The detectability of the odor of butanol¹

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Three experiments were conducted to measure the sensitivity of two Ss to the odor of butanol. In the first two experiments, the method of double random, yes-no staircases was used. A practice effect of over a $\log_{10}$ unit in millimoles decrease in apparent threshold was observed in both Ss. Consistent shifts in the response criterion were induced when Ss were paid to meet an arbitrarily determined physical criterion. In Experiment 3, the confidence rating procedure was used. Results at eight different signal intensities are of the form predicted by signal detection theory. d' is shown to be related to signal strength by a power function with a slope of about .30 which suggests that the olfactory transducer compresses sensory input produced by weak concentrations of butanol.

Several psychophysical studies in audition and vision have demonstrated that classical methods of determining thresholds do not provide for an evaluation of the S's response criterion independent of threshold measures (Swets, Tanner, & Birdsall, 1961; Swets, 1961; Green & Swets, 1966). This finding has led to the formulation of the theory of signal detection as well as a re-evaluation of classical results in other modalities. Recently the detection model has been applied with great success in, for example, taste (Linker, Moore, & Galanter, 1964), touch (Rollman, 1968), and pain (Clark & Dillon, 1968). Sensory coding in the olfactory system has not been examined within the context of detection theory.

Many threshold studies in olfaction have been performed to determine which of a number of methods of stimulus production, in terms of apparatus design, produces the most reliable reports of threshold (Wenzel, 1948; Jones, 1955; Cheesman & Kirby, 1959; Stone, 1963). Although the use of an olfactometer produces the most reliable results (Stone, 1963), the sniff method such as that described by Engen (1961), also produces highly consistent results. The sniff method was used in the present investigation because stimuli of the same concentration can easily be reproduced from session to session.

Another set of olfactory threshold experiments has been conducted to study adaptation effects, the influence of stimulus parameters on threshold, and odor similarity (Cheesman & Mayne, 1953; Moncrieff, 1956; Stuiver, 1958). Engen (1960) used lowering of absolute threshold as an index of practice effects: in addition, he found that verbal instructions to S influenced the reported threshold, but no attempt was made to analyze sensitivity independent of this response-biasing phenomenon.

EXPERIMENT 1

Experiment 1 was performed to determine whether or not practice in detecting odorous butanol stimuli lowers the apparent threshold. Gibson (1953) has reviewed the effects of practice and training on perceptual judgments. Results from several modalities involving a variety of perceptual tasks suggest that perception can be rendered more acute in the sense that S comes to discriminate smaller differences in stimulation as a function of practice. In olfaction, Engen (1960) has demonstrated clear evidence of practice effects with the forced-choice method of limits. He used six odorants which were presented in the same order to five Ss. Threshold for the first three odorants (amyl acetate, phenylethyl alcohol and heptane) decreased markedly as a function of practice, but no such effect was observed for the remaining three stimuli (heptanal, diacetone alcohol and vanillin). These results suggest a transfer of practice effect between odorants, but they do not indicate the extent to which threshold is lowered for any single odorant.

The procedure used in Experiment 1, the method of double random, yes-no staircases, was first proposed by Cornsweet (1962) as a modification of the classical method of limits. The method of limits is subject to several response biases, the most common of which are expectation and habituation. The double random staircase procedure eliminates most of these trial-to-trial within staircase dependencies because stimuli are not presented in a predictable sequence. Two staircases operate simultaneously, and the choice as to which staircase is sampled on any given trial is determined randomly. Stimuli are presented in discrete steps and the S's response dictates stimuli which are to be presented within each staircase.

METHOD

Subjects

Two female college students served as Ss. Neither reported any olfactory deficiencies. All stimuli were presented to both nostrils simultaneously. Ss were paid on an hourly pay-scale.

Apparatus and Materials

The experiment was run in an air conditioned room which had a temperature of 65-68 deg F and a relative humidity of 48-64%. S was seated in an ordinary chair facing a panel which separated him from E, but around which test tubes containing odorants could be exchanged. S indicated his responses verbally.

