Comparison of Models of Odor Interaction

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Abstract

Subjects rated the overall perceived intensity of concentrations of the odorants cineole, geraniol, hexyl salicylate, and linalyl acetate smelled alone and in binary mixtures. The subjects also rated intensity of specified constituents (e.g. amount of cineole in cineole, and in mixtures of cineole and linalyl acetate). The intensity of the stronger component alone offered a close description of perceived intensity. In addition to the Stronger Component model, two other psychological models (Vector and U model) and two psychophysical models (UPL2 and Equiratio Mixture model) offered descriptions ranging from fair to very good. Psychological models gave better fits, but lack explanatory power. Some results indicated that weaker odors add more potently than stronger odors, an outcome incompatible with these models. The psychophysical models, based on the additivity of single components, generally overestimated perceived intensity. Judgments of individual qualities gave only slight encouragement to any expectation of differences in masking or maskability among odorants. The results highlight the need to test particular critical hypotheses regarding how people perceive mixtures. Chem. Senses 20: 625–637, 1995.

Introduction

Nearly every important applied problem in odor science and technology has relevance to the perception of mixtures. The food chemist will seek to identify the blend of components that gives a natural product its characteristic aroma. The flavorist will seek to create a blend that mimics the flavor of a natural product. The perfumer will mix aroma materials to create a 'clean clothes' scent for a laundry detergent. The whiskey distiller will alter the balance of raw materials to obtain a smoother product. The chemical engineer will manipulate a manufacturing process to reduce the offensiveness of the mixture of odorous constituents emitted to the atmosphere. The industrial hygienist will analyse the complex atmosphere in an office building to seek the agents responsible for complaints of indoor pollution. The product developer in a home products company will screen for effective maskers of kitchen malodors.

In these various cases, the practitioner can gain surprisingly little guidance from the scientific literature on the perception of mixtures. The limited amount of research performed on the topic has focused principally on perceived intensity, rather than on both intensity and quality, and then generally on just simple mixtures, with only two or three components, far from the complexity of most real-world mixtures. Models of mixtures have accordingly arisen from the tradition of the study of intensity. The models differ in theoretical foundation, but little consensus has emerged regarding the most preferable one (Berglund *et al.*, 1976; Laffort and Dravnieks, 1982; Frijters and Oude Ophuis, 1983; Frijters, 1987; Laffort, 1989; Berglund and Olsson, 1993c). Lack of consensus reflects two factors: (a) the models often make reasonably similar predictions, and (b) tests of the models rely on relatively few sets of data.

A rule described by Berglund *et al.* (1973) that intensity of odor mixtures obeys principles of vector summation has received little challenge as the best empirical approximation, though the formal statement of a vector model can be criticized as theoretically limited or even devoid of meaning. The criticism rests on lack of interpretation for the interaction term that, for two-component mixtures, manifests itself as the angle between the vectors. The vectors can be seen as adjacent sides of a parallelogram where the lengths of the sides represent the perceived intensities of the unmixed components and the length of a diagonal through the figure represents the perceived intensity of the mixture. In order to surpass the vector rule in applicability, other models should fit the data approximately as well, yet offer substantive meaning for their parameters.

This study adds to the existing set of data on mixtures in the following ways:

(i) it addressed how mixing alters perceived quality as well as perceived intensity;

(ii) it compared three pairs of odorants with one constituent common to all pairs.

Furthermore, it explored mixtures constructed at two levels of perceived intensity in order to inquire whether interactions of intensity and of quality depend on level of stimulation. This matter has relevance to models. As discussed below, those models called psychological predict level independence. (A psychological model predicts perceived intensity of a mixture from the perceived intensity of unmixed stimuli.) Some investigators (Berglund and Olsson, 1993a,c; Olsson, 1993) have reported level-independence, though Laing *et al.* (1984, 1994) have found evidence of higher additivity at weaker levels of stimulation. If level dependence holds systematically, then it would rule out these models. In the present case, we consider both psychological and psychophysical models for their predictive power and their implications. (A psychophysical model predicts perceived intensity from parameters of psychophysical functions.)

Most experiments on binary mixtures have yielded surprisingly similar results. Against a criterion of psychological summation, i.e. where perfect summation would represent a mixture that equaled the sum of the perceived intensities of its unmixed components, most mixtures have shown decidedly imperfect summation or hypo-additivity of about the same degree. Within this context, the question of whether pairs of odorants differ in how they add has received little direct attention. We studied three pairs of odorants judged by the same subjects in order to test for odorant-specific differences in additivity. In order to focus on what might cause any differences in degree of summation from pair to pair, the three pairs of odorants all had a common ingredient, linalyl acetate, mixed with a different second ingredient.

In addition to how the three pairs behaved with respect to total intensity, how they behaved with respect to masking also held interest. Would, for example, the perceived amount of linalyl acetate be suppressed more against one component than against another? Would linalyl acetate suppress the different second components differently? Despite enormous commercial interest in masking, the literature on it says almost nothing regarding differences among odorants in masking power or its converse, maskability. With few exceptions (Olsson, 1994), models of odor mixing have essentially nothing to say about such differences, i.e. offer no predictions about the perceived intensity of a component 'inside' a mixture. Curiously, if different pairs of odorants behave similarly with respect to total perceived intensity, then differences in masking must show up just in the relations between qualities or perceived components inside a mixture.

Admittedly, any conclusion that subjects can perceptually 'recover' the unmixed qualities in the mixture rests on a largely undemonstrated foundation. Hence, we cannot presume to know the perceived quality of a mixture by mere acceptance of the ratings given to components. Development of a metric for the study of quality within mixtures will require much more than we venture to give here.

Materials and methods

Subjects

Thirty-three adults from the Yale community (17 females and 16 males between 18 and 45 years of age who professed normal olfaction) participated in three 1.5-h sessions each. The subjects received $5 per hour for participation.

