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Olfactory Discrimination Ability for Aliphatic Odorants as a Function of Oxygen Moiety

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Abstract

We tested the ability of human subjects to distinguish between aliphatic odorants sharing the same number of carbon atoms but differing in their functional groups. 1-Alcohols, *n*-aldehydes, 2-ketones and *n*-carboxylic acids of four, six and eight carbon atoms, respectively, were employed. In a forced-choice triangular test procedure 20 subjects were repeatedly presented with 18 odor pairs and asked to identify the bottle containing the odd stimulus. We found (i) that as a group, the subjects performed significantly above chance level in all tasks and thus were clearly able to discriminate between all odor pairs presented; (ii) marked interindividual differences in discrimination performance, ranging from subjects who were able to significantly distinguish between all 18 odor pairs to subjects who failed to do so with 1/3 of the tasks; (iii) a lack of significant differences in performance between male and female, and between Japanese and German subjects; (iv) that odor pairs that involved 2-ketones and/or *n*-carboxylic acids were significantly easier to discriminate compared to odor pairs that involved 1-alcohols and/or *n*-aldehydes, and thus a clear dependence of discriminability on type of functional group; and (v) that aliphatic odorants with eight carbon atoms (irrespective of their oxygen moiety) were significantly more difficult to discriminate from each other compared to substances with four or six carbon atoms. The results suggest that functional groups may be an important determinant of the interaction between stimulus molecule and olfactory receptor in aliphatic substances, and thus may be a molecular property affecting odor quality in a substance class-specific manner.

Introduction

The most remarkable feature of the olfactory system is its ability to recognize and discriminate between an enormous number of different odor molecules. Although the neural mechanisms underlying this amazing performance are still poorly understood, there is common agreement that the cascade of events leading to odor perception begins with differential interaction of odor molecules with different types of olfactory receptors (Hildebrandt and Shepherd, 1997). To gain insight into how the olfactory system actually recognizes a given stimulus, it is therefore clearly important to establish which properties of an odor molecule are involved in determining the degree of interaction with a given receptor and thus in determining its odor quality. Further, the assessment of odor structure–activity relationships is also of practical interest with respect to the prediction of the odor quality of a molecule or of the perceived similarity between odor molecules (Ohloff *et al*., 1991).

It is now widely accepted that both the shape of an odor molecule and the nature and disposition of its functional group(s) play a determining part in the strength and character of odorants (Beets, 1982; Boelens, 1983; Chastrette and Zakarya, 1991; Yoshii and Hirono, 1996). This should not be surprising given that the driving force of the interaction between a stimulus molecule and an olfactory receptor is considered to be a directed dipole–dipole interaction and/or hydrogen bonding. However, as all hydrophobic sites of a stimulus molecule can be involved, olfaction should be considered as a multipoint interaction between a stimulus molecule and the active site(s) of a receptor molecule (Ohloff, 1994). This latter idea concurs with recent findings which have shown that a given odor molecule may interact with different types of olfactory receptors (although possibly to different degrees) and that different types of odor molecules may interact with a given olfactory receptor (Mori and Yoshihara, 1995; Malnic *et al*., 1999).

A considerable number of psychophysical studies have tried to reveal correlations between odor quality and the first molecular property mentioned above, i.e. the shape of odor molecules, usually by using substances that differ in their degrees of structural relatedness (Pilgrim and Schutz, 1957; Engen, 1964; Henion, 1970; Theimer *et al*., 1977;

Schiffman, 1974, 1981; Schleppnik, 1981; Ohloff *et al*., 1991; Hatanaka *et al*., 1992; Rossiter, 1996; Laska and Teubner, 1999a). Most of these studies, however, have employed odor profiling or scaling procedures which are presumed to be particularly susceptible to cognitive influences (Corwin, 1992). A different means of assessing odor structure–activity relationships which largely avoids the disadvantages of comparatively poor resolution, subjectivity, semantic ambiguity and likely context dependence is to test the discrimination ability for structurally related odorants (Cain and Olsson, 1995). By systematically testing the ability of human subjects to discriminate between members of homologous series of aliphatic esters (Laska and Freyer, 1997), alcohols and aldehydes (Laska and Teubner, 1999b), as well as carboxylic acids (Laska and Teubner, 1998) and ketones (Laska *et al*., 1999b), one of us has recently shown a significant negative correlation between olfactory discrimination performance and structural similarity of odorants in terms of differences in carbon chain length in all five substance classes mentioned, and thus that this molecular feature may be an important determinant of odor quality in aliphatic odorants.