Butanol (n-butyl alcohol) was used as the odorant. Various concentrations were prepared by diluting small amounts of butanol in diethyl phthalate with a pipette. Butanol was obtained from Eastman Organic Chemicals and was redistilled. Diethyl phthalate was obtained from Fritzsche Brothers, Inc.

One cubic centimeter of each concentration was placed in separate 10 x 75 mm test tubes which were stopped with a foil-wrapped cork through which protruded a glass rod. S sniffed the stimulus from the cotton wool saturated with the solution by immersion in the test tube.

Procedure

Double random staircases were generated by reference to a table of random numbers. Each staircase occurred with an equal probability ($p = .50$), and successive run length on a given staircase did not exceed four.

The procedure also involved a modification of the method of constant stimuli. Stimulus presentation on each trial was of the form ($S, S + \Delta_i$): a standard stimulus followed by one of a number of comparison stimuli which differed from the standard by an amount Δ_i . A trial event consisted of: (1) presentation of diethyl phthalate alone which S sniffed only once; (2) a 2 sec pause; (3) presentation of the test sniffer which S sniffed only once; and (4) a 2 sec response interval. There was a 10 sec interval between trials.

Ten series of 54 trials were run. Fifty of the trials comprised a double random staircase. The remaining four trials were control trials during which only diethyl phthalate was presented in the second test tube. To discourage S from falsely reporting "Yes" in the absence of the stimulus, a "Yes" response on control trials was fined 2c. S was instructed to report whether or not butanol was present in the second test tube. In the first series a large stimulus range (0.0-109 millimoles) and large step size between stimuli (21.86 millimoles) were used. As S's threshold decreased, more restricted ranges and smaller steps were employed. In this way it was possible to follow changes in threshold as a function of successive sessions.

Fig. 1. Mean butanol thresholds in millimoles as a function of successive series for both Ss. Threshold values represent the arithmetic mean of 30 observations per point.

RESULTS AND DISCUSSION

Mean intensities and standard deviations were computed for the last 30 trials in each double random staircase. The first 20 trials were discarded because it was during this time that S's performance stabilized, that is, the staircases converged. Control trials were not included in the analysis. The mean intensity represents the midpoint of the response distribution projected on to the stimulus continuum. It corresponds to the stimulus threshold obtained with the classical method of limits (Woodworth & Schlosberg, 1954).

Mean intensities are plotted vs successive series in Fig. 1 and show the changes in threshold as a function of practice. In both Ss thresholds decreased over a $\log_{10}$ unit in the first six series. These results are similar to those reported by Engen (1960) which illustrated that absolute thresholds to several odorants decreased markedly as a function of practice in the early stages of experimentation. Although a quantitative comparison of Engen's (1960) results and these could not be made because Engen used a series of odorants, the results of both studies show that practice is an important non-stimulus variable in the study of olfactory thresholds.

EXPERIMENT 2

Experiment 2 was conducted to extend the findings with the method of double random staircases reported in audition by Semb and Saslow (1967) that human Ss can accurately and quickly change response criteria when paid to meet an arbitrarily determined stimulus criterion. Although S may produce relatively unbiased thresholds with this method (Cornsweet, 1962), it is still possible that changes in S's response criterion affect the reported threshold. Experiment 2 was designed to investigate the case in which S was paid to meet arbitrary physical criterion by E, thus maintaining a constant motivational state. Feedback is given on every trial to inform S of where his responses are relative to the physical criterion. It was expected that threshold could be controlled by this extension of the method.

METHOD

The experiment was run with the same Ss and under the same conditions as described in Experiment 1. Three 54-trial series were run at each of three criterion points. Series order was randomized for both Ss. S was informed that E was going to pick

an arbitrary stimulus criterion, and that S would be paid for responses that were correct with respect to this criterion point. Outcomes were signalled verbally by E during the 10-sec intertrial interval. If S reported "Yes" and the stimulus was above the criterion point, he received 2c; if the stimulus was below the criterion point, he lost 2c. Similarly, if he responded "No" and the stimulus was below the criterion point, he was paid 2c, but if it was above the criterion point, he was fined 2c.