Stimuli

The odorants were fragrance chemicals used often in perfumery and studied previously in mixtures by Schiet and Cain (1990): linalyl acetate (L), cineole (C), geraniol (G), and hexyl salicylate (H). Their respective qualities were lavender-woody, camphoraceous, rose-like and paste-like. The odorants were diluted into concentration series with odorless dipropylene glycol. Interflo P#375 polypropylene pellets impregnated with liquid solutions of single odorants were the odor sources for unmixed stimuli and for construction of mixtures. For presentation of an unmixed stimulus, one pellet of a given concentration was placed in a 250-ml polyethylene squeeze bottle. Head space gas chromatography (Hewlett Packard 5890) performed on the bottles established calibration curves between liquid dilution and vapor concentration. Fifty milliliters of head space at 23°C was expelled into a gas-sampling valve over 2 s and analysed on a 25-m Carbowax column.

The set of mixtures comprised three series of two-component mixtures, each with linalyl acetate (L) in common: linalyl acetate paired with cineole (LC), with geraniol (LG) and with hexyl salicylate (LH). Use of the common constituent allowed consideration of whether it would behave differently in different odor environments. Each series comprised two sets of seven vapor mixtures, a stronger set and a weaker set, as illustrated in Figure 1. To create a mixture, two pellets, one impregnated with one odorant and one impregnated with another, were placed into a bottle. The pellets were placed into the bottles days before subjects participated. This would have permitted some condensation of one vapor-phase odorant onto the other pellet, a phenomenon ignored as probably inconsequential for the resulting vapor-phase concentration of the mixture.

Fractions (F) of saturated vapor concentration in the mixtures equaled: 0.10, 0.15, 0.20, 0.25, 0.30, 0.35, 0.40, 0.50, 0.60, 0.70 and 0.80. When combined across two odorants, these equaled either 0.5 or 1.0 (see Figure 1), except for the mixtures that contained cineole (C). In addition to the 14 mixtures of each pair of odorants, the four concentrations 0.25, 0.50, 0.75 and 1.00 for each constituent alone appeared in the array of stimuli for a total of 22 stimuli per pair. Because of its high perceived intensity, C occurred at half the fraction of saturated vapor of the other constituents and thereby ranged from 0.05 to 0.5. Concentrations (ppm) at saturated vapor pressure were: L = 146; C = 2540; G = 49; and H = 5.3.

Procedure

A session began with an illustration to the subject of how to self-present a sample from a squeeze bottle. The subject learned to squeeze the bottles in a uniform way in order to expel approximately a constant volume of vapor into one nostril (chosen by the subject). A session comprised 44 trials, two passes through the set of stimuli for any pair of odorants (LC, LG or LH), at the pace of one trial per 90 s. Both concentration and composition varied irregularly from trial to trial.

To rate perceived intensity, subjects marked off distance on visual analog scales of 140-mm length. On a trial, the subject received a slip of paper with two scales, one above the other. The upper one served for the judgment of total intensity and the lower for the judgment of the amount of a particular odor component perceived in the mixture. The top scale had a slash mark 37 mm from its left end to indicate the perceived intensity of a standard stimulus given at the beginning of a session and available *ad libitum*. The standard corresponded to one of the two odorants under study in a particular session. It had low-to-moderate perceived intensity, matched across odorants, as determined by pilot measurements.

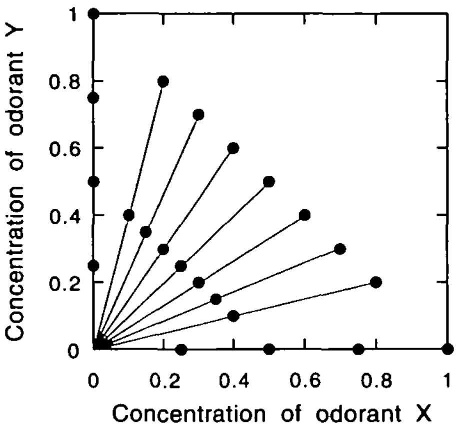

Figure 1 The array of points shows the relationship between the mixed and unmixed stimuli in terms of fraction of saturated vapor (F), the unit used in the present study. There was one exception to the rule shown in the diagram cineole was presented at half the fractions in order to bring the perceived intensity of it into coincidence with that of the other odorants

On a trial, a subject first judged total perceived intensity relative to the standard. If the test stimulus smelled twice as strong as the standard, its intensity was to be indicated by a mark twice the distance from zero as the standard mark. If the test stimulus smelled one-third as strong as the standard, its intensity was to be indicated by a mark one-third the distance from zero as the standard mark, and so on. The subject then judged the perceived intensity of a perceptual component of the stimulus. An exemplar indicated to the subject the quality of the perceptual component to be judged. For a mixture, the exemplar comprised, both in type and concentration, one of its components. For example, when presented with a mixture of 0.5 L and 0.5 H, the subject first judged overall intensity relative to the standard and then received an exemplar of either 0.5 L or 0.5 H. The subject indicated how much of the exemplar seemed to be present in the test stimulus and marked the lower scale accordingly. (Although the lower scale had the same printed length as the upper scale, the subject was told that the distance marked on the lower scale could not exceed that marked on the upper scale. Therefore, the lower scale afforded the chance to apportion perceived intensity between that of the exemplar and 'other'.) Since the mixture 0.5 L–0.5 H occurred twice in a session, on one occasion the exemplar comprised 0.5 L and on the other occasion it comprised 0.5 H.

On trials where the test stimulus itself comprised a single constituent, the exemplar comprised that same stimulus on one trial and the other odorant in that session, at its lowest fraction of saturated vapor, on the other trial.

Results

The arithmetic average taken across replicate judgments from the same subject and also across subjects summarized the judgments of both overall intensity and the intensity of particular components. Psychophysical functions obtained with four concentrations for each unmixed odorant were used to interpolate 'unmixed' perceived intensities for concentrations in the mixtures (cf. Figure 1). The exponents (n) of power functions fitted to the unmixed odorants in the three pairs equaled: $n_L = 0.27$ and $n_H = 0.33$ for LH; $n_L = 0.44$ and $n_G = 0.40$ for LG; and $n_L = 0.33$ and $n_C = 0.18$ for LC.

