stereotyped motor phenomena (*3*) which cannot be interpreted as behavioral responses (*13*). It does not seem, however, that our present findings can explain these phenomena, since the most immediate and constant motor responses are ipsilateral to the stimulated amygdala (not crossed, as they would be if the ipsilateral connection were involved), and bilateral cortical ablation does not suppress them (*14*).

The main source of amygdalo-frontal projections, that is, the basal magnocellular nucleus, is very rich in acetylcholinesterase (AChE) (*15*); hence the influence of the amygdala on the neocortex may well involve cholinergic projections. This fact, together with a recent demonstration of basal prosencephalic AChE-rich cells projecting to the motor cortex (*16*), increases the importance of making a comprehensive study of a cholinergic input to the motor cortex that interacts with noradrenergic and dopaminergic afferences.

The amygdala has played, throughout phylogeny, an important role in elaborating behavioral patterns. In lower mammals its input is chiefly olfactory; in higher mammals the amygdala becomes complicated by the increasing importance of other sensory inputs (*17*). Simultaneously there has been an elaborate development of the cerebral cortex as the ultimate associative level. Probably, the amygdala had to widen its field of action, its basolateral complex undergoing a "vertiginous" development together with the associative neocortex and the mediodorsal nucleus of the thalamus (*18*). It is likely, therefore, that two-way monosynaptic relationships between the amygdala and the neocortex and thalamus appear only above a certain evolutionary stage (*17*).

In conclusion, the amygdala has been considered as the site of evaluation of the motivational significance of stimuli from the environment and the internal milieu (*1, 19*), exerting its influence by modulating hypothalamic drive mechanisms (*19*). To this one should add that it has a double influence on the frontal cortices: indirectly through a thalamic relay (*8*) and directly by way of the paths identified here. In this way, possibly the higher the evolutionary stage, the connections between neocortex and limbic system increase in complexity, allowing progressively more complex and finely adjusted patterns of behavior.

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Differential Sensitivity for Smell: "Noise" at the Nose

Abstract. *The ability of subjects to resolve differences in concentration of chemicals in the vapor phase by smell rivaled the optimum performance of chromatographs. In some instances, subjects resolved a difference in concentration of only 5 percent. The reported inability of olfaction to register fine differences in intensity seems to be largely a result of fluctuations in the stimulus.*

The absolute sensitivity of olfaction is recognized as remarkable, exceeding that of the keenest physical instruments. However, its differential sensitivity is considered poor. The first thorough investigation of the differential sensitivity of olfaction implied that one concentration would smell just noticeably different from another if the two differed by about 25 to 33 percent (*1*). Neither the magnitude nor the generality of this estimate has since been challenged. Somewhat higher and lower values were sometimes obtained, both in the original and in subsequent studies; but the constancy of the value always seemed more impressive than the differences, both within any particular study and, to a large extent, between studies (*2*).

The apparatus used to obtain difference thresholds for smell has ranged from the relatively crude Zwaardemaker olfactometer of 19th-century origin to a relatively sophisticated flow-dilution olfactometer. Use of these devices, whether crude or sophisticated, has not been accompanied by direct assessment of the magnitude and variability of the stimulus. Accordingly, the various estimates of differential sensitivity have rested on the risky assumptions that (i) the supposed difference between one concentration and another is the true difference, and (ii) moment-to-moment fluctuations in the concentration of a "constant" stimulus make only a trivial contribution to the size of the difference threshold. The notion that noise in a sensory stimulus limits discrimination arose in the 19th century and survives in the modern theory of signal detection (*3*). It is ironic that the limiting influence of such noise has not been acknowledged explicitly for olfaction, where the stimulus is particularly difficult to control.

This study explored differential sensitivity to three odorants: *n*-butyl alcohol, ethyl *n*-butyrate, and *n*-amyl alcohol. Two untrained subjects attempted to decide, in a two-alternative forced-choice task, which of two slightly different concentrations smelled stronger (*4*). In any particular 1-hour session, a subject performed the task 100 times with the same two concentrations. After each trial, he was told whether or not he had chosen correctly. He served twice for each pair of concentrations; there were six pairs per odorant.

Concentrations were prepared by diluting the reagent-grade odorants with deionized water. A small volume (1 ml for *n*-butyl alcohol and *n*-amyl alcohol; 2 ml for ethyl *n*-butyrate) of the appropriate concentration was placed onto an absorbent cotton ball that rested on a perforated platform in a glass vessel (60 ml) designed for olfactory testing (*5*). The vessel contained two small ports, one below and one above the platform. The subject inhaled through a monorhinic nosepiece placed at the upper port.