Surprisingly few studies, on the other hand, have so far directly assessed whether correlations also exist between odor quality and the second molecular property mentioned above, i.e. the nature and disposition of functional groups. Most of these studies have concentrated on sets of aromatic substances and investigated the influence of different substituents on qualitative notes such as musk, sandalwood or ambergris which are of potential interest to the perfumer (Ohloff *et al*., 1991; Rossiter, 1996). To the best of our knowledge, no study to date has systematically investigated the impact of type of oxygen moiety on odor quality of aliphatic substances using a discrimination paradigm.

In the present study we aimed at filling this gap by testing the ability of human subjects to distinguish between 1-alcohols, *n*-aldehydes, 2-ketones and *n*-carboxylic acids with the same carbon chain length, i.e. aliphatic odorants that only differ in their respective oxygen moieties. The possibility to perform this study in two laboratories in Japan and Germany allowed us additionally to address the question of whether or not cultural differences affect olfactory discrimination performance.

Thus, the aims of the present study are threefold: (i) to provide first data on the olfactory discrimination ability of human subjects for aliphatic odorants sharing the same number of carbon atoms but differing in their functional groups; (ii) to assess whether the effect of type of oxygen moiety on odor quality and thus discriminability is substance-class specific; and (iii) to compare the olfactory discrimination performance of Japanese and German subjects.

Materials and methods

Human subjects

A total of 20 healthy volunteers (ten females and ten males) 23–38 years of age participated in the study. Half of the subjects (five females and five males) were Japanese, the remainder were German. None of the subjects had any history of olfactory dysfunction. They were informed as to the aim of the experiment and provided written consent. The study was performed in accordance with the Declaration of Helsinki/Hong Kong.

Odorants

A set of 12 odorants was used (Table 1). They comprised aliphatic substances from four different chemical classes (1-alcohols, *n*-aldehydes, 2-ketones and *n*-carboxylic acids) with four, six and eight carbon atoms, respectively. All substances were obtained from Merck (Darmstadt) and had a nominal purity of at least 99%. They were diluted using diethyl phthalate (Merck) as the solvent. In an attempt to ensure that the odorants were of approximately equal strength when presented in squeeze bottles, intensity matching was performed by a panel of six subjects using an 8.7 g/l solution of isoamyl acetate as the reference and adopting a standardized psychophysical procedure (ASTM, 1975).

Test procedure

Exactly the same procedures as described below were employed in the two laboratories in Japan and Germany. A 20 ml aliquot of each odorant was presented in a 250 ml polyethylene squeeze bottle equipped with a flip-up spout.

Table 1 Substances and concentrations used

Code	Substance	Concentration (g/l)
A	alcohols	
	1-butanol	8.0
	1-hexanol	16.4
	1-octanol	103.4
B	aldehydes	
	n-butanal	2.7
	n-hexanal	2.7
	n-octanal	2.7
C	ketones	
	2-butanone	16.0
	2-hexanone	8.1
	2-octanone	16.4
D	carboxylic acids	
	n-butanoic acid	1.0
	n-hexanoic acid	0.9
	n-octanoic acid	18.2

Subjects were instructed as to the manner of sampling and at the start of the first session were allowed time to familiarize themselves with the bottles and the sampling technique. Care was taken that the flip-up spout was only a short distance (1–2 cm) from the nasal septum during sampling of an odorant in order to allow the stimulus to enter both nostrils.

