

# Odor intensity: Differences in the exponent of the psychophysical function<sup>1</sup>

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*A series of five experiments showed that there are reliable differences among the exponents of the psychophysical power functions for odorants. There was virtually a perfect rank-order correlation between the size of the exponent and the water-solubility of the odorants. The exponents for odorants that are completely soluble in water (n-propanol and acetone) were approximately 2.5 times the size of the exponents for odorants that are insoluble in water (n-octanol and geraniol). For n-aliphatic alcohols, the size of the exponent and solubility in water decrease as a function of carbon chain-length. Although the exponents were higher when the stimuli were delivered with an air-dilution olfactometer than when they were sniffed from cotton swabs, the relative values among odorants were independent of the method of stimulus presentation.*

Olfactory intensity has been found to grow as a power function of concentration for many odorous substances (cf. Jones, 1958a, b; Reese & S. S. Stevens, 1960; Engen & Lindström, 1963; Engen, 1965). When two or more odorants have been scaled in a single study, there have usually been differences among the exponents of the power functions. Although none of the studies cited has focused on a systematic demonstration of the reliability of these differences, the evidence suggests that some are real.

Engen (1965), for example, obtained a three-to-one ratio between the exponents for n-propanol and n-octanol, two substances that belong to the series of normal aliphatic alcohols. Many of the physicochemical properties of the aliphatic alcohols vary as a function of carbon chain-length. For example, as carbon chain-length increases there is an increase in molecular size, boiling point, and oiliness, and a decrease in water solubility and vapor pressure. Such other physicochemical measures as oil-water partition coefficients, optical transmission spectra, and retentivity to various adsorbants are also related to chain-length. If, as is likely, the exponents obtained by Engen (1965) differed because of the physicochemical properties of the substances it may be possible to demonstrate a relation between the size of the exponent and carbon chain-length for the aliphatic alcohols.

The present experiments deal mainly, but not entirely, with normal aliphatic alcohols. For Experiments 1 through 4, concentration was varied by means of liquid dilution. Experiment 5 was performed after the construction of a precision air-dilution olfactometer and provided the means to check whether or not the relative differences among exponents can be due to the interaction of solvent and solute in liquid solutions.

## EXPERIMENT 1:

### MAGNITUDE ESTIMATION OF ALIPHATIC ALCOHOLS

#### Method

**Observers.** A group of 12 graduate students participated in four scaling sessions and four threshold determinations. (One O did not judge n-octanol, because he became nauseated by its odor.)

**Apparatus and materials.** The experiment was performed in an air-conditioned room with a temperature of  $70 \pm 1$  deg F and relative humidity of 50-60%. The test chamber was a

Formica-lined booth with a large glass window in the front wall.

The odorous stimuli were n-propanol (C<sub>3</sub>), n-butanol (C<sub>4</sub>), n-hexanol (C<sub>6</sub>), and n-octanol (C<sub>8</sub>). Each substance was redistilled before use in the experiment. Concentration series were made by diluting each odorant with diethyl phthalate, a relatively odorless solvent, according to the formula: volume concentration =  $(100/2^n)\%$ , where n is the dilution step. In the concentration series used for scaling, n ranged from 0 to 6, yielding concentrations that ranged from 100% to 1.56%. In series used for threshold determinations, n ranged from 4 to 24 and the concentration of the weakest member was  $6 \times 10^{-6}\%$ .

One milliliter of each concentration was placed in a separate 10 x 75 mm test tube that was stoppered with a cork wrapped in aluminum foil. A thin glass rod penetrated the stopper and was partially immersed in the solution. A piece of cotton wool was wound around the lower end of this rod; to sample the solutions, the Os removed the rod from the test tube and sniffed from the cotton.

