Odor magnitude: Coarse vs. fine grain

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Despite a dismal reputation, olfaction's resolving power actually appears to be keen, especially when the contaminating influence of noise in the stimulus is discounted from psychophysical performance. In a previous investigation, subjects were able to resolve a change of 4% in the concentration of butyl alcohol. In the present experiment, these same subjects resolved a change of 9% in the concentration of amyl butyrate. The data imply that resolving power varies among odorants. The growth of odor intensity assessed by magnitude estimations of easily discriminable (i.e., grossly different) concentrations also varies among odorants. These observations prompt the question: Does an odorant for which resolution is relatively difficult lead to slower growth of perceived intensity with concentration than an odorant for which resolution is easy? In a scaling experiment, amyl butyrate indeed led to slower growth of intensity than butyl alcohol. Nevertheless, amyl alcohol, which permitted poorer resolution than butyl alcohol, led to approximately the same rate of growth as butyl alcohol. Accordingly, growth of odor intensity with concentration may correlate only weakly with resolving power.

Odor intensity grows with concentration at different rates for different odorants. A tenfold change in concentration may lead to more than a fivefold or less than a twofold change in perceived intensity, depending on the odorant. The psychophysical functions that relate odor intensity to concentration are erected from judgments of easily discriminable concentrations that typically vary in steps of about two or three to one. The issue here is whether the differences in growth rate that emerge from judgments of such widely spaced stimuli bear any relation to how keenly persons can discriminate very small differences in concentration.

It might seem reasonable to anticipate that rapid growth of intensity would signal easy discrimination of small differences, whereas slow growth would signal only poor discrimination. No study has inspected the matter systematically, but the relevant data in olfaction have suggested no relation whatsoever between discriminability and the growth of intensity. Which is faulty, the concept or the data?

Differential sensitivity for smell has consistently appeared poor (Gamble, 1898). The 19th century finding that a 25% to 33% alteration in concentration gives rise to a just-noticeable difference has withstood most subsequent scrutiny (e.g., Stone, 1964; Zwaardemaker, 1925). Moreover, this estimate has seemed unnecessary of revision for any particular

odorants in the absence of any clear sign that differential sensitivity varied with the odorant (Stone & Bosley, 1965). In short, resolving power has appeared uniformly dull.

For differential sensitivity to be uniform in spite of variation in the growth rate of perceived intensity actually poses no theoretical dilemma. Ability to discriminate small differences in stimulation is limited largely by minor fluctuations in an observer's impression of a stimulus (Cattell, 1893; Crozier & Holway, 1937; Green & Swets, 1965; Marks, 1974). If, from moment to moment, the fluctuations are very small, then two successive stimuli may be resolved reliably when they differ by merely a few percent. If the fluctuations are larger, the stimuli may be resolved reliably only when they differ by many percent. Hence, measures of resolving power, such as the difference limen, serve primarily as measures of variability, and no a priori reason compels such measures to reflect the perceived magnitudes of stimuli that differ from each other by large amounts (see Stevens, 1975). By this reasoning, to anticipate a relation between the growth of intensity and the ease of discrimination appears faulty.

The matter could be considered more or less closed in the absence of reason to believe that the data on differential sensitivity are in fact grossly in error. Every estimate of differential sensitivity, whether for olfaction or any other modality, represents the net influence of the various sources of noise that may limit discrimination (Cain, 1977b). The moment-to-moment fluctuations in the impression of a stimulus result not merely from fluctuations in the sensitivity of the sense organ, but also from fatigue, fluctua-

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tions in attention, and, most important in the present context, from fluctuations in the physical intensity of the stimulus. Unmeasured and unacknowledged fluctuations in vapor-phase concentration have undoubtedly contaminated most previous estimates of differential sensitivity for olfaction. Reduce these fluctuations and differential sensitivity will increase. Discount them entirely by appropriate statistical means and the index of sensitivity will increase even more. The experiment that follows illustrates these matters and reveals that olfaction's differential sensitivity is actually quite keen. Comparison of the present result with results obtained under similar circumstances will reveal, moreover, that differential sensitivity depends on the nature of the odorant (Cain, 1977a). Such variation provides incentive to reinvestigate the possibility of a relation between discriminability and the growth of perceived intensity. This is the subject of a second experiment.