In a forced-choice triangular test procedure 20 subjects were asked to compare three bottles and identify the one containing the odd stimulus. Additionally, after each decision subjects were asked whether their choice was predominantly based on perceived differences in odor quality or on perceived differences in odor intensity. Each bottle could be sampled twice with an inter-stimulus interval of 10 s. Sampling duration was restricted to 1 s per presentation in order to minimize adaptation effects. The sequence of presenting the stimulus pairs was systematically varied between sessions and individual subjects while taking care that the presentation of a given odorant as odd or even stimulus was balanced within and between sessions. In order to control for possible cross-adaptation effects, the order in which the stimuli of a given triad were sampled was systematically varied between sessions. Approximately 30 s were allowed between trials and no feedback regarding the correctness of the subjects' choice was given.

According to the principle aim of the study, only odorants sharing the same number of carbon atoms were tested for their discriminability. Thus, 18 different stimulus pairs (Table 2) were presented once per session and testing was repeated in nine more sessions, each 1–3 days apart, enabling ten judgements per stimulus pair and panelist to be collected.

Data analysis

The criterion for an individual subject to be regarded as capable of discriminating a given odor pair was set at seven or more out of ten decisions correct (two-tailed binomial test, $P < 0.05$). Accordingly, the criterion for the group of subjects to be regarded as capable of discriminating a given odor pair was set at 13 or more out of 20 subjects performing significantly above chance (two-tailed binomial test, $P < 0.01$).

Comparisons of group performance across tasks were made using the Friedman two-way analysis of variance. When ANOVA detected differences between tasks, this was then followed by pairwise Wilcoxon signed-rank tests for related samples to evaluate which tasks were involved. Comparisons of performance between groups (Japanese versus German subjects and male versus female subjects) were made using Mann–Whitney *U*-tests for independent samples (Siegel and Castellan, 1988). All data are reported as means ± SD.

Results

General discrimination performance

Figure 1 summarizes the mean performance of 20 subjects in discriminating between the 18 odor pairs. As a group, the human subjects performed significantly above chance level in all tasks and thus were clearly able to discriminate between all odor pairs presented. Interindividual variability was high, particularly in odor pairs which some of the panelists were unable to distinguish above chance (cf. SDs in Figure 1). However, ANOVA detected significant differences in the group's performance between tasks (Friedman, $P < 0.001$) and subsequent pairwise tests revealed that within the C_4 group (i.e. pairs of odors sharing four carbon atoms, respectively) the odor pairs B–C (*n*-butanal versus 2-butanone) and C–D (2-butanone versus *n*-butanoic acid) were significantly better discriminated compared to all other pairs (Wilcoxon, $P < 0.01$ for both pairs and all combinations). The other four odor pairs of the C_4 group (A–B, A–C, A–D and B–D) did not differ significantly from each other in their discriminability. Similarly, within the C_6 group (i.e. pairs of odors sharing six carbon atoms, respectively) the odor pair C–D (2-hexanone versus *n*-hexanoic acid) was significantly better discriminated than all other pairs (Wilcoxon, $P < 0.01$ for all combinations). Odor pair A–B (1-hexanol versus *n*-hexanal) was significantly more difficult to distinguish than all other odor pairs within this group except odor pair B–D (Wilcoxon, $P < 0.01$ for all combinations). Within the C_8 group (i.e. pairs of odors sharing eight carbon atoms, respectively) again odor pair C–D (2-octanone versus *n*-octanoic acid) was significantly better discriminated than all other odor pairs except A–D (Wilcoxon, $P < 0.01$ for all combinations). The only other significant differences in performance within this group