**Procedure.** Suprathreshold intensity was judged by magnitude estimation without a designated modulus. The procedure was the same for each odorant. A 12.5% concentration was presented on the first trial and the O was told to assign to its intensity any number he felt appropriate. To subsequent concentrations he was told to assign numbers that reflected their apparent intensity. If a subsequent concentration smelled twice as strong as the first, he was to assign it a number twice as large as the first; if it smelled one-third as strong, a number one-third as large, etc. Fourteen intensity judgments, two for each concentration, were made in an experimental session. There was a 1.5-min interval between judgments and midway through this interval the O was again presented the 12.5% concentration to re-acquaint him with its intensity.

Thresholds were obtained by a modified method of limits. On each trial the O was presented a Plexiglas rack that contained from 8 to 18 test tubes. He started at the designated end of the rack and sniffed the solutions in sequence (30 sec between sniffs) until he reached the lowest concentration that he could recognize to have the quality of the odor of the test substance. The instructions encouraged him to proceed beyond this point and to use a bracketing procedure to pinpoint the threshold concentration. There were three ascending and three descending trials.

## Results

Figure 1 shows the geometric means of the magnitude estimates as a function of concentration (mole fraction) for each of the four odorants. In log-log coordinates the slopes of the straight lines represent the exponents of the power functions (Table 1). The exponent decreases systematically as molecular chain-length increases, although the functions for hexanol and octanol are hardly different from each other.

The threshold concentrations also decreased as a function of chain-length. These recognition thresholds correlate well ( $r = 0.99$ ) with the detection thresholds listed by Davies and Taylor (1959), but are uniformly two log units higher.

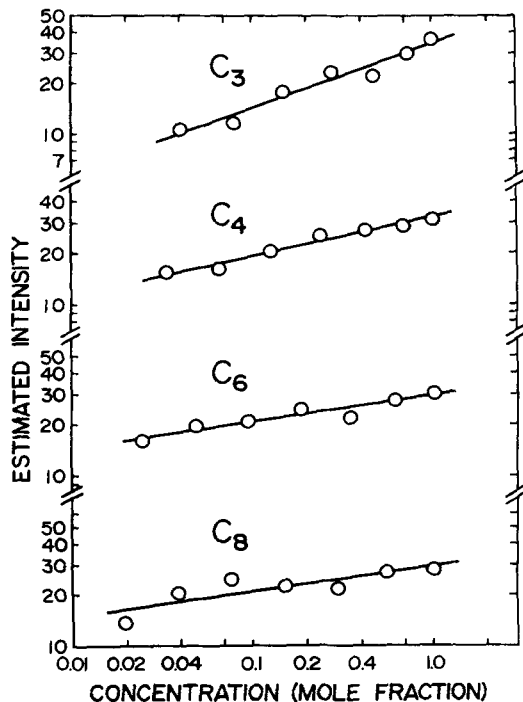


Fig. 1. Magnitude estimation as a function of concentration for four aliphatic alcohols: n-propanol ( $C_3$ ), n-butanol ( $C_4$ ), n-hexanol ( $C_6$ ), and n-octanol ( $C_8$ ). All of the functions in this figure and in subsequent figures were fitted by the method of least-squares.

Exponents were also calculated for the magnitude estimates plotted as a function of stimulus concentration minus threshold concentration. As Table 1 shows, this led to virtually no change in the exponents and thereby indicated that the proximity of the threshold to the suprathreshold concentrations made almost no contribution to the differences among the exponents. Although the variability of the data points would have necessitated caution, this same conclusion is suggested by the general lack of downward curvature at the low concentrations.

#### EXPERIMENT 2: CROSS-CONTINUUM MATCHING

One way to check the results obtained with magnitude estimation is to match the intensity of various levels of one odorant against another. Given the appropriate choice of units, if the psychophysical functions for two continua are described by the equations

$$\psi_1 = \varphi_1 \alpha \quad (1)$$

$$\psi_2 = \varphi_2 \beta, \quad (2)$$

then the equal-sensation function that results when  $\psi_1$  is matched to  $\psi_2$  should be described by the equation

$$\varphi_1 = \varphi_2 \beta / \alpha. \quad (3)$$

Equation 3 describes a straight line in log-log coordinates and its slope (exponent) is the ratio of the slopes of the original psychophysical functions, Eqs. 1 and 2.

