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Olfactory Event-Related Potentials Reflect Individual Differences in Odor Valence Perception

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Abstract

Investigating the neural substrates of perceived quality in olfaction using different odorants is intrinsically difficult. By utilizing individual differences in perceived quality of the odor of androstenone, we obtained a continuum of individual differences in rated valence of the same stimulus allowing investigations of its manifestation in the olfactory event-related potentials (ERPs). In an initial group consisting of 43 individuals that were screened for their verbal descriptors and sensitivity for the odor of androstenone, 22 normosmic volunteers were chosen forming 2 distinct groups with regard to verbal labels ("body odor" and "nonbody odor") for androstenone while maintaining chemical structure, concentration, and intensity constant. In the main experiment, these participants rated both intensity and pleasantness of androstenone during the recording of olfactory ERPs. There was a significant difference in rated valence between the groups but not in intensity. Participants in the body odor label group had larger amplitudes of the late positive ERP component than those in the nonbody odor label group. A negative correlation between valence and amplitudes of the late positive component for androstenone indicated that these differences were mediated by the difference in odor valence between the 2 groups. This was further supported by a comparison of ERP peaks in response to stimulation with androstenone and the invariably unpleasant hydrogen sulfide that had been used as a control. Altogether, the results suggest that the late positive component reflects the processing of odor valence. Future olfactory studies with the aim of assessing the dimension of pleasantness would benefit from the use of these interindividual differences in the perception of a specific odor.

Key words: androstenone, hedonic, olfaction, pleasantness, quality, valence

Introduction

Several authors have suggested that the olfactory system plays a role as a sentinel system rather than a fine-tuned selection system (cf., Hildebrand 1995). As such, a central function would be to produce emotional responses to odors that would serve as the base for approach-avoidance behaviors. This would allow the individual to initiate rapid withdrawal from potentially dangerous odor sources. In the psychological literature, a critical distinction is made between 2 affective dimensions of emotional responses. This is on one hand emotional arousal, referring to a continuum that is commonly described as varying between calmness and excitement. The other dimension is emotional valence that commonly refers to a continuum that varies in-between pleasant and unpleasant.

One of the key factors behind emotional valence reaction to an odor is its perceived quality. However, the perceptual space of odor quality has long evaded detailed description. It has been suggested that the hedonic dimension is the most significant part of odor quality perception (Wise et al. 2000). Accordingly, numerous studies have investigated the underlying neuronal substrates of olfactory hedonic judgments in humans. In respect to functional localization, olfactory hedonic experiences have been demonstrated to activate the orbitofrontal cortex (Zald and Pardo 1997; Royet et al. 2000, 2001; Zatorre et al. 2000; Anderson et al. 2003) and the amygdala (Zald and Pardo 1997; Royet et al. 2000; Winston et al. 2005; but see Anderson et al. 2003). Given the difference in behavioral response to the

2 extremes on the valence axis, one might theorize that they are processed by different subsystems. This, however, seems not to be the case. Few differences that can be attributed to a difference in valence have been demonstrated (Zald and Pardo 1997; Royet et al. 2000, 2001). Although consensus on the brain structures involved in judgments of pleasantness can be seen in the literature, studies on early cortical processing of the pleasantness of olfactory stimuli are scarce and contradictory.

The high temporal resolution in the recordings of event-related potentials (ERPs) makes the technique uniquely sensitive to minute differences in the early processing of sensory stimuli. ERP peak latencies are commonly considered to reflect the time at which certain subroutines in the brain are activated (Kok 1997), and the amplitude of these peaks is thought to reflect the intensity of the activation (Krauel et al. 1998; Hummel and Kobal 2001). Some of the first studies to investigate differential treatment of pleasant and unpleasant olfactory stimuli in the early cortical processing of odors by means of ERP recordings reported differences in the amplitudes of the late positive component of the ERP response (Kobal et al. 1992; Becker et al. 1993). Odors perceived as negative elicited higher amplitudes than did positive odors. This could be interpreted such that no differences in activation of neuronal network exist between pleasant and unpleasant odors but that negative odors provoke a stronger reaction of a common system. This interpretation is supported by an imaging study demonstrating that negative odors produce higher regional cerebral blood flow in regions of interest (Royet et al. 2003). Interestingly, a more recent study using ERP recordings reported contradictory effects in respect of amplitudes. Pause and Krauel (2000) observed that the late positive component of the ERP was larger in response to a positive odor than in response to a negative one; in other words, their observation was in the opposite direction to what had previously been reported. One plausible explanation of the discrepancy in results between these studies is the difference in odor selection.

