Perceived effort in sniffing: The effects of sniff pressure and resistance

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Previous research has shown that perceived odor strength does not vary with flow rate of an odorant vapor entering the naris when that variation is produced by subject-controlled changes in sniff pressure, but that it does vary with flow rate when the variation is produced by experimenter-controlled changes in the resistance of the olfactometric system. We have suggested an odor-constancy model in which invariance of perceived odor strength is linked to perceived effort of sniffing, and have hypothesized that changed resistance will have its effect because there is no corresponding change in perceived effort when sniff pressure is held constant. In two studies, subjects made magnitude estimations of the perceived effort of sniffing; sniff pressure was controlled by having the subject match his sniff, displayed on a storage oscilloscope face, to a pattern specifying its required shape, duration, and level. In Experiment 1, resistance was fixed while sniff pressure varied; perceived effort grew as the .8 power of the required sniff pressure. In Experiment 2, sniff pressure and resistance were varied in a factorial design; perceived effort grew as the .8 power of pressure at fixed resistance, but remained unchanged when resistance varied at fixed pressure. This outcome provides indirect support for the odor-constancy model, since it shows that perceived effort covaries with flow rate under the condition in which constancy is found but does not change under the condition in which constancy fails.

When an odorant stimulus presented to a subject is increased in concentration, his judgments of odor strength also increase; this effect of concentration is well established and is supported by neurological as well as psychophysical evidence. The belief that flow rate¹ of the odorant stimulus is also an important parameter of odor strength, though commonly held (e.g., Mozell, 1971), rests on weaker grounds. Although it has been shown in infrahuman preparations that an increase in flow rate over the olfactory mucosa can produce an increase in the discharge rate of the olfactory nerve (Beidler, 1958; Tucker, 1963a, 1963b),² there is little evidence concerning the subjective reaction of human observers sniffing odorous vapor. Indeed, we are aware of only one study (LeMagnen, 1944-1945) that reports an effect of flow rate on threshold (for eucalyptol) and of only one study (Rehn, 1978) that shows a similar relation at suprathreshold levels (for pyridine). Until the appearance of Rehn's report, the only study of flow-

rate effects on suprathreshold odor strength showed no effect at all (R. Teghtsoonian, M. Teghtsoonian, Berglund, & Berglund, 1978) for n-butanol and amyl acetate. The latter two studies also manipulated flow rate differently. Whereas R. Teghtsoonian et al. varied flow rate by having the subject achieve various levels of sniff pressure while the resistance of the olfactometric system was held constant, Rehn had his subjects maintain a constant sniff pressure while varying the resistance of the system. This procedural difference may be critical in explaining the difference between the results of the two studies, as we explain below.

In connection with our earlier results, we have proposed a perceptual constancy model (R. Teghtsoonian et al., 1978; M. Teghtsoonian, R. Teghtsoonian, Berglund, & Berglund, 1979), arguing that odor strength depends, not only on the proximal stimulus (the rate at which odorant molecules are established at the olfactory mucosa), but also on information about sniff vigor (the perceived effort associated with the sniff). Just as the perception of size entails the qualification of retinal size by perceived distance—increased retinal size is *not* interpreted as increased object size if the object is perceived as being nearer—so increased flow rate at the mucosa might, if associated with increased sniffing effort, lead to no change in perceived odor strength. An odor-response system built along these lines would arrive at the same conclusion about the concentration of an odorant regardless of whether it was sampled through weak or

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strong sniffing. If veridical perception is thought to confer survival value on the species characterized by it, our model might indeed embody an enduring property of the olfactory system.

It also follows from the perceptual constancy model that if, as the neurological evidence suggests, flow rate at the mucosa does influence the olfactory response, and if there is a change in flow rate with no concomitant information about changed effortfulness in sniffing, then perceived odor strength will directly reflect flow rate, in the same sense that perceived size becomes entirely dependent on retinal size when distance cues are eliminated. It seemed to us possible that Rehn's procedure might, by holding sniff pressure constant, create the conditions in which odor constancy breaks down and, for that reason, show a flow rate effect.

To explore this possibility, we needed to answer two questions. First, was it possible to measure the perceived effort of sniffing when sniff pressure was varied, in the same way that perceived effort has been measured when the force exerted on a hand-grip dynamometer is varied (see, for example, R. Teghtsoonian, M. Teghtsoonian, & Karlsson, 1977)? The first study to be reported addressed that question. The second question was whether, for constant sniff pressure, changes in the olfactometer's resistance would lead to corresponding changes in perceived effort. The second study to be reported concerned that question.