#### Method

*Observers.* Each of 12 graduate students participated in four

Table 1  
Exponents of the Power Functions and Threshold Values for Four Aliphatic Alcohols

Odorant	Exponent (re Physical Zero)	Recognition Threshold (Molecules/cc Air)	Exponent (re Threshold)
n-Propanol	0.38	$6.59 \times 10^{15}$	0.34
n-Butanol	0.23	$4.87 \times 10^{14}$	0.22
n-Hexanol	0.16	$2.04 \times 10^{13}$	0.15
n-Octanol	0.15	$2.31 \times 10^{12}$	0.15

experimental sessions. None had served in Experiment 1.

*Materials.* The odorants were n-propanol, n-butanol, and n-hexanol. Concentration series comprised 24 members, and each successive member was 80% of the concentration of the next higher member. In terms of volume concentration, the series ranged from 100% to 0.59%.

*Procedure.* Two balanced sets of intensity matches were made; propanol was matched to hexanol, hexanol to propanol, butanol to hexanol, and hexanol to butanol. In each session, the O matched 5 of the 24 concentrations of the comparison odorant to 5 concentrations of the criterion odorant (independent variable). The 24 concentrations of the comparison odorant were continuously available throughout the session and there was no restriction on the time allowed to make a match. However, the O was not allowed to smell more than four concentrations per minute.

#### Results

Figure 2 illustrates the results obtained when propanol was matched to hexanol and hexanol to propanol. The mean of the slopes of the two functions is 0.46, close to the value predicted—0.42. The exponent obtained when butanol was matched to hexanol was 0.65, also in good agreement with its predicted value of 0.68 (Fig. 3).

The function obtained when hexanol was matched to butanol was markedly curved and inconsistent with data obtained when butanol was matched to hexanol (Fig. 3). However, the departure from the expected trend seems to rest on the judgments of the two lowest concentrations of butanol. They fell farthest from the regression line in Fig. 3 and also exhibited excessive variability. A reasonable explanation of the inconsistency is that the intensity matches demanded for the two lowest concentrations of butanol taken together were too close to the lower end of the concentration series of hexanol. If the regression line obtained when hexanol was the independent variable is assumed to be approximately correct, the appropriate matches would have fallen at dilution steps 21 and 24.

In matching experiments, Os tend to avoid extreme values of the available range of the dependent variable (J. C. Stevens & Marks, 1965; S. S. Stevens & Greenbaum, 1966). In fact, the "regression effect" even shows itself when extreme settings are not required. The divergence in the functions in Fig. 2 indicates the presence of a small regression effect in the matching of propanol and hexanol. Balanced intensity matches in which both stimulus continua serve in turn as the independent and dependent variables are therefore advisable.

The relative intercepts of the psychophysical functions from Experiment 1 are arbitrary; therefore these functions do not allow predictions of the absolute values of intensity matches between odorants. Had such predictions been possible, the necessity to extend the concentration series for hexanol would have been apparent and the pronounced deviations probably avoided.

#### EXPERIMENT 3: MAGNITUDE ESTIMATION OF A MIXTURE

It would be predicted on the basis of Experiments 1 and 2 that

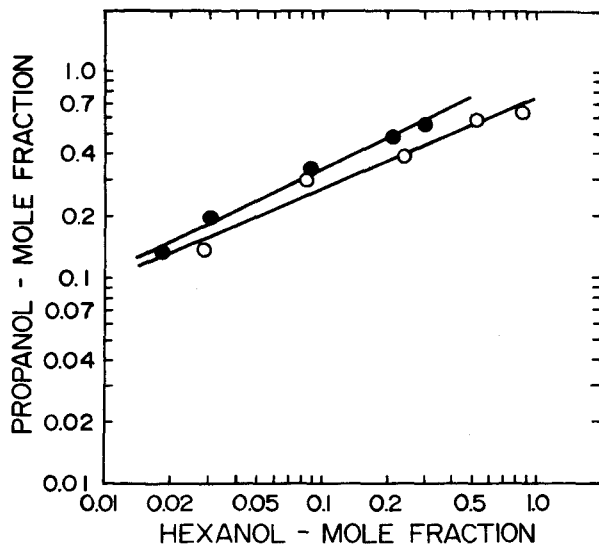


Fig. 2. Geometric means of cross-continuum matching when n-propanol was matched to n-hexanol (unfilled circles) and when n-hexanol was matched to n-propanol (filled circles).

