Research Report

AUDITORY PITCH AS A PERCEPTUAL ANALOGUE TO ODOR QUALITY

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Givaudan-Roure Fragrances

Abstract—*Experiments in cross-modal matching suggest that smells can be arranged by odor quality along the color dimensions of hue and lightness. Here we report that subjects readily adjust the loudness-equalized pitch of an auditory tone to match a stimulus odor. The results allow odors to be arranged in sequence by their pitch-equivalents. The tone matches appear to be based on perceptual features of olfaction other than stimulus intensity or pleasantness. The results suggest that features of odor quality may be more accessible and structured than previously acknowledged.*

The phenomenological description and quantification of smells is notoriously problematic. Despite the occasional development of a vocabulary for a specific application (e.g., wine tasting; Noble et al., 1987), there remains "an essential resistance of olfaction to verbalization" (Classen, 1993, p. 56). This practical difficulty is mirrored on the level of theory by the inability of psychophysicists, after a century of research (Cain, 1978), to specify the perceptual dimensions of olfaction. Stimulus intensity and pleasantness-versus-unpleasantness have been proposed as dimensions (Berglund, Berglund, Engen, & Ekman, 1973; Jones, Roberts, & Holman, 1978), but no satisfactory scheme for organizing odor quality exists.

In recent experiments, we examined the psychological processing of odor perception by means of cross-sensory techniques. Our findings suggest that smells can be arranged dimensionally, at least with respect to the dimensions available in a different sensory modality. Untrained subjects matched odors (differing in quality but not intensity) to descriptive color terms and to physical color stimuli (Gilbert, Martin, & Kemp, 1996). These techniques yield quantifiable and reliable color impressions. In other experiments, increasing odor intensity (within a given odor quality) yielded color matches of decreasing lightness (i.e., stronger odor was matched with darker color; Kemp & Gilbert, 1994, 1997). Because smells appear to have cross-modal correspondences in the color dimensions of vision, we decided to explore odor matching in the auditory realm. The ultimate goal of this line of inquiry is to characterize the salient dimensions of odor perception by means of quantified analogy to other sensory modalities.

Cross-modal correspondences involving sound are well documented, as both natural synesthetic phenomena (Marks, 1978) and experimentally controlled psychophysical results (Marks, 1975). Comparable material on olfaction is harder to find. The perfumer Piesse (1891) matched aromatic essential oils to the notes of the musical scale, and one authority has claimed that low-pitched vowels in poetry connote, inter alia, "heavy" odors, whereas high-pitched vowels connote "delicate" odors (Macdermott, 1940). According to Classen (1990), at least one South American tribe recognizes synesthetic odor-music correlations. However, there has been little experimental work on smell-sound correspondences. Juhász (1926) suggested a sensory dimension of "Geruchshöhe," or smell-pitch. Hornbostel (1931) claimed to have matched smells to tones, and tones to gray samples of varying lightness, a cross-modal set of equivalencies that he designated "Geruchshelligkeit," or smell-brightness.

In pilot experiments, we had subjects match stimulus odors to sounds selected on an electronic keyboard. Odor-pitch matches were easily elicited and reliable. However, the pilot method had certain disadvantages: a restricted range of available pitch, the subjects' bias against half-tone keys, and lack of control for loudness over the pitch range. We next developed a method based on computer-generated sine-wave tones, and the psychophysical method of limits, and we report the results of that experiment here.

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EXPERIMENT 1

Method

Odor stimuli

Twenty fragrance materials used in commercial perfumery were prepared as solutions in diethyl phthalate and were equated for perceived intensity. Both the stimuli and the method of intensity equalization were identical to those described previously (Gilbert et al., 1996). The intensity standard was a moderate suprathreshold concentration of 20% olibanum. A separately recruited set of judges used magnitude estimation to rate the intensity of the stimulus odors in relation to the standard, which was assigned a value of 100. Stimuli were tested in sets of 10 odors with the intensity standard always included. Means of the log-transformed ratings were compared with that of the standard. Stimulus concentration was adjusted and testing was repeated until all means were within 1 *SD* of the reference sample mean.