EXPERIMENT 1 PERCEIVED EFFORT OF SNIFFING AT DIFFERENT PRESSURES

Method

Subjects. The subjects were 36 undergraduates and graduate students at the University of Stockholm, who volunteered for the experiment and received either course credit or payment for their services.

Apparatus. The apparatus consisted of an olfactometric system with a pressure transducer connected to a nosepiece; it has been described in detail elsewhere (R. Teghtsoonian et al., 1978). A glass bottle with a horizontal arm held 250 ml of H₂O. At the end of the arm was a two-hole stopper fitted with a nosepiece. At the top of the bottle was a two-hole stopper supporting tubing that served as an air intake. The second hole in each stopper was linked by tubing to a membrane pump. In this study, no odorant was presented, but the olfactometric system itself was used because we wished to know about its perceived-effort characteristics.

The piezoelectric pressure transducer, with an associated amplifier, was connected by tubing to a nosepiece which, when connected to one naris, provided a voltage output proportional to the difference in pressure between air in the nostril and ambient air. This voltage was registered on a storage oscilloscope and provided a visible record of the observer's sniff-pressure amplitude.

Procedure. The sniff pressures to be produced by the subject were specified in the following way. A pattern was provided by affixing a contour to the oscilloscope face, which, when matched by the trace of the observer's sniff pressure, produced a sniff with rise and fall times of approximately 100 msec and a duration of 1.5 sec. By adjusting the setting of the amplifier for the pressure transducer, the sniff pressure required to match the height of the

contour could be varied from 13.5 to 110 mm H₂O (corresponding to inhalation flow rates from 93 to 303 ml/sec).

Each subject was given training in matching sniffs to the contour. After inserting the molded nosepiece connected to the pressure transducer into one naris, the subject breathed normally and observed the change exhibited on the oscilloscope. Then he/she attempted to match his/her sniff to the contour, first at a moderate level of pressure, then at higher and lower levels. Training was concluded when the experimenter judged that the subject had achieved a good match at each of the three training pressure levels.

The subject then matched each of seven target pressure levels, presented in random order, starting at each level with a few practice sniffs, then attempting to produce copies of the contour until two matches were judged good by the experimenter. For each of those good copies, the subject made a judgment of how much effort was required to make the sniff. The technique of free-modulus magnitude estimation was used: The subject assigned any number deemed appropriate to the effort required for a sniff at the first target pressure level, then assigned numbers that were proportional to the efforts required for subsequent stimuli.

Each subject carried out this procedure once with only a single naris engaged, by the nosepiece of the pressure transducer, and once with both nares engaged, one by the nosepiece of the pressure transducer and the other by the nosepiece of the olfactometric system. There was a 15-min rest interval between the two parts of the procedure. Half the subjects had the two-nares condition first, and the other half had it second.

Each subject was also asked to produce the weakest sniff he/she could, and then the strongest sniff. The amplitudes of these sniffs were recorded.

Results

For each subject in each condition, the log geometric mean judgment of effort was regressed on log stimulus intensity, voltage (proportional to pressure). This yields an exponent and an r^2 (the coefficient of determination, a measure of goodness of fit) for the best-fitting power function for each set of individual judgments. The r^2 s were high, indicating that power functions were good fits; the range was from .81 to .99, with a mean of .93 and a standard deviation of .05.

An analysis of variance of the individual exponents (a Latin-square design with repeated measures) evaluated differences due to period of testing (first half vs. second half of sessions), condition (one naris vs. two nares engaged), and group. None of the main effects was significant [$F(1,16)=2.34$, $p>.05$, for period; $F(1,16)<1$ for condition; $F(1,16)=3.83$, $p>.05$, for group].

The mean lowest level of sniffing was 5.28 mm H₂O, and the mean highest level was 234 mm H₂O, a dynamic range $\{\log[(\text{maximum effective stimulus})/(\text{minimum effective stimulus})]\}$ for sniff vigor of 1.65.

Figure 1 shows the overall geometric means of perceived effort as a function of sniff pressure (in mm H₂O). The two lowest points fall below the line defined by the five higher values; a power function fitted to the five top points yields Perceived Effort = $k \text{ pressure}^{.78}$.