n-heptanol ( $C_7$ ) would yield a lower exponent than n-propanol ( $C_3$ ), perhaps about 0.15. If this difference were reliable, then a half-and-half mixture of the two odorants might be expected to yield an exponent that fell between the exponents of the components.

#### Method

*Observers.* Eighteen undergraduates served as Os.

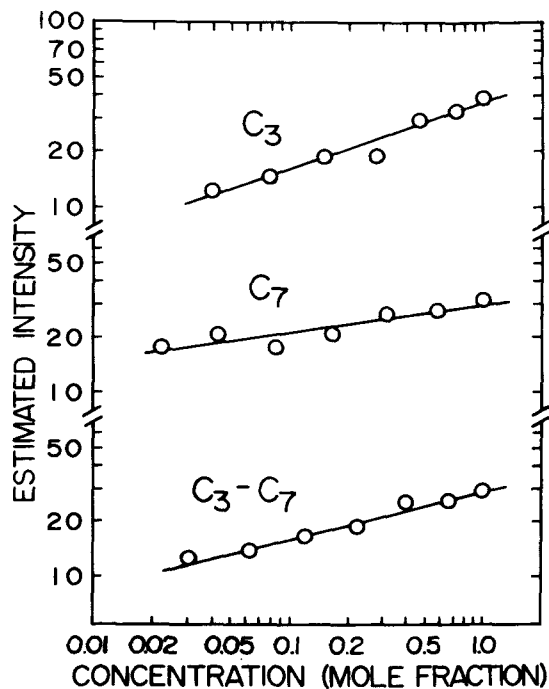


Fig. 4. Magnitude estimation as a function of concentration for n-propanol ( $C_3$ ), n-heptanol ( $C_7$ ), and a half-and-half mixture of n-propanol and n-heptanol ( $C_3-C_7$ ).

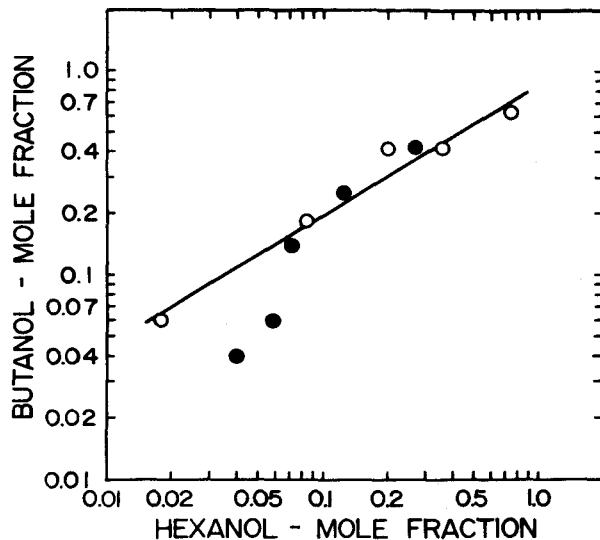


Fig. 3. Geometric means of cross-continuum matching when n-butanol was matched to n-hexanol (unfilled circles) and n-hexanol was matched to n-butanol (filled circles).

*Materials.* The odorants were n-propanol and n-heptanol. A dilution series with seven members was made of each separately, and of a one-to-one mixture of the two after the formula of Experiment 1.

*Procedure.* Judgments of intensity were made by magnitude estimation without a prescribed modulus. Each O served in one experimental session and judged two of the three odorants. Thus judgments were obtained from 12 Os for each odorant. With the exception that the standard concentration was presented only at the beginning, the procedure resembled that of Experiment 1.