RESULTS AND DISCUSSION

Similar to the preceding experiment, mean intensities and standard deviations were computed for the last 30 trials in each double random staircase. Threshold values were evaluated with a *t* test against the null hypothesis of no difference between the reported threshold and the arbitrary criterion point. The results are presented in Table 1 for S CA and Table 2 for KL. Only one significant difference was found ($p < .05$), which is not unlikely in one out of 18 tests, and this illustrates that paid Ss can consistently maintain response criteria. As reported by Semb and Saslow (1967), Ss were also able to change criteria rapidly from session to session. These results therefore support a crucial assumption of the theory of signal detection.

EXPERIMENT 3

Experiment 3 was designed to investigate the use of the confidence rating scale procedure in the study of olfactory thresholds. Several investigations have reported rating scale data in both vision and audition (Swets, Tanner, & Birdsall, 1961; Watson, Rilling, & Bourbon, 1964), but only recently has the procedure been extended to other senses such as touch (Rollman, 1968) and pain (Clark & Dillon, 1968). No rating scale data, and, in fact, no detection data have been cited in olfaction (Green & Swets, 1966; Corso, 1967).

Two studies which used procedures similar to typical detection paradigms have been reported by Engen (1960) and Pangborn et al (1964). Using a forced choice method of limits, Engen (1960) found that olfactory thresholds could be influenced by verbal instructions to the S, but he did not attempt to analyze sensitivity independent of S's response criterion. Pangborn et al (1964) used a "constant-stimulus" method but large variations in individual sensitivities between Ss precluded calculating a group threshold and no attempt was made to analyze individual performance.

A second purpose of Experiment 3 was to determine the scale which most appropriately describes the relation between d' and molar intensity of butanol. Few detection studies have analyzed the relation between d' and signal strength. It was investigated in vision by Wuest (1961) who used six Ss and a variety of binary detection procedures to estimate d' . He found that d' was related to physical luminance by a power function of the form typically found in magnitude estimation experiments with so-called supra-threshold stimuli (Stevens, 1961). Another study by Morrison and Norrison (1966) involved taste detection in rats, and these investigators also found that $\log d'$ was linearly related to $\log$ stimulus intensity (per cent concentration) for different solutions of salt, tartaric acid, sucrose and quinine sulfate. Of special

Table 1
Subject CA—Thresholds for Butanol Determined by the Method of Double Random Staircases with Payoff Enforced Criteria

Session	Step Size (Millimoles)	Enforced Criterion	Mean Threshold	Standard Deviation	*Obtained <i>t</i>
1	1.093	2.732	2.951	1.202	.982
2	5.464	13.660	13.661	.796	.001
3	1.093	2.732	2.804	1.220	.318
4	21.856	54.641	58.373	23.508	-.885
5	5.464	13.660	15.435	5.974	1.749**
6	21.856	54.641	51.784	17.422	-.894
7	5.464	13.660	13.296	6.098	-.322
8	1.093	2.732	2.659	1.220	-.321
9	21.856	54.641	56.151	23.122	.352

* $t_{.05} = 1.699$; $df = 29$

**Significant at the .05 level.

Table 2
Subject KL—Thresholds for Butanol Determined by the Method of Double Random Staircases with Payoff Enforced Criteria

Session	Step Size (Millimoles)	Enforced Criterion	Mean Threshold	Standard Deviation	*Obtained t
1	21.856	54.641	53.236	29.946	-.281
2	1.093	2.732	2.731	1.591	-.003
3	5.464	13.660	14.753	6.011	.979
4	1.093	2.732	2.805	1.460	.269
5	5.464	13.660	13.296	6.105	-.321
6	21.856	54.641	54.694	21.010	.014
7	5.464	13.660	14.571	5.870	.836
8	21.856	54.641	53.183	12.370	-.635
9	1.093	2.732	2.659	1.220	-.322

* $t_{.05} = 1.699$; $df = 29$

importance is that the slopes of their power functions for salt (.38) and sucrose (.48) are remarkably similar to slope values obtained from chorda tympani responses in the rat for various concentrations of salt of .31 (Beidler, 1953) and of sucrose of .50 (Hagstrom & Pfaffmann, 1959).