Discussion

It appears that observers are quite sensitive to vari-

Figure 1. Perceived effort of sniffing at different pressures at fixed resistance and sniff duration. Coordinates are doubly logarithmic. Each point represents the geometric mean of 144 judgments (four number matches from each of 36 subjects). The line represents the best-fitting power function for values above 19 mm H₂O. Also shown are geometric mean pressures of least and greatest possible sniffs produced by each subject.

ation in sniff pressure under our testing conditions. The results are typical of magnitude estimation experiments in which some intensive perceptual attribute is being judged: Despite the curvature at the low end of Figure 1, a power function is a good description of the relation between perceived effort and sniff pressure exerted at pressures above about 20 mm H₂O.

The obtained exponent, about .8, merits some comment. First, it is almost certain that this value underestimates the "true" value. Magnitude estimation procedures are biased by a tendency of subjects to restrict their range of judgment, and, without the data from a complementary experiment using magnitude production, it is difficult to bracket the "true" value. However, it is interesting to consider the value implied by the obtained measure of dynamic range, 1.65 log units. R. Teghtsoonian (1971) showed that, for a wide variety of scaling experiments reported by S. S. Stevens using magnitude estimation, the judgmental range tended to be invariant, having a mean value of 1.53 (and a standard deviation of only .30). Exponents for 21 different continua calculated as the ratio of 1.53 divided by the stimulus range, in log units, proved to be in excellent agreement with the obtained values. If the dynamic range estimated in the present study, 1.65 log units, is taken in conjunction with the mean judgmental range of 1.53 log units obtained from the Stevens experiments, the predicted exponent is .93. Thus, here is at least indirect evidence suggesting that our obtained value of about .8 is a reasonable estimate.

The only comparable investigations we have found were reported by Bakers and Tenney (1970) and Stubbing, Killian, and Campbell (1981) in studies of

the sensations associated with breathing. Bakers and Tenney instructed subjects to blow into a mouthpiece until various criterial pressures (expressed as percentages of maximum possible) were achieved, and then to estimate the pressure experienced relative to that associated with the maximum. They report the data as being fitted by a power function with an exponent of 1.6, but an inspection of their Figure 1 suggests that a number of their subjects showed a steepening of the function at low pressures similar to that shown in our Figure 1. We suspect that a function fitted to the upper range of pressures would yield an exponent much closer to our value. Stubbing, Killian, and Campbell, although they did not ask subjects to judge pressure, did ask them to judge volume (the "depth" of breath) and flow rate of a single breath, during mouth breathing, by a method of magnitude production; the mean exponent was 1.1 for both types of judgment. It is difficult to compare our results with theirs without knowing the relations between perceived volume, perceived flow rate, and perceived effort, and the effect that mouth or nose breathing may have on these relations.

Since Experiment 1 showed that subjects are able to make orderly, lawful judgments of perceived effort in sniffing, we undertook Experiment 2, varying both sniff pressure and the resistance to sniffing presented by the olfactometer in order to determine the effect of each on the perceived effort of sniffing.

EXPERIMENT 2 PERCEIVED EFFORT OF SNIFFING AT DIFFERENT PRESSURES AND DIFFERENT RESISTANCES

Method

Subjects. The subjects were 16 volunteers from the same group as in Experiment 1.

Apparatus. The apparatus was the same as in Experiment 1, with these modifications: The original two-hole stopper in the neck of the bottle, which supported a 30-mm length of tubing serving as the intake aperture, was replaced by a two-hole stopper with a 10-mm hole that supported a 20-mm length of Plexiglas with a hole drilled in it. The hole served as the intake aperture; it ranged in diameter from 2 to 8 mm, making it possible to produce variations in the resistance of the system over a range of 250:1.

Procedure. There were four levels of resistance, controlled by inserting one of four Plexiglas tubes (2, 3, 5, or 8 mm, i.d.).³ There were eight levels of pressure, producing an output from the pressure transducer of 2.72, 5.44, 10.9, 19.0, 29.9, 40.8, 68.0, or 109. mm H₂O. Five pressures were combined with each resistance; the combinations and resulting flow rates, ranging from 2.7 to 60.5 liters/sec (as determined by a volumeter), are shown in Table 1.