Analysis of perceived intensity of the mixtures employed two parameters (τ and σ) introduced by Patte and Laffort (1979). The τ-value reflects the relative proportion of perceived intensity for an unmixed component X of a pair X and Y:

$$\tau = \frac{R_X}{R_X + R_Y}, \qquad (1)$$

and the σ-value reflects the degree of additivity of the mixture:

$$\sigma = \frac{R_{XY}}{R_X + R_Y}. \qquad (2)$$

Values of σ for mixtures of equally strong components ($\tau = 0.5$) typically lie around 0.6–0.7 (Olsson, 1993). The present mixtures showed slightly lower additivity. Figure 2 shows, for at least two of the three types of mixtures, some level dependency in the process of interaction. For LG, degree of additivity (σ) for weaker mixtures lay above that for stronger ones, as determined by one-way ANOVA, repeated measures ($P < 0.0001$). No such clear-cut level dependency occurred for mixtures LH and LC and thereby suggests specificity to certain pairs of substances.

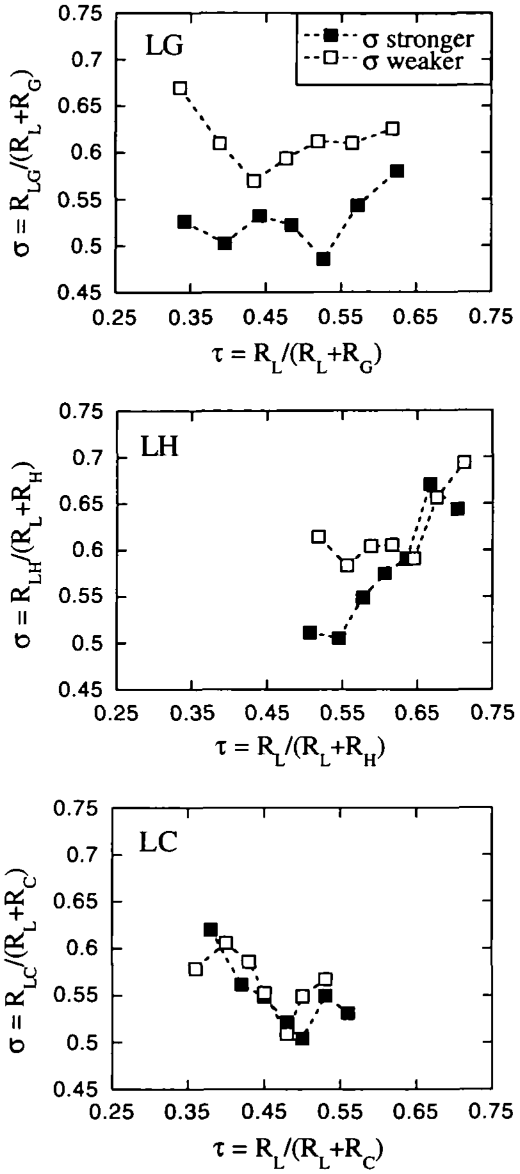

Figure 2 Degree of additivity (σ) in mixtures as a function of the relative intensity of unmixed components (τ) depicted for both stronger and weaker levels of the mixtures (see Figure 1).

Figure 3 displays the perceived intensity of the unmixed components and the intensities of their mixtures. Perceived intensity of the stronger unmixed component of a pair clearly offered a good approximation to the perceived intensity of a mixture.

The amount of any given component perceived in a mixture (R_{XIXY}) was required to lie below total perceived intensity. Olsson (1994) used a ratio similar to Patte and Laffort's τ (Equation 1) to describe relative quality in mixtures:

$$\tau' = \frac{R_{XIXY}}{R_{XIXY} + R_{YIXY}}. \qquad (3)$$

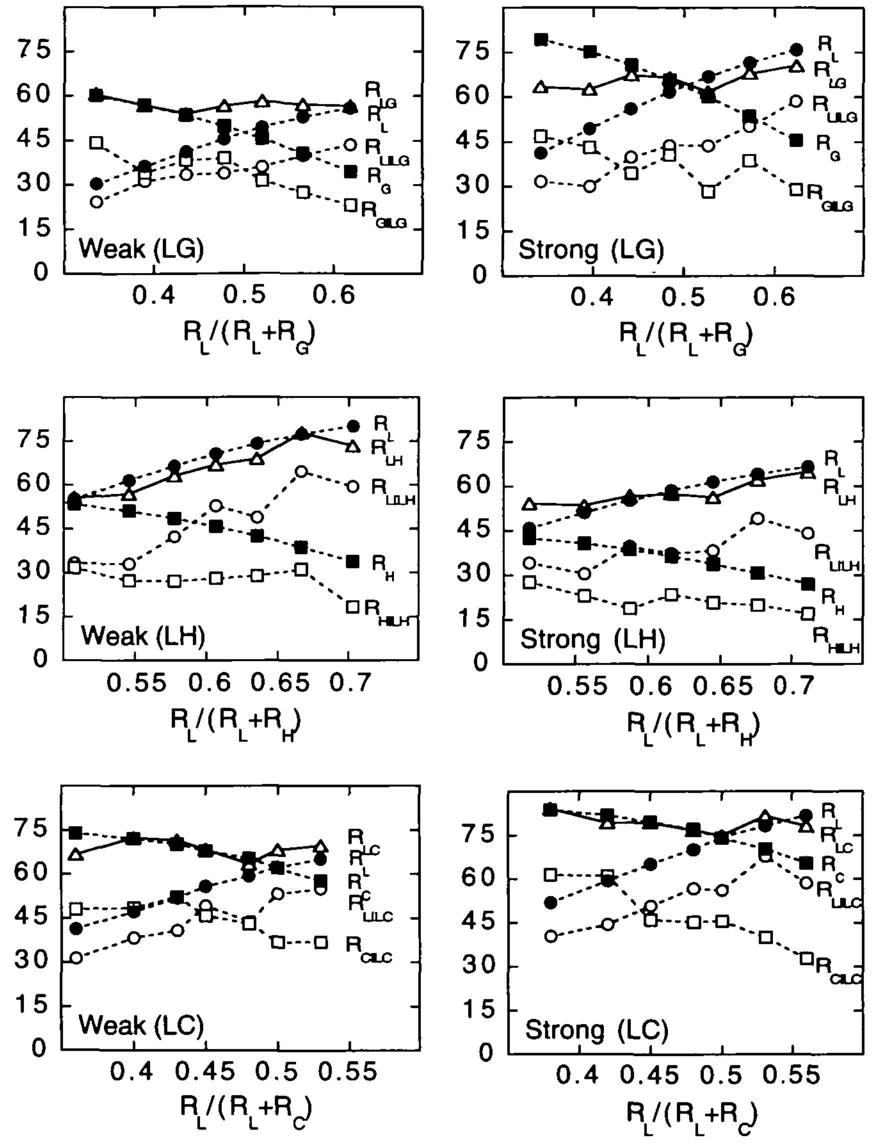

Figure 3 The ordinate represents, in mm, the rated intensity of mixtures (unfilled triangles), the rated intensity of unmixed components (filled circles and squares) interpolated from their psychophysical functions, and the rated intensity of the components when mixed (unfilled circles and squares) as a function of the relative intensities of the unmixed components (τ).

Figure 4 shows the relative intensities of the components in the mixtures (τ′) versus the relative intensities of the unmixed components (τ). For convenience alone, we will sometimes refer to the relative intensities of the components in a mixture, i.e. τ′, as the 'quality' of the mixture.) Three things stand out:

(i) The quality of a mixture did not shift drastically or categorically as its composition varied, i.e. one component never completely dominated.

(ii) Quality shifted between components close to the point τ = 0.50, i.e. where the unmixed components had approximately equal perceived intensity. Others have found the same tendency in other pairs (Laing and Willcox, 1983; Olsson, 1993, 1994). In the present case, however, linalyl acetate seemed to have more tendency to interfere with perception of cineole than with perception of geraniol or hexyl salicylate.

(iii) The general picture of how the quality of the mixture depended on the perceived intensity of the unmixed components was the same for weaker and stronger mixtures.

Discussion

Models of perceived intensity

We considered how both psychological and psychophysical models predicted the intensity of binary mixtures (cf.

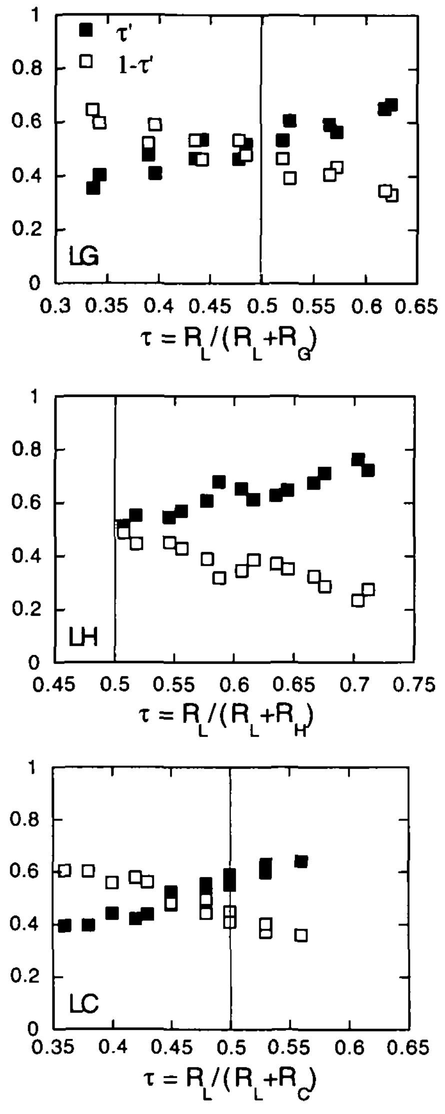

Figure 4 The ratio of perceived intensities within mixtures ($\tau' = R_{X|XY}/(R_{X|XY} + R_{Y|XY})$, defined for convenience as 'quality', plotted against the relative intensities of unmixed components (τ). Closed symbols represent weaker and open symbols represent stronger mixtures. Vertical lines denote mixtures of equally strong components.

Berglund and Olsson, 1993a). As noted earlier, psychological models predict the perceived intensity of mixtures (R_{XY}) from the perceived intensity of the components (R_X and R_Y). Those proposed have implied no particular psychological mechanism for their predictions. Psychophysical models predict intensity from information inherent in the psychophysical relations of the components in a mixture. A model that uses exponents of psychophysical power functions and concentration of components therefore qualifies as psychophysical. Descriptions of models of both types appear extensively in the literature (see Laing *et al.*, 1989) and will therefore be presented rather schematically. The psychological models include the SC Model introduced already, the Vector Model, and the U Model. The psychophysical models include the UPL2 Model, and the Equiratio-mixture (ERM) model.

Stronger Component Model

As mentioned above, the perceived intensity of the mixtures tended to fall close to that of the stronger of the unmixed components. When the data departed from that rule, which Laffort and Dravnieks (1982) called the Strongest Component (SC) Model (properly called the Stronger Component Model for a two-component mixture), they tended to exhibit slight compromise (Cain and Drexler, 1974), whereby the mixture smelled a little weaker than the stronger component (i.e. $R_X > R_{XY} > R_Y$). Berglund and Olsson (1993b) found in three sets of data on binary mixtures that 41% of 51 mixtures exhibited compromise. Olsson (1994), however, found no cases of compromise after exclusion of qualitatively weak mixtures from the data set.

Vector Model

Berglund *et al.* (1973) suggested that the perceived intensity of mixtures equaled the vector sum of the perceived intensity of their unmixed components:

$$\hat{R}_{XY} = \sqrt{R_X^2 + R_Y^2 + 2R_XR_Y\cos\alpha_V}\,, \qquad (4)$$

where $\hat{R}$ denotes predicted perceived intensity and R empirical intensity. The interaction constant α_V, typically determined empirically for components of equal perceived intensities, serves to predict the remaining mixtures in a set. α_V has proven difficult to relate to any properties of unmixed components, such as their perceived similarity to one another (Cain, 1988). For odor mixtures, it has typically fallen in the range 90–130° (cos α_V = 0 to −0.64).