EXPERIMENT 1: DISCRIMINATION

Method

Subjects. Two young adults participated. Both had served previously in an almost identical experiment, where the stimulus had been n-butyl alcohol.

Apparatus. n-Amyl butyrate served as stimulus. An air-dilution olfactometer controlled and delivered the stimulus in the form of two streams of odor-laden air (flow rate: 2 liters/min). The concentration in one stream was slightly greater than that in the other. The streams emanated from two lengths of flexible Teflon tubing. These appeared identical to the naked eye.

A gas-chromatograph (Perkin-Elmer F11), equipped with a gas-sampling valve, registered vapor-phase concentration. The instrument was used to assess both the magnitude and variability of concentration, as described below.

Procedure. In any given session, two concentrations were presented. The subject's task was to decide, in a forced-choice procedure, which seemed stronger. The tubes were presented from behind a screen and the subject sampled each monorhinically. After making a choice, the subject was told the correct answer. A session comprised 5 practice and 100 test trials.

Three pairs of concentrations were studied: (a) 1.49 and 1.67, (b) 1.49 and 1.60, and (c) 1.49 and 1.55 mg/liter. Each subject evaluated each pair in two sessions. From session to session, the order of evaluation progressed according to the sequence abccba.

Psychophysical data comprised only half the results of the experiment. The other half comprised the outcome of chromatographic analysis. The chromatograph was treated much like the human subjects and evaluated 100 samples of each pair of test concentrations.

Details of the chromatographic sampling were as follows: The tube that led from the olfactometer was connected to a bifurcated Teflon tube, one arm of which went to the atmosphere and the other to the inlet of the gas-sampling valve. A vacuum pump connected to the valve's outlet drew the odorous air through the valve at a rate of 110 ml/min. This air passed through the sampling loop (5-ml capacity) of the valve for 20 sec, whereupon the contents of the loop were shunted into the column (2% Carbowax 20M on Gas-chrom Q) for analysis. The resulting peak was integrated, thereby providing a measure of the mass of odorant in the loop. The chromatograph evaluated five samples of one concentration and then five of the other. This alternating sequence continued until 100 samples of each had been analyzed.

Both the psychophysical and the chromatographic evaluations were performed on samples at room temperature. Ambient temperature varied from day to day. Such variation altered absolute, though not relative, concentrations. Since the chromatographic analysis typically stretched across days, the outcome (average of higher and lower concentrations) on any particular day was normalized to the mean for all days. Hence, if the average concentration on one day was 90% of the grand mean, then both the higher and lower concentrations measured on that day were multiplied by 1.11, and so on.

Results

Figure 1 (left) displays how percent correct in the forced-choice task varied with difference in concentration. The bars connected to the middle data point display the *range* of performance between the subjects. Absence of bars on the other points signifies that the range failed to exceed the size of the symbol.

Keeness of discrimination can be expressed by the value of k , the Weber fraction, in the relation

$$k = \Delta c/c, \quad (1)$$

where c represents the lower concentration and Δc represents the increment necessary to permit resolution on 75% of trials. The value of k , expressed as a percentage, equaled 9.1%. This is roughly twice the size of the value (4.2%) obtained when these subjects judged n-butyl alcohol (Cain, 1977a). It is noteworthy, however, that both values are far below the commonly accepted value of about 30%.

In view of the excellent performance of the subjects, it may seem surprising that fluctuations in the stimulus might have limited performance, but they did. The average coefficient of variation of vapor phase concentration was 5.5%, large by comparison to the psychophysical performance.

In order to permit direct comparison of the psychophysical to the chromatographic data, the frequency distributions derived from chromatographic measurement were used to erect receiver operating characteristic (ROC) curves for each pair of test concentrations (right side of Figure 1). To erect each curve, various concentrations falling within the overlapping distributions for a given pair of nominal concentrations, denoted *high* and *low*, were chosen arbitrarily as locations of decision criteria. Each criterion was used in turn to address the question: Was the concentration on any given trial drawn from the distribution of *high* concentrations? Each criterion gave rise to two conditional probabilities: (1) the probability that a concentration greater than the criterion would be deemed "high," given that it was actually drawn from the distribution for the *high* nominal concentrations, and (2) the probability that a concentration greater than the criterion would be deemed "high," given that it was actually drawn from the distribution for the *low*

Figure 1. Left side shows percent correct in the intensity discrimination task vs. the average difference in vapor-phase concentration between the high and low members of each pair of test concentrations. Right side shows ROC curves derived from chromatographic measurement of the pairs of test concentrations. Inset on right side portrays the comparison of psychophysical performance, percent correct, with predictions of optimum performance, percent area under the ROC curves.

nominal concentrations. Each criterion yielded one point on a curve. In principle, the integrated area under an ROC curve represents the maximum performance achievable in the psychophysical task (Egan, 1975). The inset on the right side of Figure 1 permits a comparison of psychophysical performance with optimum performance predicted chromatographically. On the average, the subjects performed 86% as well as predicted.