To date, most imaging and behavioral studies investigating effects due to differences in odor valence have compared different odorants. Such a design makes it difficult to control other psychological and physicochemical aspects of the olfactory stimuli. One way to control for these factors would be to use an odorant that is perceived qualitatively different by distinct groups of individuals, thus controlling for chemical structure, concentration, and intensity. The valence of many odorants is commonly agreed upon and often tightly connected to the quality (verbal label or odor–object identity) of the odorant. For example, wooden and citrus odors are often perceived as pleasant, whereas acids and sulfides are commonly perceived as unpleasant. Other odorants exhibit a large range in pleasantness (Wysocki et al. 1991), such as androstenone (5α-androst-16en-3-one). Whereas some perceive the odor of androstenone as urinous or sweaty, and rate it negatively, others describe it as wooden or floral, and rate it as positive, making the odor ideally suited for the purpose of investigating the valence dimension of odors (Prelog et al. 1944; Amoore 1977; Kraft and Popaj 2004). By using a single odorant for which distinct subgroups report contrasted quality, a marked difference between groups in rated valence is possible, thus limiting the confounding factors that are inevitable with the use of multiple stimuli.

The aim of the present study was to investigate the reflections of perceived quality on olfactory ERPs. To this end, we studied the difference in the early cortical processing of androstenone between 2 established groups differing only in their perceived quality of androstenone. In doing this, we especially monitored the dimensions of rated valence and intensity. Further, hydrogen sulfide (H_2S) was used as a control odor to monitor valence which most people describe as the smell of rotten eggs and, in turn, perceive it as unpleasant.

Materials and methods

Participants

A total of 22 healthy, right-handed, normosmic participants (11 women) with a mean age of 26.6 (standard deviation [SD] ± 9.6, range 17–55) years participated in the study. These participants were selected from an initial group consisting of 43 individuals who were screened for consistency in their verbal descriptors (excluded participants: $n = 11$) and sensitivity for the odor of androstenone (excluded participants: $n = 10$). Inclusion criteria were lack of specific anosmia to, and consistent labeling of, the odor of androstenone as in the section *Psychophysical Testing*. Moreover, all participants were screened for the absence of nasal congestion, acute infection, or decreased olfactory function. Participants were asked not to wear perfume on the day of testing and not to eat or drink anything other than water 1 h before testing. Detailed information about the experiment was given to the participants and written consent was obtained. All aspects of the study were performed in accordance with the Declaration of Helsinki for the experimentation with human subjects.

Procedure

Psychophysical testing

Prior to the electrophysiological measurements, olfactory function of the participants was ascertained using the "Sniffin' Sticks" 16-item screening set to control for olfactory dysfunction (Hummel et al. 1997). Participants' sensitivity to androstenone was initially assessed with a 3-alternative forced-choice test consisting of 4 concentrations of androstenone (pure crystalline form; 25, 1.5, and 0.25 mM) dissolved in propylene glycol (purity ≥ 99%; Sigma, Deisenhofen,

Germany). Testing of the 4 concentrations was paired with 2 lures consistent of only propylene glycol. All stimuli were presented in 120 ml glass bottles with 10 ml of solution in each. Correct discrimination of each concentration was a prerequisite for inclusion. Moreover, participants described the odor's quality by selecting 1 verbal descriptor among 6 that had been preselected based on free verbal judgments of a panel of trained observers in a pilot study. These verbal descriptors were "smoky," "fresh," "sweet," "chemical," "urinous," and "sweaty." Participants who described the odor as either urinous or sweaty were placed in the "body odor" label group, whereas participants describing the odor as smoky, fresh, sweet, or chemical were denoted as the "nonbody odor" label group. Only the 22 participants who were consistent in their labeling throughout the experiment were included in the final analyses. Participants' general sensitivity for androstenone was then assessed with an ascending staircase method using a computer-controlled air-dilution olfactometer. Five concentrations of androstenone (5%, 10%, 20%, 30%, 40%; v/v) based on 4 mM androstenone (for more stimulus details see Electrophysiological Recordings and Perceptual Ratings) were administered in a 3-alternative forced-choice paradigm; 2 correct discriminations were required for a reversal of the staircase (Hummel et al. 1997). The average of the last 4 of the total of 7 reversals defined the participant's sensitivity. After the initial psychophysical tests, participants completed the Edinburgh Inventory for handedness (Oldfield 1971) to ensure that only right-handed individuals were included in the study due to a previous report of cortical asymmetries of olfactory processing between right- and left-handed individuals (Royet et al. 2003).