The Vector Model predicts some degree of compromise at angles greater than 90° and level independence at all angles. It cannot predict hyperadditivity, where perceived intensity of a mixture exceeds the sum of the perceived intensities of the unmixed components.

U Model

In order to overcome the inability of the Vector Model to predict hyperadditivity, Patte and Laffort (1979) suggested a modified version called the U Model:

$$\hat{R}_{XY} = R_X + R_Y + 2\cos\alpha_U\sqrt{R_XR_Y}\,. \qquad (5)$$

Other than ability to predict hyperadditivity, the U Model essentially shares characteristics with the Vector Model.

When tested on the same data, both models give approximately equally good fits (Patte and Laffort, 1979; Berglund and Olsson, 1993c).

The models discussed above relate the intensity of mixtures to the perceived intensities of their unmixed components. Even if fairly descriptive of odor interaction, the models fail to explain all of the variance. Moreover, they lack an analytical principle in that they fail to convey information about the process behind odor interaction. Consequently, they fail to make independent predictions of intensity. As indicated above, the psychological models imply the criterion for arithmetic additivity to be $R_{XY} = R_X + R_Y$. Laffort and Dravnieks (1982) pointed out that an odorant added to itself via its own psychophysical function failed to show arithmetic additivity by the criterion of psychological models.

UPL2 Model

Equation 6 shows the power function that normally relates perceived odor intensity (*R*) to concentration (*C*) for single constituents:

$$R_X = k_x C_X^{n_X}\,, \tag{6}$$

where *k* and *n* are constants. The exponent *n* typically falls well below 1.0, as it did for the present constituents, but only an exponent of 1.0 would lead to arithmetic additivity by the criterion of the psychological models.

Laffort and Dravnieks (1982) proposed a psychophysical model in which the exponents of the unmixed components had relevance to odor interaction. Originally called the UPL Model, an improved version with the name UPL2 Model (Laffort *et al.*, 1989) has an interaction constant α_{UPL2} estimated from the exponents as follows:

$$\cos \alpha_{\text{UPL2}} = \frac{R_X \cos \alpha_X + R_Y \cos \alpha_Y}{R_X + R_Y}\,, \tag{7}$$

where

$$\cos \alpha_X = \frac{1 - P^{n_X} - (1 - P)^{n_X}}{2P^{n_X/2}(1 - \mathrm{P})^{n_X/2}}\,, \tag{8}$$

$$\cos \alpha_Y = \frac{1 - P^{n_Y} - (1 - P)^{n_Y}}{2P^{n_Y/2}(1 - \mathrm{P})^{n_Y/2}}\,, \tag{9}$$

and

$$P = \frac{R_Y^{1/n_Y}}{R_X^{1/n_X} + R_Y^{1/n_Y}} \tag{10}$$

For calculation of perceived intensity, α_{UPL2} replaces α_U in Equation 5. Accordingly, the UPL2 Model shares with the U Model the theoretical possibility of hyperadditivity, as well as hypoadditivity, and predictions of compromise.

ERM Model

The ERM Model, originally proposed in gustatory psychophysics (Frijters and Oude Ophuis, 1983), has made accurate predictions of homogeneous taste mixtures (Frijters *et al.*, 1984; De Graaf and Frijters, 1987). When applied to olfaction, the model proved less successful (Schiet and Frijters, 1988):

$$\hat{R}_{XY} = k_{XY} C_{XY}^{n_{XY}}\,. \tag{11}$$

The ERM Model indicates that just as power functions can describe the perceived intensity of substance X or Y, so an appropriate power function can describe a mixture composed of a fixed ratio of concentrations, e.g. 0.50:0.50 in our units of proportion of saturated vapor concentration. The ERM Model suggests that the function for the mixture would lie between the functions of the components. For any fixed ratio *p* of concentrations *i* and *j* such that $p = i/(i + j)$, it is possible to write the multiplicative constant and the exponent for the mixture function as:

$$k_{XY} = \frac{\dfrac{pk_X}{C_{XS}} + \dfrac{qk_Y}{C_{YS}}}{\dfrac{p}{C_{XS}} + \dfrac{q}{C_{YS}}} \tag{12}$$

and

$$n_{XY} = pn_X qn_Y\,, \tag{13}$$

where $q = 1 - p$ and C_{xs} and C_{ys} represent concentrations that correspond to the same perceived intensity as that of a standard stimulus (*S*) and are used to compensate for a constant error in response thought to occur for certain scaling methods (Frijters and Oude Ophuis, 1983).

Equations 12 and 13 comprise weighted averages of the two psychophysical functions for unmixed components. The higher the concentration of odorant X the greater impact of the constants k_x and n_x on the shape of the function for the mixture.

Indices of fit

Two different measures of goodness of fit were applied to predictions of perceived intensity calculated for the five

Table 1 Pearson coefficient of correlation (*r*) and U-index of fit calculated between the predicted and obtained perceived intensity of mixtures for the five models

Model	Type of Mixture							
	LH		LG		LC		Median	
	r	U	r	U	r	U	r	U
SC Model	0.93	0.69	0.82	−0.82	0.87	0.70	0.87	0.69
Vector Model	0.89	0.77	0.87	−0.17	0.85	0.70	0.87	0.70
U Model	0.78	0.58	0.86	−0.17	0.80	0.56	0.80	0.56
UPL2 Model	0.87	−3.86	0.82	−9.89	0.80	-48.88	0.82	−9.89
ERM Model	0.92	0.39	0.89	−1.46	0.89	−5.04	0.89	−1.46

models, the Pearson coefficient of correlation (*r*) and the U index of fit (Eisler and Roskam, 1977):

$$U = 1 - \frac{\Sigma(R_{XY} - \hat{R}_{XY})^2}{\Sigma(R_{XY} - \bar{R}_{XY})^2}, \qquad (14)$$

where $\bar{R}$ in Equation 14 refers to the mean intensity of all mixtures in a set. Whereas *r* assumes linearity in the relationship between empirical and predicted intensities, the U-index makes no such assumption. The farther from identity the empirical and predicted intensities, the lower will be U, which can range from 1 at identity to negative infinity.