The stimuli were drawn from several fragrance categories (e.g., floral, citrus, woody, earthy) and included essential oils extracted from botanical sources as well as synthetic aroma compounds. Some of the test odors (e.g., pine oil and lavender oil) were familiar to the general public, but others were unlikely to have been experienced outside of the fragrance industry. Examples include galbanum oil (potato, earthy) and artificial civet (animal-like, fecal). The sequence in which odors were presented was randomized for each subject. Samples were presented in 0.5-oz. (14.5-ml) amber glass bottles containing 10 g of solution. Sample solutions were replaced every 10 trials.

Auditory stimuli

A software program (Geotest ATEasy version 2.0) was used to produce 1-s sine-wave tones through stereo headphones (Telephonics TDH-50P) via a function generator board (Geotest GT 1012-FA). The experimenter selected stimulus frequency with a mouse. Sound output through the headphones was calibrated across ⅓-octave bands using the data of Stevens (1971) so that different frequencies would be perceived as equal in loudness to an 80-dB 1000-Hz tone.

Procedure

A method of limits was used to identify a tone matching each test odorant. After smelling a sample, the subject was given an initial tone and asked whether it matched the sample. If it did not, the experimenter presented another tone that was higher or lower in pitch, as directed by the subject. Pitch differences between successively presented tones began at one octave. This difference was reduced each time the subject reversed direction when requesting a change of pitch. Across a series of reversals, pitch intervals were reduced from one octave, to a half octave, to a quarter octave, and so on. The trial ended when the subject judged the pitch to match the odor. Statistical analyses were performed on $\log_2$-transformed values of the final selected frequencies, in order that equal numerical intervals would correspond to equal changes in perceived pitch. Prior to testing, the subject was presented with 9000-Hz and 100-Hz tones to illustrate the available range.

Each subject was tested in two 1-hr sessions, held on different days. In one session, the initial tone for all 20 trials was 200 Hz, and in the other session, it was 1000 Hz. The order of the two sessions was counterbalanced across subjects. The mean interval between sessions was 7 days; the minimum interval was 2 days.

Subjects

Thirty-two subjects (15 women, 17 men) between 19 and 40 years of age participated ($M \pm SD = 33 \pm 6$ years). Subjects were recruited via newspaper advertisements and screened by self-report for normal sense of smell, normal nasal breathing, and absence of active head cold, sinus infection, or allergy. Additional exclusion criteria were professional employment as a musician, use of a hearing aid, or self-reported hearing loss. Subjects provided their informed consent and were paid for their participation.

Results

A repeated measures analysis of variance showed significant effects of both odor ($F[19, 589] = 4.14, p < .001$) and initial frequency ($F[1, 31] = 204.68, p < .001$) on the matching frequencies selected by the subjects. The odor-by-initial-frequency interaction term was not significant, $F(19, 589) = 1.08, p > .05$. For every odor tested, the mean matching frequency was lower in the 200-Hz condition than in the 1000-Hz condition (Fig. 1). The mean difference in $\log_2$ matching frequencies between the two initial-tone conditions was 1.18 ± 0.23 ($n = 20$). Thus, the matching frequencies were on average 2.27 times (or roughly an octave) higher in the 1000-Hz than in the 200-Hz condition.

Matching frequencies ranged from approximately $F^{\#}3$ to $F^{\#}4$ in the 200-Hz condition (mean $\log_2$ from 7.51 ± 1.31 to 8.53 ± 1.01), and from G3 to $B^{b}5$ in the 1000-Hz condition (mean $\log_2$ from 8.64 ± 1.53 to 9.85 ± 1.10).