Between 50 and 60 vessels were prepared just before each session. Half contained the higher and half the lower concentration. They were presented for evaluation in pairs (high versus low) from behind a screen. On another occasion, the vapor-phase concentration of freshly prepared samples was measured by gas chromatography. The chromatograph was treated as an ideal observer and tested much as the human subjects were (*6*). A gas-sampling valve was set up to "inhale" the vapors from the vessels, and the chromatograph evaluated the magnitude of the higher and lower concentrations 100 times (*7*).

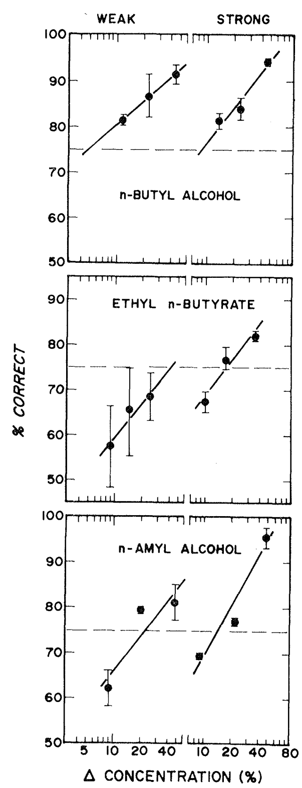
Human discrimination was best for *n*-butyl alcohol and poorest for ethyl *n*-butyrate (Fig. 1). Keenness of discrimination can be expressed by the value of k in the relation $k = \Delta C/C$, where ΔC represents whatever increment above a reference concentration C is necessary to produce correct resolution 75 percent of the time. The intersections of the fitted functions with the dashed lines (Fig. 1) provide estimates of k expressed as a percentage. The average, 19 percent, is low by comparison to other studies. The average for *n*-butyl alcohol, 7 percent, is low enough to suggest that intensity discrimination of certain odorants may rival that for sequentially presented auditory and visual stimuli, in which k is approximately 10 percent (*8*).

Chromatographic analysis revealed the great variability of vapor-phase concentration. Possible contributors to the variability are such factors as the fluctuation in adsorption on the interior walls of the vessel, the distribution of odorant on the cotton, and the pattern of airflow through the cotton. The average coefficient of variation for the least variable of the three odorants, *n*-butyl alcohol, was 9.7 percent. In order to check whether the chromatograph and associated electrical equipment contributed substantially to the variability, 1.15 percent *n*-butane in nitrogen was flowed from a compressed-gas cylinder into the gas-sampling valve and analyzed 100 times. The coefficient of variation (standard deviation expressed as a percentage) under these circumstances was only 1.6 percent, too small to be of consequence. When the coefficient of variation for butyl alcohol was corrected for the noise contributed by the electrical equipment, the coefficient became 9.6 percent (*9*).

To what degree did trial-to-trial fluctuation in concentration limit discrimination? A theorem developed within the context of signal detection theory offers a way to compare the psychophysical with the chromatographic results. The theorem reveals the compatability between results obtained in a two-alternative forced-choice task and those obtained in a yes-no decision task under various decision criteria ranging from conservative to liberal: the percentage of the area under a receiver operating characteristic (ROC) curve erected from the yes-no task equals the percent correct in the forced-choice task (*10*). In the present case, ROC curves were erected from the frequency distributions of vapor-phase concentrations for the members of each pair of nominal concentrations (Fig. 2). If the chromatographic analysis reflects the fluctuation in vapor-phase concentration accurately, then the area under the ROC curves should represent the best possible performance that subjects could achieve in the psychophysical task.

The ROC curves reveal that variation in vapor-phase concentration often limited the optimum performance that can be achieved psychophysically. In view of these limitations, the subjects discriminated all three odorants very well. In the forced-choice task, the ratio of percent correct to the area under the curves averaged .96 for *n*-butyl alcohol, .98 for ethyl *n*-butyrate, and .87 for *n*-amyl alcohol. These results suggest that noise in the stimulus contributed considerably to the size of k in the present study. They raise the suspicion that this source of noise may account for the dismal reputation of olfaction at the task of intensity discrimination.