The question arises, What is the differential sensitivity to amyl butyrate when the fluctuations in the stimulus are discounted? In order to address the question, the measures *percent correct*, predicted and obtained, were converted to d' . This, in turn, permitted calculation of the relative variances, S_p^2 and S_s^2 , of the psychophysical performance and the stimulus, respectively, via the relation

$$S^2 = (1/d')^2. \quad (2)$$

On the assumption that the variance of the psychophysical data (S_p^2) equals the linear combination of the variance of the stimulus (S_s^2) and the variance of the olfactory system (S_o^2), i.e.,

$$S_p^2 = S_s^2 + S_o^2, \quad (3)$$

the percent of the total variance that arises from the stimulus is given by S_s^2/S_p^2 . This analysis was conducted for each pair of nominal concentrations. On the average, the stimulus accounted for 32% of the total variance.

The terms S_p , S_s , and S_o in Equation 3 were initially known only relative to one another. Nevertheless, knowledge of the standard deviations of the fre-

quency distributions of vapor-phase concentration allowed exact specification of S_s . This, in turn, permitted exact specification of the coefficient of variation for the olfactory system (i.e., S_o expressed as percent). The average value turned out to be 8.1%. This is the value of k , expressed as percent, that could be expected if the stimulus were controlled with great precision.

When the same analysis was conducted on data for butyl alcohol, the corrected value for k turned out to be 1.3%. This seems unrealistically low. When, as in this instance, subjects show particularly good acuity (uncorrected $k = 4.2\%$) despite fluctuations in the stimulus, even small random deviations in chromatographic analysis or in psychophysical performance may cause relatively large percentage alterations in the "corrected" value of k . The matter of particular interest here, however, is that k , corrected or uncorrected, is substantially smaller for butyl alcohol than for amyl butyrate.

EXPERIMENT 2: SCALING

Does the finding that discriminability of amyl butyrate, though excellent, is poorer than that of butyl alcohol imply that the odor magnitude of amyl butyrate grows less rapidly than that of butyl alcohol? The same question can be asked with respect to butyl alcohol and amyl alcohol. In a previous experiment, where stimuli were delivered via glass vessels rather than via an olfactometer, the values of k , corrected for noise in the stimulus, were 6.8% for butyl alcohol and 16.3% for amyl alcohol (Cain, 1977a). The following experiment seeks to answer the questions and provides mixed support for

the conclusion that discriminability is linked to the growth of intensity.

Method

Subjects. Nineteen young adults participated.

Apparatus. Stimuli were delivered in two ways: (1) via glass vessels used in a previous study (Cain, 1977a), and (2) via the olfactometer described above. The glass vessels (60 ml) contained two ports, one near the bottom and one at the top. A perforated filter-disk rested in the interior of the vessel a short distance above the lower port. A cotton ball impregnated with 1 ml of odorous solution sat upon the disk. In order to smell the contents of the vessel, the subject drew air through the lower port, up through the cotton, and into the nose.

The vessels were used for presentation of n-butyl alcohol and n-amyl alcohol. Five concentrations of each were prepared in aqueous solution. These gave rise to vapor-phase concentrations, assessed chromatographically, that spanned the range 0.065 to 4.30 mg/liter for butyl alcohol and 0.070 to 4.30 mg/liter for amyl alcohol.

The olfactometer, a two-channel device, was used to present butyl alcohol and amyl butyrate. There were five concentrations of each: 0.070 to 4.10 mg/liter for butyl alcohol and 0.040 to 2.00 mg/liter for amyl butyrate.