Electrophysiological recordings and perceptual ratings

Participants were seated comfortably in a secluded air-conditioned area. White noise delivered via headphones was administered throughout the experiment to mask potential clicks from the switching valves of the stimulator. In order to keep the participants in a wake and vigilant state during ERP recordings, they were instructed to perform a tracking task on a video monitor, before and during stimulation (Hummel and Kobal 2001). Using a joystick, they had to keep a small square inside a larger one that moved in an unpredictable pattern across the screen. After each block of androstenone stimulus presentation, the tracking task was interrupted, and subjects had to rate the intensity and valence of the androstenone stimulus. For intensity, responses were made by moving a marker on a scale presented on the screen in front of them. The scale ranged from "0" on the left, indicating that the stimulus had not been perceived, to "+++" on the right, indicating maximum intensity. Ratings on the scale were automatically transformed to a scale ranging from 0 to 100. After each rating of intensity, they were asked to pick a verbal descriptor of the odor from the list of verbal descriptors mentioned above. Valence ratings of their experience were indicated on a symmetric visual analogue scale ranging from "0" (extremely unpleasant) to "100" (extremely pleasant).

For stimulation, a computer-controlled olfactometer based on air-dilution olfactometry was used (OM6b; Burghart Instruments, Wedel, Germany). This allows administration of chemical stimuli embedded in a continuous air stream such that stimulation would not alter the mechanical or thermal conditions of the nasal mucosa (Kobal and Hummel 1989). To produce the stimuli, odorless air was bubbled through solutions of 4 mM androstenone (Steraloids, Newport, RI), dissolved in propylene glycol (purity ≥ 99%; Sigma), and this odor-saturated air stream was then diluted to produce a stimulus consisting of 20% (v/v) androstenone. H_2S (Air Liquide, Krefeld, Germany) was presented at a concentration of 4 ppm. A total of 48 stimulations were presented within the session corresponding to 24 stimulations of each odorant. Presentations of each odorant were grouped in blocks of 8 and presented alternatingly. The odors were presented nonsynchronously to breathing with an average interstimulus interval of 30 s (range 28–32 s) with 250 ms stimulus duration. Participants were trained in and instructed to use the technique of velopharyngeal closure during the whole session to restrict respiratory airflow to the oral cavity (Kobal 1981).

Olfactory ERPs were recorded at 5 positions according to the international 10–20 system (Fz, Cz, C3, C4, and Pz) with silver electrodes (Grass E5SH, Astro Med, West Warwick, RI) using an 8-channel amplifier (SIR, Röttenbach, Germany), referenced to linked earlobes (A1 + A2). Vertical eye movements were monitored at the Fp2 lead. The sampling frequency was 250 Hz (bandpass 0.02–30 Hz); segments of 2048-ms length were recorded including a 500-ms pretrigger period. Recordings were additionally filtered off-line (low pass 15 Hz). Eyeblink-contaminated recordings with artifacts larger than 40 μV in the Fp2 lead were discarded; averaging of responses yielded late near-field ERPs (Hummel and Kobal 2001). Mean base-to-peak amplitudes (P1, N1, and P3 [the late positivity was labeled as P3]) and peak latencies (P1, N1, and P3) were measured using BOMPE software (Kobal, Erlangen, Germany).