#### Results

The results were quite close to expectations. Propanol yielded an exponent of 0.36 and heptanol an exponent of 0.15 (Fig. 4). The exponent of the one-to-one mixture was 0.26. This value is approximately midway between the exponents of the components and probably indicates that neither propanol nor heptanol dominated the intensity or the odor quality of the mixture. Had the quality of one component predominated, the exponent of the mixture would probably have fallen closer to the exponent of that component, but still between the exponents of the two components.

#### EXPERIMENT 4:

##### MAGNITUDE ESTIMATION OF A TERPENE ALCOHOL

Geraniol is a 10-carbon, terpene alcohol. Its molecular size is relatively large and it has low vapor pressure at room temperature, an oily consistency, and is insoluble in water. In terms of these more obvious physical characteristics it is similar to the higher aliphatic alcohols and accordingly might be expected to yield a low exponent.

#### Method

*Observers.* Twelve undergraduates served as Os.

*Materials.* N-propanol and geraniol were chosen as odorants, and a dilution series with seven members was made of each after the formula of Experiment 1.

*Procedure.* Each O judged both geraniol and propanol in a single session. The seven concentrations of each odorant were represented twice in a session. Half of the Os judged propanol

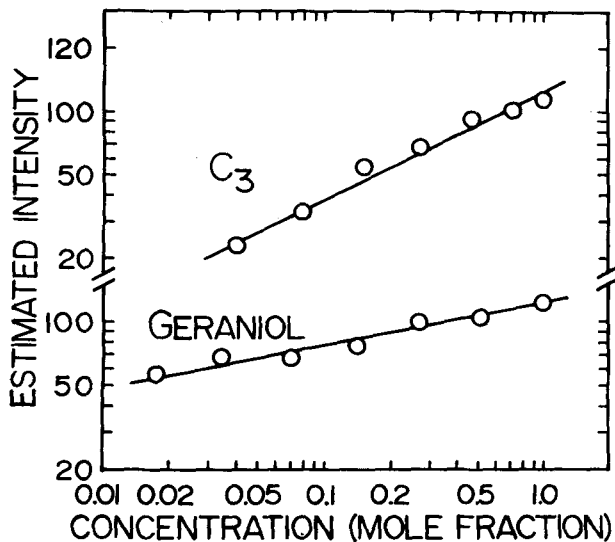


Fig. 5. Magnitude estimation as a function of concentration for n-propanol (C<sub>3</sub>) and geraniol.

first and the other half judged geraniol first. In this experiment the Os were told to assign the number 100 to the intensity of the middle concentration of the series, and this concentration was not presented repeatedly as in Experiment 1.

### Results

The exponents of the power functions for geraniol and propanol were 0.20 and 0.52, respectively (Fig. 5). Both values are somewhat higher than expected. There is variability in the exponents yielded by individual Os, and it is to be anticipated that the average values of the exponents will also vary from one group to another (cf. Marks & J. C. Stevens, 1966). Note, however, that the exponents for propanol and geraniol were in the same ratio as the exponents for propanol and the higher aliphatic alcohols, viz., about 2.5 to 1.

### EXPERIMENT 5:

#### OLFACTOMETRIC STIMULUS PRESENTATION

The results obtained with liquid solutions of odorants can depend on the solvent used in the preparation of a concentration series (Ottoson, 1958). This disadvantage probably results from the interaction of liquid solutes and solvents of different polarity. Since there is, moreover, no liquid that is both completely odorless and an effective solvent for all odorants, dilution of the odorant in air (or another gas) is preferable to dilution in a liquid. Accordingly, an air-dilution olfactometer was used to control and deliver the stimuli used in Experiment 5.

### Method

**Observers.** Fifteen undergraduates served as Os. These Os, unlike those of Experiments 1 through 4, were paid (\$1.50 per session).