Table 2 Assignment of odor pairs to groups according to carbon chain length

Code	C_4 group	C_6 group	C_8 group
A–B	1-butanol versus *n*-butanal	1-hexanol versus *n*-hexanal	1-octanol versus *n*-octanal
A–C	1-butanol versus 2-butanone	1-hexanol versus 2-hexanone	1-octanol versus 2-octanone
A–D	1-butanol versus *n*-butanoic acid	1-hexanol versus *n*-hexanoic acid	1-octanol versus *n*-octanoic acid
B–C	*n*-butanal versus 2-butanone	*n*-hexanal versus 2-hexanone	*n*-octanal versus 2-octanone
B–D	*n*-butanal versus *n*-butanoic acid	*n*-hexanal versus *n*-hexanoic acid	*n*-octanal versus *n*-octanoic acid
C–D	2-butanone versus *n*-butanoic acid	2-hexanone versus *n*-hexanoic acid	2-octanone versus *n*-octanoic acid

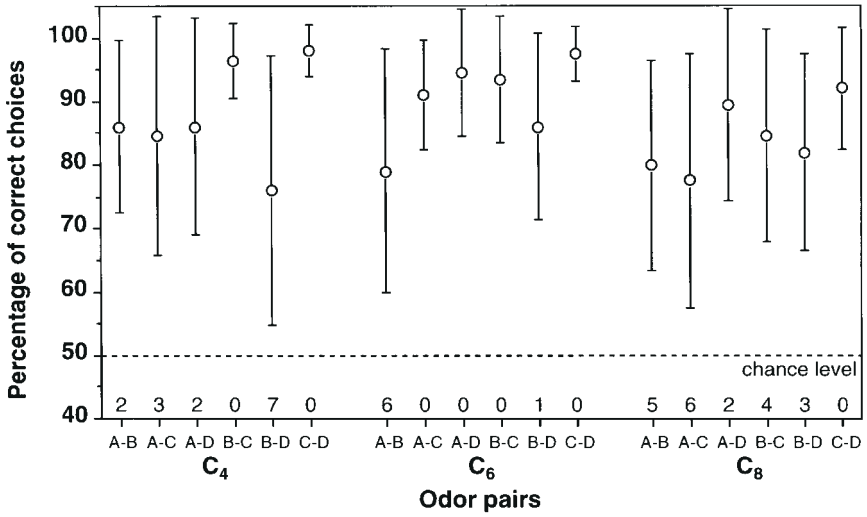

Figure 1 Performance of 20 subjects in discriminating between aliphatic odorants with the same number of carbon atoms but different functional groups. Each data point represents the percentage (means ± SD) of correct choices from ten decisions per odor pair and subject. The figures above the abscissa indicate the numbers of subjects that failed to perform above chance in the corresponding task. Names of substances for each odor pair are given in Table 2.

were found between odor pairs A–B and A–D, and between A–C and A–D (Wilcoxon, $P < 0.05$).

Comparisons of performance for a given pair of substance classes across the three C groups showed no significant differences except for combination B–C (*n*-aldehyde versus 2-ketone) which was significantly better discriminated in the C_4 group than in the C_8 group (Wilcoxon, $P < 0.01$).

Functional groups

Figure 2 shows the mean performance of 20 subjects in discriminating between aliphatic odorants with the same number of carbon atoms but different functional groups, irrespective of carbon chain length (i.e. each data point represents the combined data for a given combination of substance classes from the C_4, C_6, and C_8 groups). ANOVA detected significant differences in the group's performance between tasks (Friedman, $P < 0.001$) and subsequent pairwise tests revealed that the discrimination between aliphatic 2-ketones and *n*-carboxylic acids (i.e. odor pairs C–D, cf. Table 2) was significantly easier than that between all other odor pairs (Wilcoxon, $P < 0.01$ for all combinations). Discrimination between aliphatic *n*-aldehydes and 2-ketones (i.e. odor pairs B–C) was significantly easier compared to the discrimination between odor pairs A–B, A–C and B–D (Wilcoxon, $P < 0.01$ for all three combinations), and the discrimination between aliphatic 1-alcohols and *n*-carboxylic acids (i.e. odor pairs A–D) was significantly easier than that between odor pairs A–B and B–D. The remaining combinations did not differ significantly from each other in their degree of discriminability.