Results

Electrophysiological recordings

As noted above, only participants consistent in their verbal descriptors throughout the experiment were included in the final analyses. To explore potential differences between the 2 label groups, multivariate analyses of variance (MANOVA; with Greenhouse–Geisser correction of degrees of freedom) with "labels" (body odor/nonbody odor) as a between-subject variable and "electrode" as a within-subject variable were performed for each ERP component for both amplitudes and latencies (see Table 1). For peak amplitudes,

Table 1 Means and SDs for latencies and base-to-peak amplitudes at the Cz electrode for androstenone and H_2S

	Group	P1	N1	P3
Androstenone				
Latencies (ms)	Body odor	522 (*112*)	628 (*134*)	899 (*118*)
	Nonbody odor	597 (*151*)	697 (*155*)	927 (*118*)
Amplitudes (μV)	Body odor	1.84 (*1.09*)	−3.53 (*1.86*)	8.50 (*3.86*)
	Nonbody odor	1.36 (*2.61*)	−3.74 (*2.35*)	2.97 (*2.25*)
H_2S				
Latencies (ms)	Body odor	456 (*88*)	560 (*110*)	825 (*121*)
	Nonbody odor	523 (*148*)	610 (*155*)	920 (*138*)
Amplitudes (μV)	Body odor	1.85 (*4.63*)	−4.60 (*6.41*)	10.97 (*5.67*)
	Nonbody odor	1.93 (*2.09*)	−2.81 (*2.64*)	7.15 (*4.71*)

Italics denote the standard deviation.

there was a main effect of labels only for the P3 component (P1 $F(5, 14) = 0.36$, P not significant (ns); N1 $F(5, 15) = 0.45$, P ns; P3 $F(5, 14) = 4.88$, $P < 0.01$). When electrodes were analyzed separately, pairwise comparisons with Bonferroni corrections revealed that participants who labeled androstenone as a body odor had larger P3 amplitudes than participants who labeled androstenone as nonbody odor (all P values < 0.05). The difference was largest for the Fz electrode ($P < 0.01$, Figure 1). There were no main effects on peak latencies for the factor labels on any of the other ERP components (all F values < 1.26; all P values > 0.32).

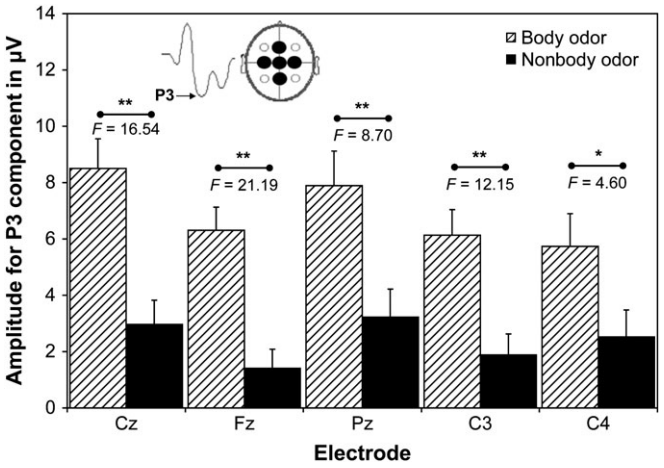

Figure 1 Mean base-to-peak amplitudes and standard errors of means for the P3 ERP component separated by electrodes. * denotes $P < 0.05$ and ** denote $P < 0.01$ as indicated by pairwise comparison. Values in graph indicate differences between groups for each electrode as expressed in F values. Cartoon indicates ERP peaks and electrode placement.

Perception

There was no significant difference in sensitivity for androstenone between the 2 groups (body odor group: mean = 27.0, SD ± 13.0; nonbody odor group: mean = 34.2, SD ± 9.7; $t(20) = 1.48$, P ns; see Figure 2). However, as suggested by the labeling of the odor, there was a significant difference in perceived pleasantness between the 2 groups in that the nonbody odor labels group rated the odor of androstenone as less negative than the "body labels" group as indicated by a 2-tailed Students' t-test (body odor group: mean = 34, SD ± 6; nonbody odor group: mean = 46, SD ± 12; $t(20) = 3.01$, $P < 0.01$). Although there was a reliable difference in rated pleasantness between the 2 groups, there was no significant difference in intensity between them for either androstenone (body odor group: mean = 27.8, SD ± 15.5; nonbody odor group: mean = 18.1, SD ± 14.1; $t(20) = 1.51$, P ns) or H_2S (body odor group: mean = 25.7, SD ± 16.2; nonbody odor group: mean = 37.0, SD ± 11.5; $t(20) = 1.90$, P ns). To directly test the relationship between rated valence of androstenone and the P3 component, a correlation between the averaged P3 amplitude of all electrodes and participants' valence ratings was performed. The correlation indicated a relationship between the P3 amplitude and rated valence of androstenone [$r(22) = -0.42$, $P = 0.03$; one tailed].