**Apparatus and materials.** The odorants were geraniol, n-propanol, n-butanol, n-pentanol, and acetone. They were controlled and delivered by an air-dilution olfactometer (Fig. 6). Desired concentrations were obtained by mixing, in various proportions, air saturated with the odorant and pure, odorless air.

Materials used in the construction of the device were all odorless and easily cleaned. The odorous air came into contact predominantly with Teflon and glass, and with small amounts of polypropylene and brass.

Saturation was accomplished by sparging air through 400 ml of the odorant distributed into three gas washing bottles. Empirical tests of the weight lost from the odorants when known volumes of air were sparged through the washing bottles confirmed that saturation was complete.

The overall flowrate was fixed for each odorant but was varied from one odorant to another. It ranged from 1.8 L/min for acetone to 6 L/min for geraniol. These values were chosen to ensure that the psychophysical functions would occupy corresponding segments of the dynamic range of intensity, since functions for separated segments may not be comparable. For four of the five odorants the concentration series ranged from 100% to 1.59% of the saturated vapor in six equal logarithmic steps. The series for acetone was similarly constructed but from a maximum concentration of 71.1%.

The experimental chamber was the same as used in Experiments 1 through 4. The stimulus delivery tube (1.5 in. diam) protruded from the front wall at a 45-deg angle to a point just in front of the O. A series of relays and timers controlled the amount of time a stimulus was available to the O on a trial and the amount of time between trials.

**Procedure.** Each odorant was judged by an O in a separate experimental session. Judgments of intensity were made by magnitude estimation without a prescribed modulus. On each trial the O placed his nose approximately 1 in. above the end of the delivery tube and took one inhalation of the odorous air during the 3.5-sec period that it was available. Each of the seven concentrations of an odorant was presented twice in a session, and the order of presentation was irregular. In all of the sessions, the Os also judged the intensity of a 100% solution of ethyl acetate presented on a cotton swab, so that later the psychophysical functions could be tied together at a common point.

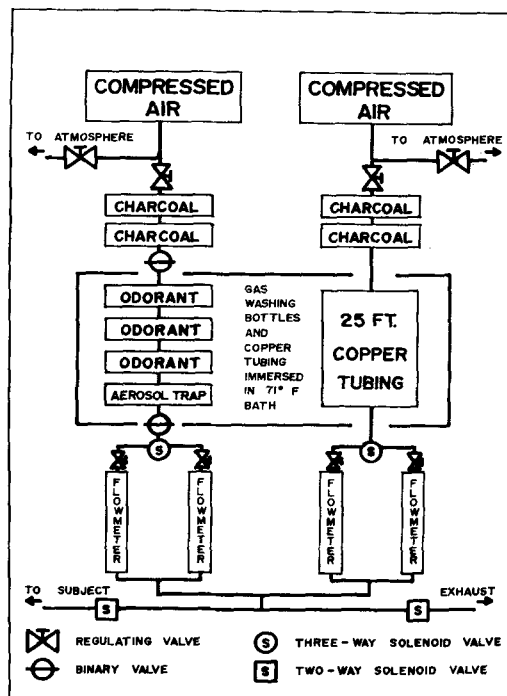


Fig. 6. Schematic diagram of the olfactometer.

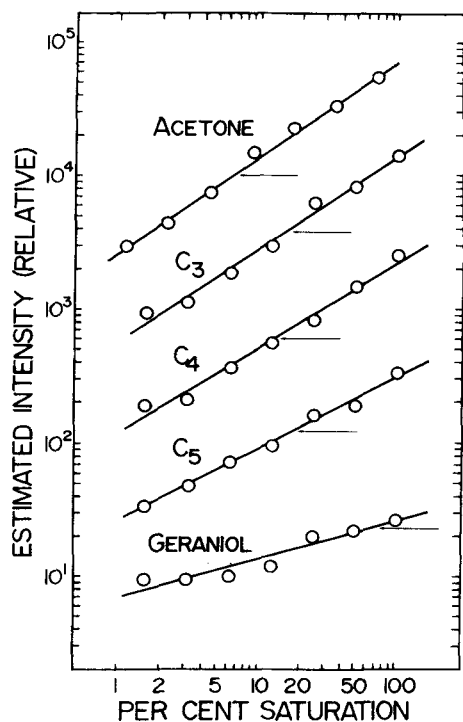


Fig. 7. Magnitude estimation as a function of concentration for five odorants. The functions have been displaced in the vertical dimension for clarity. The arrows indicate points of equal intensity across odorants and provide the means to relate the functions to each other.