The models did not vary greatly in correlational fit, with the U and UPL2 models somewhat poorer than the others. By the U-index, the three psychological models (Vector Model, U Model, and SC Model) outperformed the two psychophysical models (Table 1). In considering the results of the U-index, bear in mind that the Vector and the U models use part of the very data they wish to describe, i.e. the relationship between mixed and unmixed intensities for equally intense unmixed stimuli, to estimate their relevant parameters and to fit the rest of the data. They therefore have a distinct, though somewhat dubious, advantage.

How do the models fail? As shown in Figure 2, there was some level dependency which neither of the psychological models can rationalize despite their apparent accuracy. The models that predicted intensity from the exponents of psychophysical functions, the ERM Model and UPL2 Model, made predictions that lay farther off the diagonal (Figure 5). The UPL2 Model over-predicted the perceived intensity of all three pairs, whereas the ERM Model over-predicted two and under-predicted one. Hence, the principle by which psychophysical information on single components reflects itself in a model of interaction seems to evade the psychophysical models presented here.

Perceived components in mixtures

Evidence suggests that the perceived quality of a binary mixture lies between those of its components (Engen, 1964; Moskowitz and Barbe, 1977; Gregson, 1980). Our data indicated that, for equally strong unmixed components, what we have denoted the quality of a mixture tends to lie about midway between that of the components (Figure 4). Such an outcome suggests little differential masking from one odorant to another, i.e. B would mask A neither better nor worse than A would mask B. The pair linalyl acetate-cineole, however, gave some reason to doubt strict generality of the rule (see Figure 6). If the generality proved true for all pairs of odorants, and for all triads, tetrads, etc., then the special efficacy of a masking agent would lie strictly in whether it imparts an acceptable quality rather than in whether it suppresses the intensity of a malodor (see Laing *et al.*, 1994). Research on odor mixtures has hardly explored enough odorants, not to mention single aroma chemicals or blends chosen from practical experience for high masking power, to have settled the question.

How one sees the role of quality in masking can depend on the point of view (see Rabin and Cain, 1989). Some masking in real-world applications may arise from an assimilation of qualities, rather than mere replacement of quality. The malodor may become part of a blend, much like a small ink spot on a piece of paper might become part of the black and white pattern of a Dalmatian dog drawn around the spot. If shown the ink spot separately and asked to find it, a person would readily do so, even though he might never have suspected that the dog had been drawn to assimilate or obscure the ink spot.

In the present case, we gave the subject the 'ink spot' in the form of an exemplar of a component in the mixture. We asked not only about presence or absence, but also about

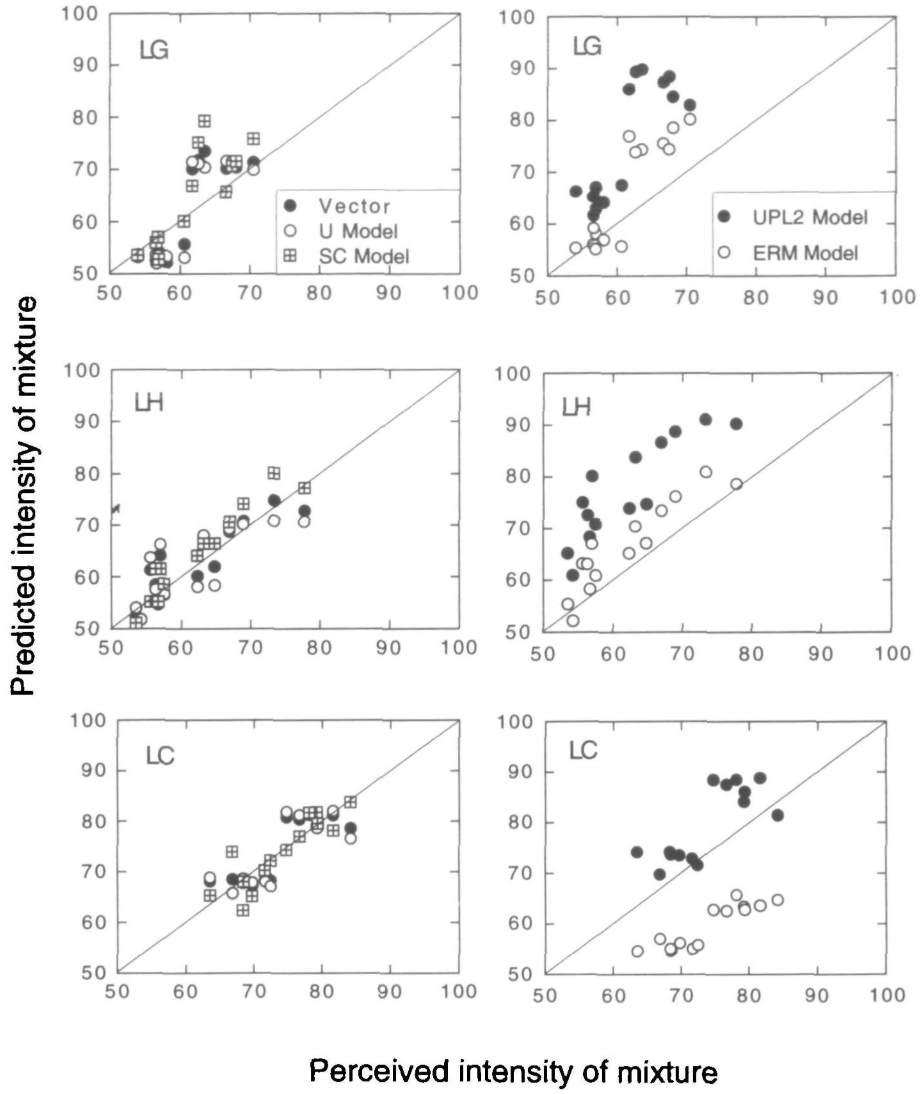

Figure 5 Rated intensity versus predicted intensity according to five models: the Vector, U and SC models on the left, and the UPL2 and ERM models on the right.