Procedure. An experimental session consisted of two parts. The first part required judgments of butyl alcohol and amyl alcohol presented via the vessels, and the second part required judgments of butyl alcohol and amyl butyrate presented via the olfactometer. In each half, the subject assigned the number 10 to the middle concentration of butyl alcohol and subsequently assigned numbers proportional to perceived magnitude (method of magnitude estimation). Order of presentation varied irregularly with respect to concentration and, from trial to trial, alternated from one odorant to the other. This permitted the subject to use the same unit of subjective magnitude for both odorants (see Cain & Moskowitz, 1974). Furthermore, it offered the closest possible comparison of the psychophysical functions.

Results

Figure 2 portrays the psychophysical functions for butyl alcohol and amyl butyrate presented via the olfactometer (upper pair) and those for butyl alcohol and amyl alcohol presented via the vessels (lower pair). The rate of growth for butyl alcohol was markedly higher than that for amyl butyrate. For instance, a tenfold change in concentration caused, on the average, about a threefold change in the intensity of butyl alcohol and less than a twofold change in the intensity of amyl butyrate. The reliability of this difference in growth-rate was checked by means of a *t* test performed on the exponents of power functions fitted to the data of individual subjects. Seventeen of the 19 subjects produced a higher exponent for butyl alcohol than for amyl butyrate. The average exponent was 0.48 for butyl alcohol and 0.26 for amyl butyrate. This difference was significant ($t = 5.14$, 18 df, $p < .001$).

The function produced when butyl alcohol was presented by means of vessels was similar to that produced when this odorant was presented by means of the olfactometer. Moreover, the function for amyl alcohol was quite similar to that for butyl alcohol.

Figure 2. Upper part depicts psychophysical functions for amyl butyrate and butyl alcohol delivered via an olfactometer. Lower part depicts psychophysical functions for amyl alcohol and butyl alcohol delivered via glass vessels.

DISCUSSION

Olfaction's differential sensitivity no longer seems inferior to that of other modalities, including vision and hearing, where *k* is approximately 10% (i.e., 0.10) for successively presented stimuli (Mueller, 1951; Schacknow & Raab, 1973). Unacknowledged fluctuations in the stimulus are apparently responsible for olfaction's previous reputation. These fluctuations must have been large indeed for *k* to equal, and in some cases exceed, 30%. Without intending to do so, laboratory experiments apparently mimicked actual environmental conditions where concentration fluctuates considerably from moment to moment.

Theoretical arguments aside, Teghtsoonian (1971) has observed that there is a high (negative) correlation between the growth of perceived intensity on various sensory continua and corresponding Weber fractions (*k* in Equation 1). This prompted him to propose that the direct scaling experiment and the experiment on differential sensitivity measure a common intensive characteristic of sensory systems.

The present results could be viewed to suggest a less-than-perfect negative correlation between differential sensitivity and the growth of odor intensity.

It remains to be seen whether the true correlation is negative and whether it is high or low. Whatever, the outcome, however, it is important to recognize that each sense modality must be considered, sooner or later, on its own terms. Upon close inspection, each sensory system possesses unique properties, both neural and nonneural in origin, that may force nonconformity to any general rule of sensory function.

Olfaction offers unmatched opportunities for nonlinear distortion of the stimulus as it is conducted to the receptors. For instance, uptake of vapors in the nasal epithelium seems to be a nonlinear function of both concentration and flow rate, and the magnitude of the departure from linearity varies with the nature of the stimulus (Aharonson, Menkes, Gurtner, Swift, & Proctor, 1974). Furthermore, the pattern of deposition of molecules onto the olfactory epithelium varies with the nature of the stimulus (Hornung & Mozell, 1977). Once in the mucus, molecules of odorant will migrate to the membrane of the receptors at a rate and concentration that will depend on poorly specified and generally unpredictable interactions between solvent and solute (Haring, 1974). These nonneural sources of distortion make it unclear whether differences in the growth of the psychophysical function or in the Weber fraction bear any relation to neural functioning. Some of the nonneural modifications may merely add noise to the stimulus and may thereby influence the Weber fraction, whereas other modifications may induce a systematic alteration in concentration and may thereby alter the growth of the psychophysical function. Such possibilities suggest that olfaction may hardly qualify at present as the best battleground for any theoretical disputes regarding a general linkage between the growth of perceived intensity and differential sensitivity. Nevertheless, the finding that the Weber fraction, like the psychophysical function, varies from odorant to odorant opens new possibilities to relate the coarse to the fine grain of odor perception.

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