Discussion

Groups perceiving the odor of androstenone differently exhibited differences in the P3 component of the olfactory ERP. These findings were observed in the presence of profound difference in the perceived valence of androstenone but in the absence of significant differences in suprathreshold intensity and sensitivity to androstenone. Results of the present study therefore suggest that the pleasantness/unpleasantness aspect of odors is represented in the late positivity of olfactory ERPs.

That a negative percept of androstenone induces larger amplitudes of the P3 component is in direct contrast to

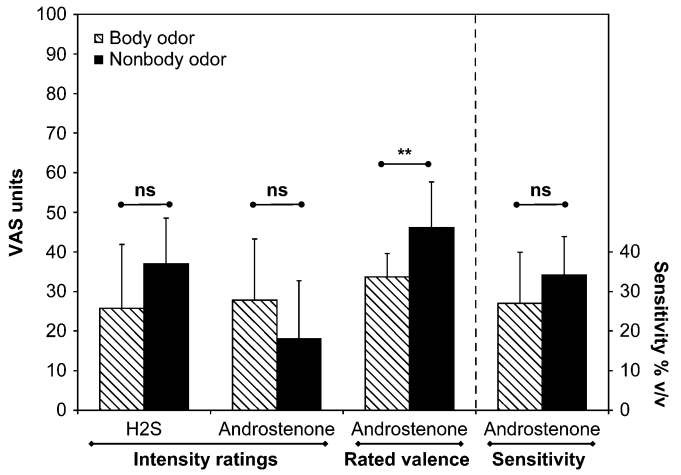

Figure 2 Mean (error bars: standard errors of means) intensity, thresholds, and rated valence of the stimuli divided into labeling groups. For rated valence, high values indicate pleasant and low values indicate unpleasant ratings. Please note the differences in scaling. ** denotes $P < 0.01$.

the results obtained by Pause and Krauel (2000) but corroborates earlier observations by Kobal et al. (1992). Comparative studies on early cortical activity for emotional stimuli in other modalities, especially for the visual system, generally support the observation from Pause and Krauel (2000) that emotionally pleasant stimuli evoke larger amplitudes of the late positive component of the ERP curve than do unpleasant stimuli (Dolcos and Cabeza 2002; but see Scheffers et al. 1991; Naumann et al. 1997). Interestingly, a difference in the latency of the late positive ERP peak for visual stimuli seems to further indicate that pleasant stimuli are processed faster than negative stimuli (Dolcos and Cabeza 2002). Dolcos and Cabeza (2002) recently suggested that this may reflect the so-called Pollyanna effect, a general preference and attention toward pleasant visual stimuli. As in previous olfactory studies where odors were presented to one nostril only (Hummel and Kobal 1992; Becker et al. 1993; Pause and Krauel 2000), we did not observe valence-dependent differences in latencies. Altogether, these results indicate that visual and olfactory stimuli processing may differ significantly rendering a comparison difficult. The olfactory system is frequently viewed as a warning system rather than the hypothesized selection function of the visual system (cf., Hildebrand 1995). The processing of negative odors could hence be hypothesized to be of a higher relevance than that of positive odors.

The acoustic startle reflex is an evoked preattentative reflex that is modulated by the affective valence and attentional merit of the foreground stimulus and in that is often used to investigate the emotional affect of stimuli (Dawson et al. 1999; Koch 1999). In light of this, it is of interest to note that only negative odors seem to be able to readily modulate the acoustic startle response (Ehrlichman et al. 1995; but see Miltner et al. 1994; Kaviani et al. 1998). This lends support to the notion that a primary function of the sense of smell is to act as a sentinel.

Comparison of results between modalities is important in order to draw conclusions about general principles of information processing. Unfortunately, close to all studies using visual stimuli have used either arousal-inducing stimuli, such as faces with different emotional expression (Balconi and Pozzoli 2003), or semantic information with arousal-inducing messages (Naumann et al. 1997). Few studies have made a distinction between pleasant and unpleasant stimuli (Vanderploeg et al. 1987). This is problematic because, as previously noted, a crucial difference exists between emotional arousal and emotional valence. However, notwithstanding these inherent problems in making comparisons between modalities, in the case where a distinction between these 2 emotions has been made experimentally, an interesting pattern emerges. Emotional valence produced higher amplitudes in the late positive component at frontocentral sites, whereas emotional arousal produced higher amplitudes in parietocentral sites (Dolcos and Cabeza 2002). Participants in the body odor group who perceived androstenone as more negative demonstrated similar results in that the largest difference between the 2 groups occurred at the frontal recording position (Fz). Although the inverse problem makes the prediction of underlying neuronal substrates of the ERP signal uncertain (Koles 1998), these findings are congruent with previous imaging studies in that odor valence judgments activate the orbitofrontal cortex (Zald and Pardo 1997; Zatorre et al. 2000; Royet et al. 2001).