amount. This situation favored a very analytical perspective which may not translate into real-world applications of maskers. Based upon their judgments of unmixed stimuli, subjects nevertheless found it quite challenging to quantify components. When presented with a single odorant and an exemplar of the same odorant, subjects typically estimated the odorant to contain less than 100% of itself. This could reflect conservatism brought about from insecurity in the judgment (see Laing and Francis, 1989). It could alternatively reflect a tendency to attend to a characteristic of the odor which somehow fails to constitute the whole percept (Gregson, 1986). The argument in favor of conservatism seems bolstered by a finding that subjects would typically 'find' some of the other component of a mixture in each unmixed component. The usual split between appropriate and inappropriate components for the unmixed stimuli averaged about 80:20, rather than the theoretically expected 100:0.

Whatever biases operated for single components presumably operated as well for the mixtures. These should, to some degree, cancel each other in a plot such as that shown in Figure 6 which relates the perceived intensity of a quality in a mixture (e.g. R_{XIXY}) to the perceived intensity of the same quality of the relevant component presented separately (i.e. R_{XIX}). As could be expected, most points fell below the line of identity and thereby reflected some degree of masking. The only exception occurred for the mixture LC, where

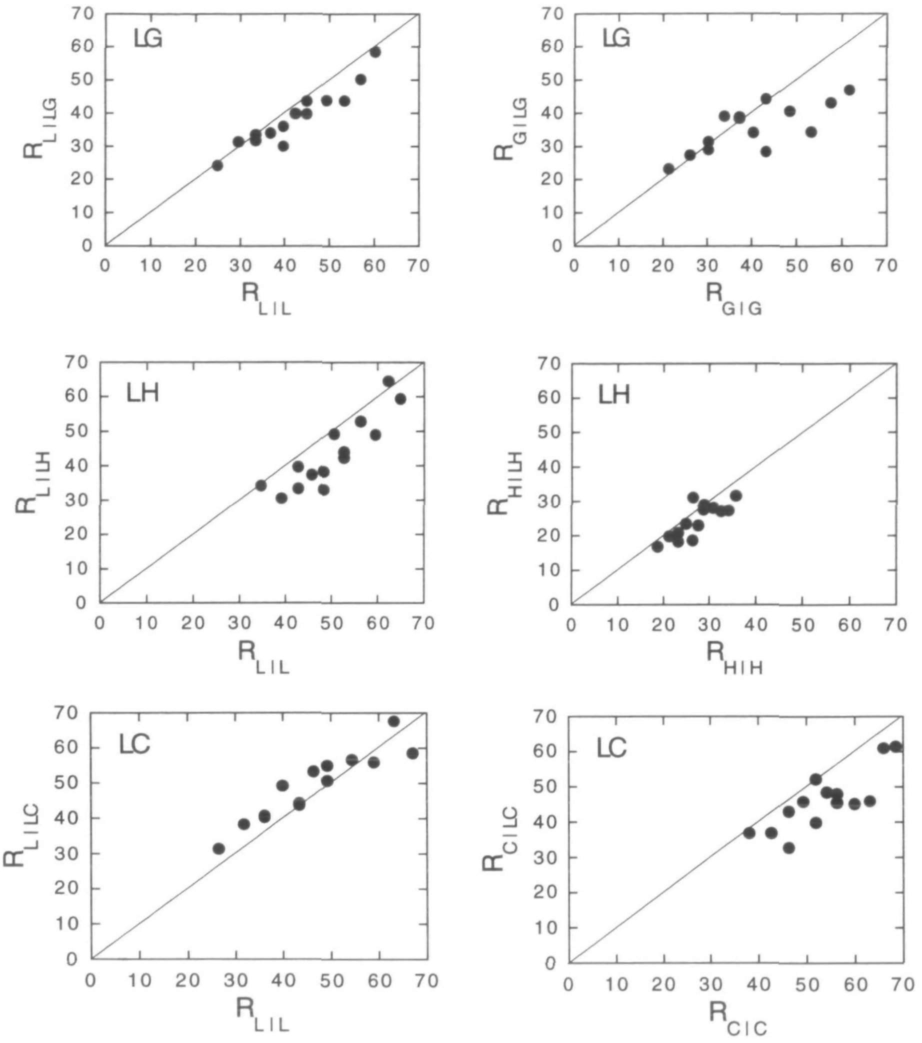

Figure 6 Rated intensities of individual components in mixtures versus rated intensities of the same components in unmixed stimuli.

the intensity of L seemed, if anything, slightly enhanced. Correspondingly, the intensity of C in the mixture seemed more suppressed.

Mixture show apparent suppression

Why did the empirical mixtures show such low additivity relative to the predictions of the psychophysical models? Perhaps additivity of mixtures falls below the additivity of substances added to themselves. The additivity of a single component can be defined from its exponent such that (from Laffort, 1989):

$$\sigma_X = [\tau^{1/n} + (1-\tau)^{1/n}]^n, \qquad (15)$$

where τ now represents the relative intensity of one 'component' (R_{X_1}) to another 'component' (R_{X_2}) of the same substance.

To compare the additivity of the mixtures to the 'self-additivity' of components, σ was determined by inserting the exponents of the psychophysical functions into Equation 15 for each single odorant. For this, we kept τ at 0.5, i.e. dealt only with components of equal strength. The six σ-values for the three odorant pairs were: $\sigma_L = 0.60$ and $\sigma_H = 0.63$ for the pair L and H, $\sigma_L = 0.68$ and $\sigma_G = 0.66$ for L and G, and $\sigma_L = 0.63$ and $\sigma_C = 0.57$ for L and C. The σ-values for the mixtures of equally strong components were: $\sigma_{LH} = 0.55$, $\sigma_{LG} = 0.55$, $\sigma_{LC} = 0.53$. The additivity of the mixtures is lower than that of the components and, incidentally, more stable from mixture to mixture. Berglund and Olsson (1993b) found a very similar outcome for three binary odor mixtures of pairs of the odorants ethyl acrylate, pyridine and acetone. The additivity of the mixtures approximated that of the less additive component in a pair.