## Results

The exponents of the functions obtained with the olfactometer were as follows: acetone, 0.71; geraniol, 0.28; propanol, 0.69; butanol, 0.64; and pentanol, 0.56 (Fig. 7). Although these exponents are significantly higher, their relative values agree with the values obtained with liquid solutions. Notably, the exponent for propanol was approximately 2.5 times the exponent for geraniol, and the exponents for the three aliphatic alcohols decreased as a function of carbon chain-length. The exponents for propanol and butanol were, however, more similar than anticipated.

## DISCUSSION

It is clear that the size of the exponent for odor depends on a number of factors. Most important in the present experiments, however, were the physical properties of the odorants and the manner of stimulus presentation. Although the olfactometer provided more reliable control of concentration than did liquid dilution, it is unlikely that this alone caused the exponents of Experiment 5 to be higher than those of Experiments 1 through 4. Os who were exposed to both methods of stimulus presentation claimed that it was basically more difficult to judge the intensity of an odorant presented on a cotton swab than one presented with the olfactometer. In the former case the O must present the stimulus to himself; he must be careful not to touch his nose with the swab but he must also hold it not more than a few millimeters away from his nostrils. The necessity for such care undoubtedly acts as a constraint on the O and the usual effect of constraining influences is conservatism of judgment, i.e., constriction of the range of intensity estimates. As S. S. Stevens and Greenbaum (1966) pointed out, this regression effect is ubiquitous in psychophysical judgment. For example, even when

constraining influences are minimized, magnitude estimation produces an underestimation of the size of the exponent and magnitude production an overestimation. Furthermore, the regression angle between the functions obtained with estimation and production increases with conservatism of judgment. Unfortunately, it is difficult to arrange for Os to do magnitude production with odors (especially if an olfactometer is used), and therefore it is difficult to obtain an estimate of the exponent that is relatively free of the regression effect. However, if the regression effect could be eliminated it is possible that there would be little or no difference between the exponents obtained with the two methods of stimulus presentation.

Of prime consideration in the present context are the relative values of the exponents. In the four experiments that allowed comparisons among aliphatic alcohols there was a perfect rank-order relation between the size of the exponent and those physicochemical properties that are monotonically related to chain-length. However, when all the odorants are considered, the physical property that seems to show the best correspondence with the exponents is water-solubility. The rank-order correlation between solubility in water and the exponent was virtually perfect in each of the five experiments, and there was a striking correspondence between the relative exponents of those substances that are completely miscible with water (acetone and propanol) or insoluble in water (octanol and geraniol). Various investigators (e.g., Backmann, 1917; Ottoson, 1958; Davies & Taylor, 1959; Moulton & Eayrs, 1960; Engen, 1964) have related oil and water solubility to effectiveness of olfactory stimulation, but not to the growth of suprathreshold intensity. Jones (1958a) found a ratio of 1.4 to 1 between the highest and the lowest exponent in a group of six chemically diverse odorants. Although the differences among some of the exponents were quite small, an analysis of his data also reveals a general relationship between water-solubility and the size of the exponent. There is a rank-order correlation of +0.94 between his exponents and water-solubility as listed in the *Handbook of chemistry and physics*.

The physicochemical properties of odorous substances are often interdependent and may exert their biological effects in concert. Thus, it is important to proceed with caution in any attempt to relate psychophysical properties with a specific physicochemical property. For now, it seems appropriate to conclude that the rate of growth of suprathreshold odor intensity is at least partially dependent on the solubility characteristics of odorants.

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#### NOTES

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