The marked differences in discriminability of aliphatic substances sharing the same number of carbon atoms as a function of the substance classes involved (irrespective of carbon chain length) is also mirrored by the number of individual cases of failure to significantly distinguish between a given odor pair (cf. upper line of abscissa in Figure 2): whereas none of the subjects failed correctly to discriminate between any pair of a 2-ketone and an *n*-carboxylic acid of the same carbon chain length (i.e. odor pairs C–D), there were 13 cases of failure with the discrimination of an aliphatic 1-alcohol and an *n*-aldehyde

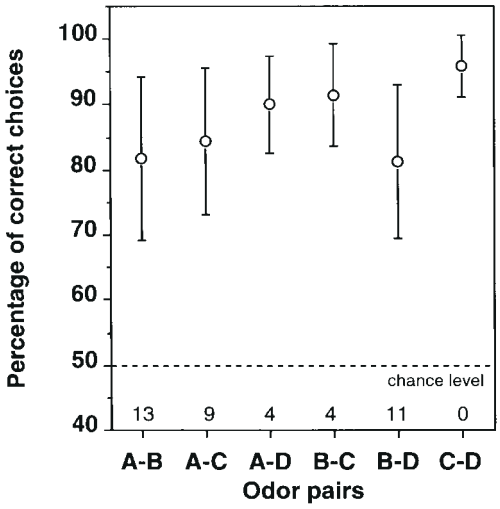

Figure 2 Performance of 20 subjects in discriminating between aliphatic odorants with the same number of carbon atoms but different functional groups. Each data point represents the combined data (means ± SD) for a given combination of substances from the C_4, C_6 and C_8 groups (cf. Table 2). The figures above the abscissa indicate the numbers of subjects that failed to perform above chance in the corresponding tasks. Names of substances for each odor pair are given in Table 2.

sharing the same number of carbon atoms (i.e. odor pairs A–B).

A further reduction of these data reveals that there was a sum total of only 13 cases of failure to discriminate between aliphatic odorants of the same carbon chain length when a 2-ketone (substance class C) was involved, and 15 cases when an *n*-carboxylic acid (substance class D) was involved (cf. upper line of abscissa in Figure 2). These numbers are significantly lower than the sum total of failures observed with 1-alcohols (substance class A; 26 cases) and *n*-aldehydes (substance class B; 28 cases). This suggests that 2-ketones and *n*-carboxylic acids are more distinct in their odor qualities and thus more easily discriminated from other aliphatic compounds sharing the same number of carbon atoms but differing in their oxygen moiety, compared to 1-alcohols and *n*-aldehydes.

Carbon chain length

Figure 3 shows the mean performance of 20 subjects in discriminating between aliphatic odorants with the same number of carbon atoms but different functional groups as a function of carbon chain length (i.e. each data point represents the combined data from the six odor pairs within a given C group; cf. Table 2). ANOVA detected significant differences in the group's performance between tasks (Friedman, $P < 0.001$) and subsequent pairwise tests revealed that the discrimination of odor pairs belonging to the C_8 group was significantly more difficult than for the C_6 group (Wilcoxon, $P < 0.01$) and the C_4 group (Wilcoxon, $P < 0.05$). The odor pairs belonging to the latter two C groups did not differ significantly from each other in their degree of discriminability (Wilcoxon, $P > 0.05$).

The differences in discriminability of aliphatic substances sharing the same number of carbon atoms as a function of carbon chain length (irrespective of the substance classes involved) is also mirrored by the number of individual cases of failure significantly to distinguish between a given odor pair (cf. upper line of abscissa in Figure 3): whereas only seven subjects failed correctly to discriminate between any pair of odors within the C_6 group, there were 14 cases of failure within the C_4 group and 20 cases within the C_8 group.

These data suggest that aliphatic odorants with eight carbon atoms are less distinct in their odor qualities and thus more difficult to discriminate from other aliphatic compounds sharing the same number of carbon atoms but differing in their oxygen moiety, compared to substances with four or six carbon atoms.