The subject was trained as in Experiment 1 to match the trace of his/her own sniff to a displayed contour; during training, the subject practiced matching sniffs that varied both in pressure required and resistance introduced, but was not informed that these two factors varied independently. When training was completed, the subject matched the target contour 20 times and then, after a 15-min rest, another 20 times. Flow rates for the 20 tested combinations of resistance and pressure are shown in Table 1. These

Table 1
Flow Rates (in Liters per Minute) Produced by Combinations
of Eight Sniff Pressures and Four Resistances

R	Pressure (in Millimeters of Water)							
	2.72	5.44	10.9	19.0	29.9	40.8	68.0	109.
2				2.7	3.5	4.4	5.8	7.6
3			6.3	8.6	11.1	13.2	17.7	
5			17.5	23.5	29.8	35.0	45.5	
8	17.5	25.2	36.0	51.5	60.5			

Note—R = resistance (ID in millimeters).

were presented in random order once, and then again. The amplifier linking the output of the pressure transducer to the oscilloscope was adjusted each time so that, at the designated resistance, a sniff of the designated pressure would match the target contour. Each time the subject attempted matches until, in the judgment of the experimenter, two good copies had been made. For each good copy, the subject assigned a number to represent the perceived effort required to produce that sniff.

Results and Discussion

Figure 2 shows the perceived effort of sniffing corresponding to various flow rates. The effortfulness of a sniff increases with flow rate when pressure is increased at a fixed resistance (shown by points connected by solid lines). But the effortfulness of a sniff shows no change as flow rate increases when resistance is decreased at a fixed pressure (shown by points connected by dashed lines).

Statistical evaluation of these effects took advantage of the complete factorial design embedded in the larger incomplete factorial constituting the ex-

periment. The three highest resistances (identified as 2, 3, and 5) were each paired with four pressures (19.0, 29.9, 40.8, and 68.0 mm H₂O); judgments of perceived effort for these 12 combinations were subjected to an analysis of variance for a two-factor design with repeated measures. The outcome confirms the conclusions suggested by an inspection of Figure 2—a significant effect of sniff pressure [$F(3,45) = 61.33$, $p < .05$], none for resistance [$F(2,30) = 1.33$, $p > .05$], and a nonsignificant interaction [$F(6,90) = 1.00$, $p > .05$].

When perceived effort is plotted against sniff pressure, as shown in Figure 3, the separation of functions according to resistance that occurs when flow rate is substituted for pressure, as in Figure 2, disappears. Since Experiment 1 showed that the power function relating effort to pressure holds only for values at or above 19.0 mm H₂O, judgments of target values of 5.44 and 10.9 mm H₂O were discarded in fitting a power function to the effort-pressure relation in Experiment 2. Regressing log geometric mean judgments of effort on log pressure produces the function represented by the straight line in Figure 3; the slope of the line is .79, not different from the .78 found in Experiment 1.

Figure 2 suggests that there may be an interaction between sniff pressure and resistance, which, however, is not confirmed by the analysis of variance. The steepening of the effort/flow-rate slopes as resistance decreases results from two nonlinearities, one in the subject's judgments and one in the physical situation. Below pressures of 19.0 mm H₂O, subjects give effort judgments that are smaller than those predicted by the power function fitted to values equal to or greater than 19.0 mm H₂O. Since, in our design, lower resistances are associated with lower pressures, these low judgments will produce a steeper function at lower resistances when effort is plotted against flow rate. The second nonlinearity is between pressure and flow rate; while measured flow rate is approximately the square root of sniff pressure in our apparatus, the nonlinearity is more marked at higher flow rates. Thus, for resistance 2 with flow rates between 2.5 and 7.7 liters/min, flow rate grows as the .63 power of sniff pressure, whereas at resistance 8 with flow rates between 17 and 61 liters/min, flow rate grows as the .53 power of sniff pressure. This means that, when the four effort-pressure functions for the four resistances are shown with flow rate substituted for pressure, the slope will increase as resistance decreases. Figure 4 shows a model of these two effects, where perceived effort of sniffing is assumed to grow as the .8 power of sniff pressure only above 19.0 mm H₂O but to be unaffected by resistance, when the physical characteristics of the olfactometric system introduce a flow-rate dependence of the function relating sniff pressure and flow rate. The open circles represent the data points shown in Figure 2.