A question may be raised about the use of d' as applied to sensory scaling near threshold. In audition and vision, d' has a specific meaning related to the theory of the ideal observer (Tanner & Birdsall, 1964), but as yet no one has analyzed the specific parameters of the olfactory stimulus. In the present study d' was simply used as a convenient index of sensitivity.

METHOD

Subjects

The two Ss used in Experiments 1 and 2 also served in Experiment 3. Ss were paid only by performance. They received 1c for correct responses and were fined 1c for incorrect responses.

Fig. 2. $P(S|s)$ and $P(S|n)$ values obtained from observer CA plotted on linear normal-deviate scales. Each isosensitivity curve represents 400 trials. Straight lines were fit by the method of least squares using $z(S|n)$ and $z(S|s)$ values. The stimulus intensity indicated by the circled point ($\odot$), afforded less than two separate estimates of z values, thus an isosensitivity curve could not be generated. The major diagonal represents a d' of 0.0.

Apparatus and Materials

The apparatus and materials were the same as those described in the preceding experiments. Eight different concentrations of butanol were chosen for each S to represent an approximate detectability range of 0.0 to 3.0 in d' units. The solutions were prepared before the experiment began and were stored in glass-stopped bottles. Ten separate test tubes were used during each series. Five contained diethyl phthalate and five contained diethyl phthalate plus a given amount of butanol. New sniffers were prepared before each session and S was told that if he could identify any of the sniffers on the basis of their appearance (e.g., chipped test tube, unwound cotton, etc.), he should inform E immediately so that it could be discarded. On several occasions E presented a chipped test tube or wound the cotton in a peculiar fashion to see whether or not S was following instructions. Both Ss consistently reported these sniffers on the first trial on which they were presented.

Fig. 3. $P(S|s)$ and $P(S|n)$ values obtained from observer KL plotted on linear normal-deviate scales. Each isosensitivity curve represents 400 trials. Straight lines were fit by the method of least squares using $z(S|n)$ and $z(S|s)$ values. Stimulus intensities indicated by circled points ($\otimes$, $\triangle$ and $\odot$) afforded less than two separate estimates of z values, thus isosensitivity curves could not be generated. The major diagonal represents a d' of 0.0.

Procedure

The confidence rating procedure used employed the same presentation format as the yes-no procedure described in Experiment 1. That is, the sequence of physical events occurring on each trial was the same. It should be re-emphasized that diethyl phthalate was always presented preceding judgment of the second test tube. This was done to insure that S had the same reference point on every trial. Stimulus presentation on signal trials was of the form (S, S + Δ) and on noise trials (S, S).

In the rating task six response categories were allowed:

- 6 - Very certain that signal was present.
- 5 - Quite certain that signal was present.
- 4 - Uncertain, but signal was present.
- 3 - Uncertain, but noise was present.
- 2 - Quite certain that noise was present.
- 1 - Very certain that noise was present.

S was told to be as consistent as possible in assigning numbers to his judgments. He was also informed that he would be paid for correct responses, and that he would be fined for incorrect responses. Feedback was given on every trial.

