks the other odorant, thus, reducing its intensity. That reduction intensity will also correlate with a change in the liking/disliking score given to the odor, even if nothing else occurs (Lawless, 1977).

2. There is an antagonistic effect of liked versus disliked odors which, when put together, produces an intermediate hedonic response.

Masking and counteraction

The studies above suggest that when we consider the so-called masking and counteraction effects in odor, we recognize that masking may be a manifold phenomenon. The following effects usually occur. Whether we call *these* effects "masking" and "counteraction," or whether effects greater in magnitude beyond those expected in ordinary mixtures of odors are called "counteraction" is really a semantic issue.

1. Each odorant in a mixture diminishes in sensory intensity, but may or may not disappear.

2. The total odor intensity of a mixture is usually in between (intermediate to) the component intensities of the odorants.

3. The hedonic tone of the mixture is usually intermediate to the hedonic tones of the components.

4. Rarely is a mixture totally odorless (i.e., absolute and total disappearance of the constituent odors, which are easily perceivable when they are presented separately). What may occur is a moderate to great disappearance of character in the odor, and a hard-to-describe residual. Unless the odorant is totally destroyed physically, something in the mixture still provokes a smell (albeit a weaker, and probably less obnoxious smell).

Conclusion

By themselves, odor intensity and odor hedonics are fairly easily quantified by psychophysical methods. Appropriate scaling of sensory responses to pure odorants allows the experimenter to assign to these odors numbers which reflect sensory intensity and liking. These numbers can be used as reference points for comparing the performance of the same odorants in binary or higher odor mixtures. The existence of an adequate measure of these sensory/hedonic responses to odors opens up an exciting experimental arena wherein experimenters can, for the first time, develop and test out models to describe the sensory events which occur in odor mixture perception. One can expect some interesting data and some useful models in this area in the next few years.

References

Berglund, B., Quantitative and qualitative analyses of industrial odors with human observers, Ann. N.Y. Acad. Sci. 237, 35-51, 1974.

Berglund, B.; Berglund, U.; and Lindvall, T., On the principle of odor interaction, Acta Psychol. 35, 255-268, 1973.

Cain, W. S., Odor intensity: Mixtures and masking, Chemical Senses and Flavor 1, 339-352, 1975.

Cain, W. W., and Drexler, M., Scope and evaluation of odor counteraction and masking, Ann. N.Y. Acad. Sci. 237, 427-438, 1974.

Jones, F. N., and Woskow, M. H., On the intensity of odor mixtures, Ann. N.Y. Acad. Sci. 116, 484-494, 1964.

Köster, E. P., Intensity in mixtures of odorous substances. In: Olfaction and Taste III, C. Pfaffmann, ed., The Rockefeller Press, New York, 1969, 142-149.

Lawless, H., The pleasantness of mixtures in taste and olfaction, Sensory Processes, in press.

Moskowitz, H. R., Fragrance intensity measurement by magnitude estimation, Perfumer and Flavorist 1, 18-26 (Oct/Nov), 1976.

Moskowitz, H. R., and Barbe, C., Profiling of odor components and their mixtures, Sensory Processes, in press.

Moskowitz, H. R.; Dubose, C. N.; and Reuben, M. J., Flavor chemical mixtures—A psychophysical analysis. Paper presented at the symposium "Objective Measurement of Flavor Quality," American Chemical Society, Agricultural and Food Division, San Francisco, August 1976.

Salo, P., Interactions among volatile aroma compounds in a whiskey imitation, Lebensmittel, Wissenschaft und Technologie 6, 52-58, 1973.

Spence, W., and Guilford, J. P., The affective value of combinations of odors, American Journal of Psychology 45, 495-501, 1933.

Zwaardemaker, H., Smell compensation, Perf. & Essent. Oil Rec. 50, 217-221, 1959; Trans. Die Compensation von Geruchsempfindungen Arch. Physiol. Leipzig, 1900.