One might argue that the applied measure of sensitivity was inadequate and therefore unable to detect a difference between the 2 groups in their sensitivity to the odor of androstenone. Indeed, evidence exists that sensitivity to androstenone is correlated with perceived valence to the odor (Dorries et al. 1989; although this effect is confounded by age and hormonal status), and although the difference in sensitivity between the 2 groups was not significant, this could mediate the demonstrated difference. However, perceived intensity of an odor has repeatedly been demonstrated to be highly correlated with sensitivity (cf., Doty et al. 1994), and we here demonstrate that there is no significant difference between the groups in either how intense they perceive the odor or their measured sensitivity. We thus believe that the demonstrated difference is not primarily mediated by a difference between the 2 groups in sensitivity to androstenone.

Androstenone has been identified as a component of human axillary sweat (Brooksbank et al. 1974). This may explain why some participants labeled the odor as body odor. Cortical responses to the natural mixture of body odors have been studied in the past (Krauel et al. 1998; Pause, Krauel, et al. 1999; Pause, Rogalski, et al. 1999). However, to the best of our knowledge, no studies to date have investigated whether natural body odors are processed differently to "common" odors exhibiting no potential relation to body odors, rendering conclusions of potential

confounding influences of the endogenous origin of androstenone purely speculative. Notwithstanding, a comparison between amplitudes obtained for androstenone in the body odor group and those previously reported in the literature for body odors (Krauel et al. 1998; Pause, Krauel, et al. 1999; Pause, Rogalski, et al. 1999) does not support the conclusion that androstenone was processed in a similar fashion to that of body odors. Future studies employing direct comparisons are needed to clarify potential differences in cortical processing between common odors and odors of human origin.

It has previously been proposed that perceived pleasantness is encoded in the late positive component of the ERP curve (Kobal et al. 1992; Pause and Krauel 2000). The strong effect demonstrated for the P3 component in the absence of any effects for the 2 early components in this experiment strengthens this notion. The results in the present study thus reflect what is commonly seen in olfactory ERP recordings when perceived pleasantness is investigated. Only the amplitudes of the late positive component (P3) were significantly different between the 2 groups, indicating that the main difference between them in the cortical processing of androstenone was mediated by the difference in valence. According to the general literature on ERPs, the early components of the ERP curve encode sensory stimulus characteristics to a stronger degree compared with later components that reflect cognitive processes to a larger extent (Hugdahl 1995). It is thus possible that other cognitive factors such as verbal or associative memories interact with the demonstrated difference. The reported differences between the 2 groups could also arguably be mediated either by the demonstrated difference in valence or by the difference in other aspects of the perceived quality. To control for whether the difference in P3 amplitude between the 2 label groups was driven by perceived valence or quality, we analyzed the difference in shape of the ERP curves between androstenone and H_2S for the 2 groups. If the main mediating mechanism behind the difference is valence, then the ERPs of the 2 ''negatively perceived'' odors should be similar in shape for the body odor group but be different for the nonbody odor group. In contrast, if the main mediating mechanism is quality, then it can be expected that the ERPs in response to androstenone and H_2S for the nonbody odor group should be similar in shape to the same extent as the body odor group. To this end, MANOVA with ''odor'' (androstenone/H_2S), ''ERP peaks'' (P1/N1/P3), and electrodes as within-subject variables were performed for each label group separately. For the participants who perceived the odor of androstenone as body odor and reported a negative valence, no significant interaction between odor and ERP peaks for androstenone and H_2S was found, $F(2, 9) = 1.50$, P ns. However, there were significant interactions between odor and ERP peaks for the subjects who perceived the odor of androstenone as nonbody odor and reported a relatively less negative valence of androstenone, $F(2, 10) = 7.34$, $P > 0.01$. The observation that the group reporting androstenone as more unpleasant showed similar ERP curves to those generally observed for H_2S, together with the negative linear correlation between valence ratings and P3 peak amplitudes for androstenone, strengthens the notion that the demonstrated differences between groups is primarily mediated by the difference in valence rather than other variables such as the difference in quality.