Table 3
 d' , Ratio of Signal to Noise Standard Deviations, Goodness of Fit, Mean d' over Series and Their Standard Deviations

Subject CA					
Intensity in Millimoles	d'	σ_s/σ_n	r^2	Mean d' over Series	SD of d' within an Intensity Level
0.109	0.133	1.006	0.969	0.065	0.146
0.546	0.676	1.036	0.996	0.685	0.059
1.093			(data discarded—see Text)		
5.464	1.215	1.043	0.992	1.328	0.103
10.928	1.560	0.990	0.992	1.648	0.095
27.320	1.950	1.072	0.981	2.078	0.202
54.641	2.522	1.205	0.968	2.635	0.083
109.282	3.390			3.233	0.094
Subject KL					
0.055	0.220			0.240	0.169
0.109	0.570	0.977	0.996	0.660	0.088
0.546	1.066	0.970	0.988	1.153	0.098
1.093	1.497	0.907	0.958	1.612	0.135
5.464	1.898	1.019	0.999	1.925	0.138
10.928	2.430	0.925	0.997	2.405	0.145
27.320	3.030			2.958	0.143
54.641	4.070			3.900	0.100

Four series of 120 trials were run during each session. S was allowed to rest at least 3 min between series. Each S made 600 observations (five series of 120 trials) at each intensity. The order of 120-trial series was randomized for both Ss, thus it was possible for S to make judgments at four different concentration levels during the same experimental session. Intensity series consisted of an equal number of signal (s) and noise (n) trials, that is $P(s) = P(n) = .50$, arranged in an order generated from a table of random numbers.

RESULTS AND DISCUSSION

Although 600 trials were run at each concentration, only 400 trials were considered in the analysis. The first 120-trial series at each concentration was disregarded following the fairly typical detection procedures of discarding the unstable data which tend to characterize the early stages of detection tasks (Green & Swets, 1966). In addition the first 20 trials of each succeeding series were discarded in order not to contaminate the results with changes in S's response criterion which occurred when switching from concentration to concentration.

CA's data were analyzed for only seven of the eight stimulus concentrations. Due to an error by E, the same intensity stimulus was not consistently used in the 1.093 millimole series and S was not available for replication of this part of the experiment.

In order to generate ROC curves, the rating scale data were converted to yes-no data by considering in turn each of the five successive response category boundaries of the rating scale as defining a yes-no criterion. The maximum number of points obtainable is one less than the number of categories, or five in this instance. Probabilities for the various criteria were calculated for both Ss, and ROC curves are plotted in linear normal deviate coordinates in Fig. 2 (CA) and Fig. 3 (KL). Several of the curves in Figs. 2 and 3 have less than the maximum number of five points, and in four instances (circled points) no ROC curves could be generated. Because S was instructed to use the categories in any way he chose, there was no way to predict how he would distribute his responses among the six categories, so in several instances $P(S|s)$ and $P(S|n)$ values were equal to 0.0 and 1.0. Such values were not included in the analysis because they could not be translated into z scores. This was a serious limitation of the rating method only when very intense or very weak signals were used. At high signal intensities, S typically distributed his responses such that s was nearly always assigned a 4, 5, or 6, and n

a 1, 2, or 3. At low signal strengths, S was usually so uncertain that he used only categories 3 and 4.

Straight lines for each signal strength in Figs. 2 and 3 were fit by the method of least squares to the z scores. The reciprocal of the slope of the function in normal-deviate coordinates is equal to the ratio of the standard deviation of the signal distribution to the standard deviation of the noise distribution. The intercept of each ROC curve, $z(S|n) = 0.0$, is equal to d' . When there were insufficient data to generate a ROC curve, equal-variance, normal distributions were assumed and d' was obtained from the formula: $d' = z(S|s) - z(S|n)$. d' values, and when appropriate the ratio of the standard deviations of the signal and noise distributions, σ_s/σ_n , and goodness of fit criteria, r^2 , are listed in Table 3 for both CA and KL.