The excellent performance of the subjects relative to stimulus-imposed limita-



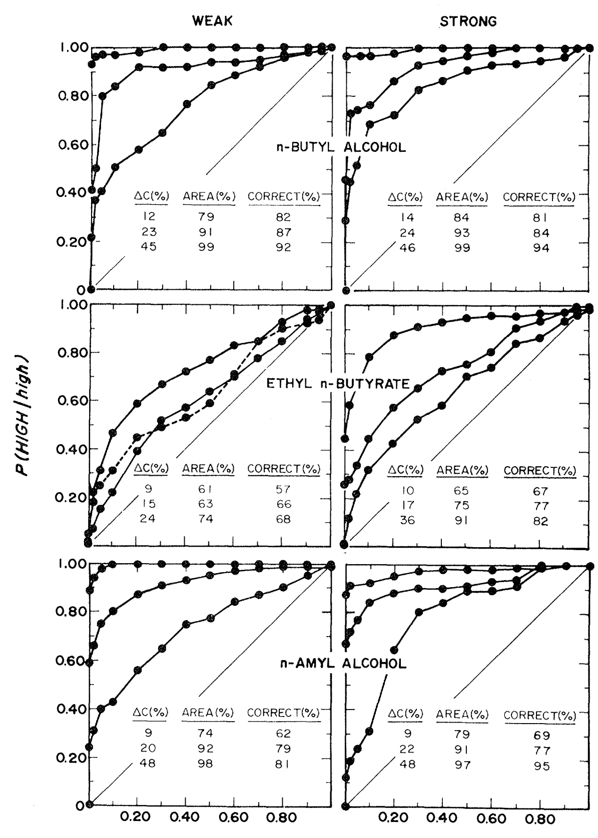


Fig. 1 (left). Percent correct in the psychophysical task versus difference in vapor-phase concentration. Points represent the average performance of two subjects and bars show the range. The portions labeled "weak" show discrimination between relatively low concentrations. The nominal concentrations of the weak pairs, expressed in terms of percent volume in water, were: 0.30 and 0.34, 0.30 and 0.38, and 0.30 and 0.45 for *n*-butyl alcohol; 0.040 and 0.045, 0.040 and 0.050, and 0.040 and 0.060 for ethyl *n*-butyrate; 0.100 and 0.110, 0.100 and 0.125, and 0.100 and 0.150 for *n*-amyl alcohol (*13*). The portions labeled "strong" show discrimination for samples ten times more concentrated. Fig. 2 (right). ROC curves erected from the frequency distributions of vapor concentration for the stimuli used in the psychophysical task. To generate each curve, various response magnitudes (vapor-phase concentrations) were chosen arbitrarily as locations of decision criteria. Each yielded one point on a curve. In effect, the criterion was used to answer the question: Was the vapor-phase concentration from a particular vessel produced by the higher nominal concentration? Computed at each criterion were (i) the conditional probability that a sample greater in magnitude than the criterion would be deemed high (a response of "yes" to the question above), given that its nominal concentration was in fact the higher of the pair, and (ii) the conditional probability that the sample would be deemed high, given that its nominal concentration was the lower of the pair. The table in each component of the figure lists the percentage area under the curves and the corresponding psychophysical performance.

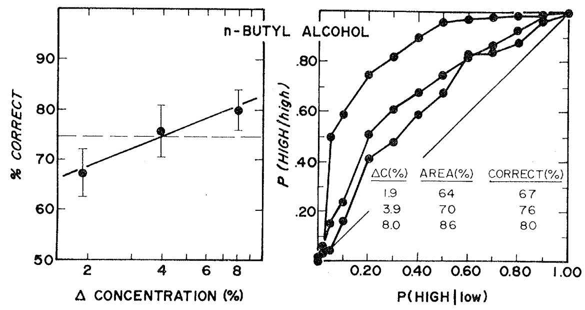


Fig. 3. (Left) Percent correct versus difference in concentration of *n*-butyl alcohol delivered through an olfactometer. (Right) ROC curves for *n*-butyl alcohol.

tions suggests that discrimination could be keener if the variability of the stimulus were reduced. Accordingly, an air-dilution olfactometer was set up to deliver concentrations of *n*-butyl alcohol with greater precision (coefficient of variation equal to 5 percent) than obtainable with the glass vessels (*11*). Discrimination was, in fact, keen under these circumstances (k = 4.2 percent) and, as in the earlier experiment with *n*-butyl alcohol, rivaled the optimum performance predicted by the corresponding ROC curves (Fig. 3).

In 5 of the 21 cases, discrimination exceeded predictions based on the ROC curves. These cases could reflect the operation of chance or they could represent overestimation of the variability in the stimulus. Despite attempts to minimize all extraneous variability, some factors, such as adsorption of odorous vapors on the walls of the sampling valve, could have added noise to the measurements. This possibility does not, however, detract from the correlation (r = .87) between the performance predicted by the ROC curves and that measured psychophysically (Fig. 4).