Interindividual differences

Interindividual differences in subjects' ability to discriminate between the 18 odor pairs were quite large (Figure 4). The percentage of errors ranged from only 2.2% for the best-performing subject up to nearly 27%. Accordingly, the best panelists were able significantly to distinguish all 18 odor pairs, whereas the poorest-performing subject failed to do so with 1/3 of the tasks.

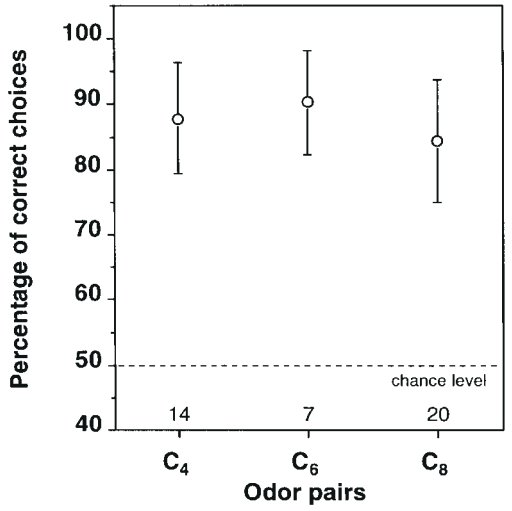

Figure 3 Performance of 20 subjects in discriminating between aliphatic odorants with the same number of carbon atoms but different functional groups. Each data point represents the combined data (means ± SD) from the six odor pairs within a given C group. The figures above the abscissa indicate the numbers of subjects that failed to perform above chance in the corresponding tasks. Names of odor pairs for each C group are given in Table 2.

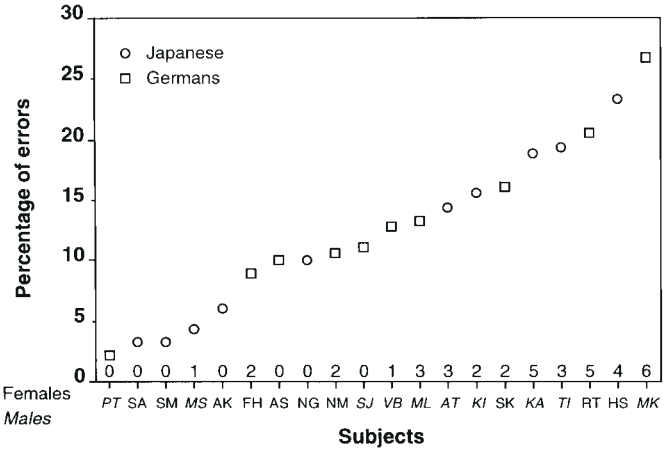

Figure 4 Distribution of individual performance in discriminating between aliphatic odorants with the same number of carbon atoms but different functional groups. Each data point represents the percentage of errors from 180 decisions per subject. The figures above the abscissa indicate the numbers of odor pairs that a subject failed to discriminate significantly above chance.

Gender differences

No significant differences in discrimination performance between male and female subjects were found with any of the 18 odor pairs (Mann–Whitney, $P > 0.05$ for all odor pairs). Likewise, the individual scores across all tasks (in

terms of percentage of errors, cf. Figure 4) did not differ between males and females (Mann–Whitney, $P > 0.05$).

Cultural differences

Japanese and German subjects did not differ significantly in their discrimination performance with any of the 18 odor pairs (Mann–Whitney, $P > 0.05$ for all odor pairs). Likewise, the individual scores across all tasks (in terms of percentage of errors; cf. Figure 4) did not differ between the two ethnic groups (Mann–Whitney, $P > 0.05$).

Training effects

The mean performance of the group of 20 subjects across the ten test sessions was quite stable. Error rates did not differ significantly between sessions (Friedman, $P > 0.05$) and thus no training or learning effects at the group level were found.

Odor intensity

With all 18 odor pairs <16% of decisions were reported to be based upon perceived differences in odor intensity rather than odor quality (cf. Test procedure). Altogether, 92.9% of decisions were reported to be based upon perceived differences in odor quality.