These results clearly show that the confidence rating scale procedure applied to the analysis of olfactory detection are of the form predicted by the theory of signal detection. First, that ROC curves can be fit by straight lines in normal-deviate coordinates with precision ($r^2 > .950$) supports the assumption of detection theory, that S reports a signal occurrence because the likelihood ratio, or some monotonic function of it, exceeds some criterion level. Second, because estimates of σ_s/σ_n for both Ss is approximately unity, the assumption of equal-variance, normal signal and noise distributions is supported.

In the typical detection experiment, several hundred trials are run successively at each intensity. The present design differed from this procedure in that intensity series were presented in a random order. d' values were calculated for each intensity level series by assuming that the criterion fell between the third and fourth categories which corresponds to the yes-no detection task. Mean d' values over four series at each intensity and their standard deviations are shown in Table 3. With the exception of the weakest concentration, variability is small which suggests the random arrangement of intensity series with a practiced S produces consistent results.

The final stage of analysis was concerned with d' , an unbiased estimate of S's sensitivity, which is plotted as a function of stimulus concentration in Fig. 4 (CA) and Fig. 5 (KL). Log-log plots of the data are fairly well-described by straight lines which indicates that d' grows as a power function of concentration. The equation is of the form

$$d' = kS^c$$

Fig. 4. A log-log plot of d' as a function of the concentration of butanol in millimoles for S CA. Each d' value represents 400 trials. The data are fairly well described by a straight line which indicates that d' grows as a power function of physical concentration. The slope of the line, determined by the method of least squares, is .298. The circled point, O, was not included in the analysis. (See text.)

where d' is a measure of detectability, k is an arbitrary constant which depends upon the units of measurement, S is concentration in millimoles, and c is the slope of the function. The first point (circled) in both Figs. 4 and 5 was not included in the least-squares fit of the data.

These results agree with those reported by Wuest (1961) in visual detection and by Morrison and Norrison (1966) in rat taste detection that d' is related to stimulus intensity by a power function. Theoretically it is interesting that an indirect measure of sensitivity such as d' should be related to stimulus intensity by a power function. In supra-threshold scaling experiments the relationship is logarithmic (Ekman & Kunnapas, 1963), but until the exact stimulus correlates of d' can be determined in olfaction, these results must be accepted as only a description of the data. In both Ss the circled point represents a d' of less than .35, which is very near chance performance. Rather than attempt to explain a divergent point, the results here are meant to apply only to the middle range of d' values where the function is reasonably linear.

Despite its descriptive nature, the relation between d' and butanol concentration still provides useful information about sensory coding in the olfactory system. The slopes of the power functions for both Ss is about .30 which supports the notion of an olfactory compressor for weak concentrations of butanol. Cain (1966) reported a slope of .18 when human Ss judged supra-threshold concentrations of butanol with the method of magnitude estimation. Although the slopes obtained in Experi-

Fig. 5. A log-log plot of d' as a function of the concentration of butanol in millimoles for S KL. Each d' value represents 400 trials. The data are fairly well described by a straight line which indicates that d' grows as a power function of physical concentration. The slope of the line, determined by the method of least squares, is .295. The circled point, O, was not included in the analysis. (See text.)

ment 3 are somewhat higher, the fact that both investigators found power functions with slopes less than .50 supports Reese and Stevens' (1960) view of the olfactory transducer as a sensory compressor.

Finally, these results illustrate that the olfactory "threshold" encompasses a large dynamic stimulus range. In fact, in both Ss, d' values were obtained over nearly a two $\log_{10}$ unit range which makes it difficult to compare these results with threshold values reported by other investigators. Cain (1966) found a group threshold of .238% (26 millimoles) for butanol. This value corresponds closely with the 27 millimole series (both Ss) in the present experiment. No direct comparisons can be made with the data collected with the judgmental procedure and analytic method in Experiment 3. What is important to emphasize is that in any psychophysical study of olfaction in which changes in threshold are used a dependent variable E must devise methods which provide both estimation of motivational effects and correction for estimated biases. Mere specification of a threshold value, without control for the effects of nonstimulus parameters, is simply inadequate.

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