The ordering by pitch of the odor stimuli was similar in the 200- and 1000-Hz conditions (Fig. 1). The Pearson correlation between matching frequencies in the two conditions was significant, $r = .80$, $p < .001$. An alternative analysis with the Spearman rank-order correlation was also significant, $r_s = .66$, $t(18) = 2.98$, $p < .05$.

Discussion

Using a method of limits, subjects matched auditory tones to smells that varied in odor quality but not intensity. The tone matches varied significantly in pitch across odors, indicating that subjects could use information about qualities other than intensity to arrange smells along a perceptual dimension.

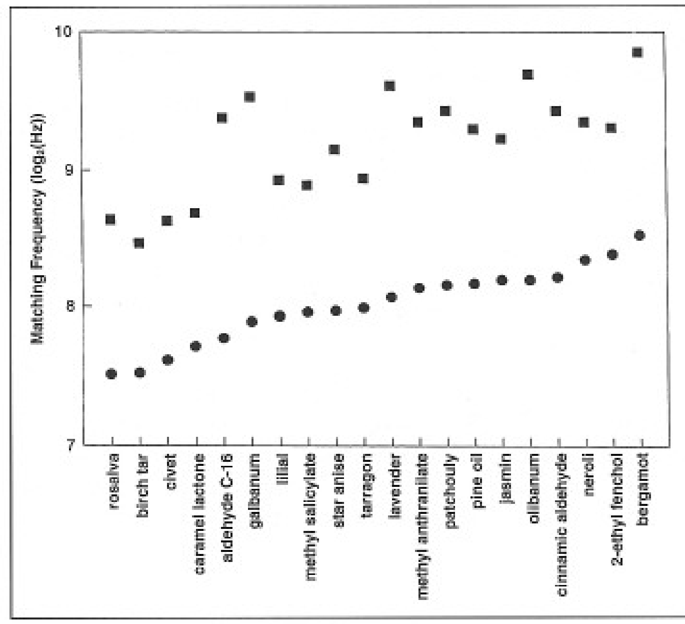

Fig. 1. Matching frequencies for odors in the 200-Hz (filled circles) and 1000-Hz (filled squares) conditions.

Two test sessions, held on different days and with different initial tones, provided an internal control that demonstrated the sequencing of the odors to be consistent from test to test, even with minor changes in protocol.[1] Although higher initial tones produced higher pitched matches, the two conditions produced rank orders that were significantly correlated. Thus, the relative pitch-equivalents of smells were stable, while the absolute pitch of the matched tones showed a sensitivity to initial conditions. Frequency matches to most odors were between 200 and 1000 Hz (i.e., between the two initial-tone frequencies), suggesting that the matching tones were converging on a set of intermediate frequencies.

EXPERIMENT 2

Before concluding that features of odor quality were the likely basis of the pitch matches in Experiment 1, we tested the counterhypothesis that subjects merely judged the hedonic value of each stimulus odor, and assigned it a correspondingly high or low pitch value. We had another panel of subjects provide hedonic ratings of the same stimuli, and we compared rank orderings based on pitch and hedonic value.

Twenty-nine subjects (15 women, 14 men) between 22 and 40 years of age ($M \pm SD = 32 \pm 5$ years) were recruited via newspaper advertisements and screened by self-report for sense of smell, as in

1. Within-subjects reliability is an ongoing issue with respect to synesthesia and cross-modal correspondences. Accordingly, we used a repeated measures design to examine this feature of the phenomenon. However, because we did not use a randomized group design, we are unable to rule out the possibility that similarity in matching judgments arose, in part, from subjects remembering their previous judgments.

Experiment 1, and for criterion performance on a visual scaling task. Subjects practiced bipolar hedonic scaling using printed words as stimuli. In the actual experiment, they rated the pleasantness of each odor by marking a 15-cm scale presented on a computer screen. The scale was anchored by "extremely unpleasant" on the left, "neither pleasant nor unpleasant" at the midpoint, and "extremely pleasant" on the right.