Figure 2. Perceived effort of sniffing at different pressure-resistance combinations, at fixed sniff duration. Coordinates are doubly logarithmic. Sniff pressure is given in mm H₂O; resistance is identified by the inside dimensions, in millimeters, of intake tube. Each point is the geometric mean of 32 judgments (two number matches from each of 16 subjects). Solid lines connect judgments made at different sniff pressures at fixed resistance; dotted lines connect judgments made at different resistances at fixed pressure.

Figure 3. Perceived effort of sniffing at four resistances as sniff pressure varies. Coordinates are doubly logarithmic. Resistances are identified by the inside dimensions, in millimeters, of intake tube. Each point represents the geometric mean of 32 judgments (two number matches from each of 16 subjects). The line represents the best-fitting power function for values above 19 mm H₂O.

Figure 4. Model of perceived effort of sniffing, based on the assumption that effort is the .8 power of pressure above 19.0 mm H₂O, and taking account of nonlinearities in the pressure/flow-rate functions. Sniff pressure is given in mm H₂O; resistance is identified by the inside dimensions, in millimeters, of intake tube.

The results are quite clear: Sniff pressure, at a fixed resistance, is a clear correlate of perceived effort, whereas resistance, at a fixed pressure, is not. Thus, it appears that Rehn's experimental technique for manipulating flow rate, a constant sniff pressure exerted against variable resistance, fulfills exactly the conditions under which, according to the perceptual constancy model, constancy is expected to fail. Flow

rate is indeed changing, but in a way that leaves the perceived effort of sniffing invariant; hence, there is no basis for odor constancy to occur. The disparity between Rehn's (1978) results and those reported by R. Teghtsoonian et al. (1978) is empirically real, but theoretically there appears to be no conflict. It remains, of course, desirable to replicate the design of the present study using odorant stimuli. Such an experiment is tantamount to simultaneous replication (and extension) of Rehn's experiment and of ours. If, as we expect, both sets of results are reproduced, the findings of the present study provide a theoretical resolution and at least indirect support for the odor-constancy model.

The conclusion that observers are insensitive to changes in the resistance to sniffing may seem to some to be counterintuitive. Anyone who has suffered nasal congestion can have little doubt about the detectability of increased resistance under those circumstances (and sensitivity to airflow resistance has been demonstrated by, e.g., Gottfried, Altose, Kelsen, Fogarty, & Cherniack, 1978, and Wiley & Zechman, 1966/1967). However, in normal breathing, a constant volume, the tidal volume, is inspired during each respiratory period. Stubbing, Killian, and Campbell (1981) have shown that subjects can match a control tidal volume as accurately and precisely with the addition of inspiratory resistance as with normal resistance. When nasal resistance is sharply increased, as in the case of congestion, greater pressure is required to achieve normal tidal volume without dramatically altering the duration of the respiratory period. It seems likely that it is the increased pressure required to produce normal tidal volume that cold sufferers experience in the form of increased perceived effort during nasal inspiration. In short, we believe that the nose knows when it is stuffed. But, on the basis of our study, we do not believe that such knowledge is associated with normal sniff pressures exerted against increased nasal resistance.

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1. Tucker, D. Personal communication, 1975.

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NOTES

1. Here, and in all later occurrences of the term "flow rate," we refer to the volume of gas per unit time passing *from the olfactometer* to the subject's nose. It is generally recognized that, due to the architecture of the nasal cavity and the associated turbulence during respiration, flow rates at the entrance to the nares cannot be assumed to apply at the olfactory mucosa. We do assume that flow rate over the mucosa increases monotonically with flow rate at the nares.

2. Although the published literature on the neurological response to flow rate is limited, investigators in the area regard the relation as beyond doubt. Tucker (Note 1) says of the flow rate effect, "We see it so routinely in our recording experiments that we are continuously aware of it."

3. It is not possible to provide a unique specification for each of those inserts because, as our calibration measurements revealed, the relation between flow rate and pressure in our apparatus is not linear. As indicated by the values in Table 1, flow rate grows with negative acceleration as pressure increases. It is for this reason that subsequent references to the four "resistance" conditions are in terms of the internal diameters of the Plexiglas inserts rather than in conventional units of resistance. But it may be helpful for the reader to know that, under ideal flow conditions, resistance is inversely related to the fourth power of tube diameter. When considering the effects of resistance, as shown in Figures 2, 3, and 4, larger numbers (internal diameters of inserts) mean smaller resistances.

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