If the chromatographic analysis reflects the true degree of noise in the stimulus, it is appropriate to partition the psychophysical performance into two components, one based on variance in the stimulus and one based on variance in the olfactory system. The variance can be partitioned by means of the relation $s_p^2 = s_s^2 + s_o^2$, where s_p^2 is the variance of the psychophysical data, and s_s^2 and s_o^2 are the variances of the stimulus and olfactory system, respectively. For any given psychophysical and chromatographic comparison, the relative sizes of s_p and s_s can be assessed from values for d', a common measure of sensitivity employed in signal detection theory and one that can be derived directly from the measure percent correct (*12*). The variance terms s_p^2 and s_s^2 were replaced by the terms $(1/d')_p^2$ and $(1/d')_s^2$, thereby permitting computation of the relative size of s_o^2 for each of the 21 psychophysical and chromatographic comparisons. On the average, noise in the stimulus accounted for 75 percent of the total variance. Average values for the odorants considered individually were 87 percent for *n*-butyl alcohol, 88 percent for ethyl *n*-butyrate, and 36 percent for *n*-amyl alcohol.

With the variance partitioned into two components, it is also possible to ask what is the coefficient of variation of the olfactory system when the noise in the stimulus is discounted. Since the magnitudes of s_s and s_o were known only relative to each other, the answer to the question hinges on knowledge of the absolute magnitude of s_s. This existed in the form of the coefficients of variation for the frequency distributions of vapor-phase concentration. Accordingly, s_o could be expressed relative to the measured fluctuations in the stimulus. The average value of s_o for the three odorants was 11 percent, ranging from 5 percent for *n*-butyl alcohol to 16 percent for *n*-amyl alcohol. These reflect the values of k that could be expected if the stimulus were controlled with great precision.

Thus, olfaction displays greater differential sensitivity than has hitherto been thought; for some stimuli, it may exceed previous estimates by almost an order of magnitude. Unrecognized noise in the stimulus must account for much of olfaction's seeming dullness. Furthermore, the noise has probably obscured important differences in discriminability from one odorant to another. Use of a physical reference, such as a gas chromatograph, seems to offer the only way to uncover the intricacies of olfactory discrimination.

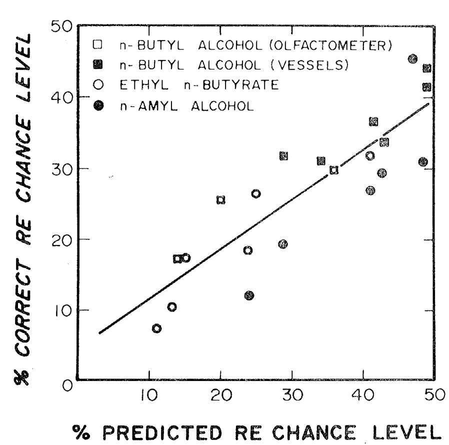


Fig. 4. Percent correct obtained psychophysically versus prediction of optimum performance from assessment of vapor-phase concentration.

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4. Subjects A and B served when *n*-butyl alcohol and ethyl *n*-butyrate were stimuli, and subjects B and C when *n*-amyl alcohol was the stimulus.
5. Stability of vapor-phase concentration was the criterion used to decide the volume of odorant to be placed on the cotton.
6. D. M. Green and J. A. Swets, *Signal Detection Theory and Psychophysics* (Wiley, New York, 1966), pp. 149–179.
7. A vacuum source drew 110 ml of room air per minute through the gas sampling valve (Perkin-Elmer). A sample of air from the vessel was drawn straight through the valve for 25 seconds and then into the valve's sampling loop (5 ml) for the next 20 seconds; it then swept into the column (2 percent Carbowax 20M on Gas-Chrom Q or 1.5 percent DC-200 methylsilicone on Gas-Chrom Q) of the chromatograph (Perkin-Elmer F11, flame ionization detector) for analysis. Peaks were integrated with a Disc integrator. Since chromatographic analysis took far more time than psychophysical testing, only 15 to 25 pairs were analyzed at a time, until 100 pairs had been analyzed. Invariably the analysis stretched across days. Because changes in barometric pressure and ambient temperature led frequently to small but systematic changes in vapor-phase concentration from day to day or from morning to afternoon of the same day, the data from each segment (15 to 25 pairs) were normalized to the mean for all pairs. Hence, if the mean for one segment was 90 percent as large as the grand mean, all the data for that segment were multiplied by 1.11, and so on.
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11. Subjects C and D participated. Flow rate of the stimulus was 2 liter/min. Average vapor-phase concentrations of the pairs were 0.320 and 0.326, 0.320 and 0.332, and 0.320 and 0.345 mg/liter.
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13. For reference, the lowest aqueous concentrations of *n*-butyl alcohol (0.30 percent), ethyl *n*-butyrate (0.040 percent), and *n*-amyl alcohol (0.10 percent) produced vapor-phase concentrations of 1.00, 0.11, and 0.53 mg/liter, respectively. These concentrations produced roughly equal perceived intensities, far above the level of detection.
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