Some conclusions

At this relatively early, one might even say primitive, stage of research on odor mixtures, models might serve principally to highlight issues that require focal attention, such as the following:

1. The precision of the data used to test models or any other features of mixture perception needs improvement. The present investigation employed a larger than usual number of subjects ($n = 33$) in order to reduce uncertainty in testing models, but the precision of the data still left much to be desired. The strongly compressive nature of olfaction means that perceived odor intensity in an experiment may span only a two- or three-to-one range and even 10–15% variations in perceived intensity can obscure relevant effects. Although we do not mean to impugn the data from other studies, the amount of apparently random variation seen in most studies has been large. In such apparently random variation may lie some systematic effects.

   Imprecision in the data on perceived intensity could derive from various sources, each of which could be laboriously studied for its contribution: inclusion of some subjects who discriminated poorly, asking subjects to rate too many stimuli per session or per unit time, poor choice of scaling methods (see McBride and Anderson, 1991), or studying untrained or unpracticed subjects. Rather than following the laborious path, we might approximate a solution to the problem by studying a few screened, practiced subjects presented with only a few well-spaced trials per session over many sessions. Whatever increase in labor accompanies this strategy may prove worthwhile.

2. Lack of reliability has left uncertainty regarding, for example, the phenomenon of compromise, where the perceived intensity of a mixture falls between the intensities of the components. (To think of compromise more dramatically, one can think of the weakening of net odor intensity with the addition of a second component, i.e. add more, get less.) Cain and Drexler (1974) and Cain (1975) found it consistently, though to different degrees, whereas Olsson (1994) did not find it consistently. Even though most studies have technically found compromise (Berglund and Olsson, 1993c), its existence remains hazy. If compromise occurs predictably, it would place a seemingly important limitation on possible mechanisms for odor interactions since it would suggest active suppression rather than merely hypo-additivity. The investigation of mixtures should decide whether compromise occurs reliably and systematically. Demonstration of the phenomenon can depend upon choice of appropriate proportions for the components of a mixture. Large steps in concentration between stimuli may, for example, skip the zone at which the phenomenon appears most prominently. Because of the critical nature of compromise to the general understanding of mixtures, it should be explored with various stimuli at critical concentrations in binary and higher order mixtures.

3. Our finding that a lower level of stimulation might show greater additivity than a higher level highlights the need for more explicit concern with level dependence. Some investigators have found it whereas others have not. The previously unaddressed question of whether level independence holds for odor quality also merits further attention. Our data say that independence occurs. In Figure 4, the quality of mixtures gave little reason to suggest a difference due to level of intensity. With respect to both intensity and quality, a thorough understanding of the perception of mixtures needs to include both threshold stimuli and suprathreshold stimuli across the dynamic range of the olfactory continuum.

   At threshold levels, the concept of 'additivity' of mixtures translates into whether stimuli behave independently in their sensory effects. Some data imply that mixtures of two or three components exhibit independence of components, what one might see as 'stimulus additivity' (Guadagni *et al.*, 1963; Köster, 1969; Patterson *et al.*, 1993). Laska and Hudson (1991) found that mixtures of more components exhibited complexity-dependent synergy. This provocative result requires replication.

4. Any 'models' of mixtures might usefully make predictions about masking, i.e. might predict intensity of components within mixtures as well as total intensity. The study of masking seems fraught with difficulties. The ability of a subject to make a quantitative judgment about the amount of a particular sensory quality 'present' in a mixture implies preservation of information about the qualities of the ingredients in the sensory message. To talk about the 'amount' present, however, biases the discussion. It is a little like saying, 'I can see a lot of John, Sr in the facial expressions of John, Jr.' Although John Jr did in fact obtain half his genes from John, Sr, it is not as if John, Sr's facial expressions are literally 'in' John, Jr. Perhaps the judgment should be one of

similarity both in the case of odors and in the case of John, Jr's various characteristics. The study of similarity tends to bias perception toward holistic processing and the study of 'amount in a mixture' biases perception toward analytical processing. It is not yet clear which approach, if either, is preferable.

From the laboratory data collected in this and other studies (Cain and Drexler, 1974; Cain, 1975; Gregson, 1980, 1986; Laing and Willcox, 1983; Laing *et al.*, 1984; Laing, 1988; Olsson, 1994), which have put subjects in an analytic mode of processing, masking of one odor by another appears to reflect just the general reduction in intensity that occurs when any two odorants are mixed. If odor A with a perceived magnitude of 10 is mixed with odor B also with a perceived magnitude of 10, the resulting mixture will have a perceived magnitude of 14, with A and B now each at 7. The tendency for equally strong unmixed components to yield equally potent components in the mixture (Olsson, 1993, 1994) suggests that neither A nor B possesses a more potent masking ability. Nevertheless, manufacturers of finished fragrances assert that some odors have much more masking potency than others. Whether this disparity represents differences in how the task is approached or differences in the materials studied is unknown.

Insofar as masking often involves the assimilation of the quality of the masked into the masker, then some new experimental and perhaps conceptual approaches seem called for. Unfortunately, there exists no truly satisfactory metric for odor quality, yet this would seem essential to any broad study of quality assimilation. The reasons to study masking go well beyond any commercial applications. Odor masking is just as important a basic phenomenon as sound masking, which also happens to have practical consequences, but which has provided important information about the mechanisms of hearing. Recent work on how odorants themselves modulate the flow of odorant-activated current in olfactory receptor cells has apparent relevance both to transduction and, interestingly, to masking (Kurahashi, *et al.*, 1994).

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