None of the statistical comparisons mentioned above led to significantly different results when the decisions reported to be based upon perceived differences in odor intensity rather than odor quality were removed from the data set.

Discussion

The results of this study demonstrate (i) that human subjects possess a well-developed olfactory discrimination ability for aliphatic odorants sharing the same number of carbon atoms but differing in their oxygen moieties, (ii) a clear dependence of discriminability on type of functional group, (iii) that discriminability changes as a function of carbon chain length and (iv) a lack of significant differences in performance between male and female, and between Japanese and German subjects.

Our findings lend support to the notions that the human sense of smell is far better than the held in the traditional view and that it is capable of discriminating between almost any pair of odorants (Cain, 1995). Whereas human subjects indeed perform comparatively poorly in tasks of verbal odor identification, discrimination and recognition (Cain, 1982; Ayabe-Kanamura *et al.*, 1998), the results obtained from non-verbal approaches to assess olfactory discrimination performance, such as that employed here, suggest that language-bound paradigms—which are undoubtedly useful in investigation of various aspects of cognitive odor processing—might be less suitable to assess odor structure–activity relationships.

However, the question arises as to whether the performance of the human subjects shown in the present study was indeed based on the ability of the olfactory system to discern between odor qualities, or whether other sensory systems or talents of the olfactory system may have been involved. The possibility that the nasal trigeminal system might have contributed to the discrimination of odorants (Doty, 1995) can be excluded as recent psychophysical studies have shown nasal pungency thresholds, mediated by the trigeminal nerve, of human subjects for the substances used here to be at least two orders of magnitude higher than odor thresholds, mediated by the olfactory nerve (Cometto-Muniz and Cain, 1995; Cometto-Muniz *et al.*, 1998). Thus, although congenitally anosmic subjects have been shown to possess at least a coarse ability to distinguish between highly concentrated odorants using information provided by their fifth cranial nerve (Laska *et al.*, 1997), the dilutions employed here (cf. Table 1) reliably prevent trigeminal involvement in the discrimination of stimuli.

Although the possibility that differences in perceived odor intensity might have contributed to the discrimination performance cannot be ruled out completely, this seems quite unlikely as our attempt to present stimuli at equal subjective intensities was confirmed by the fact that in the critical discrimination tasks >90% of the subjects' decisions were reported to be based on perceived differences in odor quality rather than odor intensity (cf. Test procedure). This is remarkable given that we performed the intensity-matching of odorants using a panel of subjects that did not participate in the actual experiments. Thus, the inevitably occurring interindividual variability in perceived intensity of single odorants did not render our attempt of intensity-matching invalid.

Further, the few instances in which perceived differences in odor intensity were reported seem to mirror a subjects' difficulty in discriminating at all, as error rates in such cases tended to be higher compared to the regular case of reported differences in odor quality. Therefore, we believe the discrimination scores found here to reflect the ability of the human olfactory system to distinguish between odor qualities.

The most important finding of the present study is that the ability of human subjects to distinguish between aliphatic odorants solely on the basis of functional groups is clearly substance-class specific. Although members from all four substance classes tested were discriminable above chance, it was apparent that aliphatic odorants with a functional carboxyl or keto group were more easily discriminated than odorants of the same carbon chain length with a functional alcohol or aldehyde group (cf. Figures 1 and 2). One hypothetical explanation for this finding is that the presence of a carboxyl or keto group might lead to more specific interactions with olfactory receptors and/or that stimulus molecules bearing such functional groups might interact with a smaller subset of receptors compared to substances with functional alcohol or aldehyde groups. This idea of substance- or substance-class-specific differences in

stimulus–receptor interactions is supported by electrophysiological findings that showed certain odor molecules to interact with a larger number of receptors than others (Sicard and Holley, 1984). Whether the mechanism underlying this phenomenon is related to differences in the dipole qualities of the oxygen moieties—carboxyl and keto groups are stronger dipoles than alcohol and aldehyde groups when attached to the same alkyl radical—remains to be revealed. One possible means to address this question is to assess the molecular receptive ranges of identified olfactory receptors for sets of substances that are similar to the one employed here using cellular recording techniques. A first step into this direction has recently been accomplished with the successful cloning, functional expression and characterization of a rat olfactory receptor (Zhao *et al*., 1998) and a human olfactory receptor (Hatt *et al*., 1999).