Subjects rated the entire set of odors on two different occasions, and the mean of the two ratings for each odor was used for analysis. Hedonic ratings were not significantly correlated with matching frequencies in either initial-tone condition (hedonic vs. 1000 Hz: $r = .10$, $p > .05$; hedonic vs. 200 Hz: $r = .22$, $p > .05$). A similar result was obtained using the Spearman rank-order correlation to compare hedonic rank ordering to rank orderings based on pitch (hedonic vs. 1000 Hz: $r_s = .01$, $t[18] = 0.06$, $p > .05$; hedonic vs. 200 Hz: $r_s = .18$, $t[18] = 0.79$, $p > .05$). On the basis of these results, we conclude that it is unlikely that subjects in Experiment 1 were using covert hedonic evaluations of the stimuli as a substitute or stand-in for features of odor quality.

GENERAL DISCUSSION

Despite the fact that most people in most circumstances find it difficult to articulate their experience of odors, untrained subjects were able to use perceptual features extracted from smells to select auditory matches based on pitch. Because stimulus intensity and pleasantness cannot account for the result, the relevant perceptual feature appears to be some aspect (or aspects) of odor-quality coding. As is evident from the consensus sequencing of smells by pitch, subjects share a common interpretation of these features of odor quality. The exact nature of these features, which are central to the unresolved question of how odor quality is coded, remains elusive. Existing schemes of odor classification (e.g., Amoore, Henning) are based on typologies rather than stimulus features or sensory dimensions, and there is little evidence that subjects can or do use these categories when judging odor quality (Cain, 1978). Subjects could have based their pitch matches along such putative olfactory dimensions as dull-aromatic (Wender, 1968), heavy-light, bright-dark, or hard-soft (Klutky, 1990). The cross-sensory technique developed in this study provides a means by which such putative dimensions of odor quality can be isolated and studied experimentally.

Elsewhere, we have shown that odors differing in quality produce consistent associations to color (Gilbert et al., 1996; Kemp & Gilbert, 1997); in this study, we have shown that they produce associations to auditory pitch. Along with other psychophysical studies of cross-modal perception and clinical demonstrations of synesthesia (Cytowic & Wood, 1982), our observations raise a phenomenological question: Are smell-sound and smell-color associations experienced as synesthetic perceptions, or are they metaphors based on semantic equivalence? To ascribe quantifiable and reliable sensory correlations to a metaphor merely defers the question to the semantic domain; the question must ultimately be answered in the sensory domain. In the present case, however, even the metaphor is elusive: By what metaphor do subjects match birch tar to a low-pitched tone and bergamot to a high-pitched one?

Smell-sound correspondences are probably more than metaphor, but less than truly synesthetic perception. Few people spontaneously "hear smells." This particular form of synesthesia appears to be rare even in clinically identified synesthetes, and our subjects were not selected on the basis of this or any other synesthetic ability. Thus, the sensory correspondences described here are not synesthesia in the strong sense. Rather, our results show that people can analogize perceptual dimensions from the auditory and olfactory modalities in the context of a cross-modal matching task. In this respect, our results confirm the early claim of Hornbostel (1931). His experiment, however, lacked stimulus control: The undiluted odorants varied in perceived strength, and the tones were presented with tuning forks. Subjects may have matched stimuli based on loudness as well as pitch, and odor strength as well as quality. By minimizing differences in loudness and odor strength, we were able to go beyond Hornbostel's results and identify an orderly relation specifically between pitch and odor quality.

Sensory analogies between olfaction and the other senses (Gilbert et al., 1996; Kemp & Gilbert, 1997) could serve as the basis of a research strategy to characterize the key perceptual dimensions of odor quality. By systematically comparing smell with the other senses on a dimension-by-dimension basis, researchers can determine which cross-modal relations are relevant and which are not. A logical next step given the present results is to examine the relation of auditory timbre to odor quality.

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