In one of the few psychophysical studies to date that assessed the significance of functional groups for odor quality Schafer and Brower (Schafer and Brower, 1975) tested a group of professional organic chemists for their ability to name organic unknowns by chemical class, functional groups, certain heteroatoms and possible identity, solely on the basis of odor. They found that, with the exception of ethers and halides, all major functional types had a measurable degree of recognizability. The most highly recognizable functional types were the amines (87% correct identifications), sulfur compounds (61%), esters (64%), phenols, (62%) and carboxylic acids (53%). Recognizability was less pronounced but still markedly above chance for the ketones (42%), aldehydes (40%) hydrocarbons (36%) and alcohols (25%). The data also showed that certain confusions of type conformed to a pattern, especially among the oxygen-containing groups. For example, alcohols were often called ketones (but not vice versa!), whereas carboxylic acids were only rarely mistaken for any other class of substances. Thus, both the rank order of correct identifications for and the frequency of confusions between substance classes are in general agreement with our results.

It is interesting to note that honeybees, when tested for their olfactory discrimination abilities with aliphatic 1-alcohols, *n*-aldehydes and 2-ketones sharing the same number of carbon atoms (C_4–C_{10}), performed equally well with all combinations of substance classes and thus did not show the dependence of discriminability on type of functional group that our human subjects did (Laska *et al*., 1999a). As insects are believed to differ substantially in their repertoire of olfactory receptors from mammals (Clyne *et al*., 1999), the observed differences in relative discrimination performance between honeybees and humans emphasize the role of receptor specificity for odor recognition.

A final aspect of the present study is our finding of a lack of significant differences in performance between male and female, and between Japanese and German subjects. Gender differences in olfactory performance have repeatedly been reported in tasks that are thought to represent 'higher' cognitive processing of olfactory information, such as identification of or recognition memory for odor stimuli, and usually found a superiority of females over males (Cain, 1982; Lehrner, 1993). In contrast, most studies failed to find significant differences in performance between sexes in tasks that are thought to represent more 'basic' processing of olfactory information such as measurements of odor sensitivity or discrimination abilities (Laska and Hudson, 1991, 1992). The results of the present study are thus in line with the vast majority of studies which assessed gender differences in olfactory discrimination performance.

Cultural differences in olfactory perception have been reported in several studies of odor identification abilities and measures of subjective valuation of odors such as familiarity, edibility and pleasantness (Wysocki *et al*., 1991; Ayabe-Kanamura *et al*., 1998), and have been attributed to differences in experience with the stimuli. Given that the substances employed in the present study are components in a large number of naturally occurring odors (Maarse, 1991; Knudsen *et al*., 1993) that are ubiquitous in our natural environment and thus presumed to be equally familiar to Japanese and Germans, it seems plausible that we failed to find any significant differences in performance between the two ethnic groups tested.

Nevertheless, we cannot completely rule out the possibility that the lack of significant differences in performance between male and female, and between Japanese and German subjects might, at least partly, be due to the considerable degree of interindividual variability in performance that we found. This, however, is an inherent feature of olfactory psychophysical studies which seems difficult to circumvent, if possible at all. The fact that we found significant differences in human discrimination performance at the group level despite considerable interindividual variability suggests that we describe a quite robust phenomenon.

Taken together, the findings of the present study provide evidence of a well-developed discriminatory ability of human subjects for aliphatic odorants on the basis of oxygen moieties, and that this capability clearly depends on type of functional group. Thus, the results support the assumption that functional groups may be an important determinant of the interaction between stimulus molecule and olfactory receptor in aliphatic substances, and therefore may be a molecular property affecting odor quality in a substance-class-specific manner.

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