Androstenone is an odorant with a high frequency of specific anosmia in the population (Amoore 1977; but see Bremner et al. 2003; Boyle et al. forthcoming) that renders the odorant problematic to use in experiments. However, there are other odorants with lower prevalence of anosmia that seem to have the same characteristics as androstenone in that a high variability in rated valence with 2 separate clusters can be observed (Gross-Iserhoff and Lancet 1988; Lundstrom et al. 2003; Jacob et al. 2006). The use of an odorant with these characteristics means that the psychological component ''valence'' as well as other aspects of quality can be addressed with a single stimulus. We believe that future olfactory neuroimaging studies with the aim of assessing neural substrates of the pleasantness dimension would benefit from the use of these interindividual differences.

To conclude, by utilizing individual differences in quality, and with that rated valence, of a physically identical stimulus, it was possible to study its reflections in the olfactory ERP. This difference was represented in the amplitude of the late positivity that may be used in future studies as an indicator of the processing of odor valence.

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References

Amoore JE. 1977. Specific anosmia and the concept of primary odors. Chem Senses Flavor 2:267–81.

Anderson AK, Christoff K, Stappen I, Panitz D, Ghahremani DG, Glover G, Gabrieli JD, Sobel N. 2003. Dissociated neural representations of intensity and valence in human olfaction. Nat Neurosci 6:196–202.

Balconi M, Pozzoli U. 2003. Face-selective processing and the effect of pleasant and unpleasant emotional expressions on ERP correlates. Int J Psychophysiol 49:67.

Becker E, Hummel T, Piel E, Pauli E, Kobal G, Hautzinger M. 1993. Olfactory event-related potentials in psychosis-prone subjects. Int J Psychol 15:51–8.

Boyle JA, Lundstrom JN, Knecht M, Jones-Gotman M, Schaal B, Hummel T. On the trigeminal percept of androstenone and its implications on the rate of specific anosmia. J Neurobiol. Forthcoming.

Bremner EA, Mainland JD, Khan RM, Sobel N. 2003. The prevalence of androstenone anosmia. Chem Senses 28:423–32.

Brooksbank BW, Brown R, Gustafsson JA. 1974. Detection of 5-alpha-androst-16-en-3 alpha-ol in human male axillary sweat. Experientia 30:864–5.

Dawson ME, Schell AM, Bohmelt AH. 1999. Startle modification: implications for neuroscience, cognitive science, and clinical science. New York: Cambridge University Press.

Dolcos F, Cabeza R. 2002. Event-related potentials of emotional memory: encoding pleasant, unpleasant, and neutral pictures. Cogn Affect Behav Neurosci 2:252–63.

Dorries KM, Schmidt HJ, Beauchamp GK, Wysocki CJ. 1989. Changes in sensitivity to the odor of androstenone during adolescence. Dev Psychobiol 22:423–35.

Doty RL, Smith R, McKeown DA, Raj J. 1994. Tests of human olfactory function: principal components analysis suggests that most measure a common source of variance. Percept Psychophys 56:701–7.

Ehrlichman H, Brown S, Zhu J, Warrenburg S. 1995. Startle reflex modulation during exposure to pleasant and unpleasant odors. Psychophysiology 32:150–4.

Gross-Iserhoff R, Lancet D. 1988. Concentration-dependent changes of perceived odor quality. Chem Senses 13:191–204.

Hildebrand J. 1995. Analysis of chemical signals by nervous systems. Proc Natl Acad Sci USA 92:67–74.

Hugdahl K. 1995. Psychophysiology: the mind-body perspective. Cambridge, MA: Harvard University Press.

Hummel T, Kobal G. 1992. Differences in human evoked potentials related to olfactory or trigeminal chemosensory activation. Electroencephalogr Clin Neurophysiol 84:84–98.

Hummel T, Kobal G. 2001. Olfactory event-related potentials. In: Simon SA, Nicolelis MAL, editors. Methods in chemosensory research. Boca Raton, FL: CRC Press. p 429–64.

Hummel T, Sekinger B, Wolf SR, Pauli E, Kobal G. 1997. 'Sniffin' sticks': olfactory performance assessed by the combined testing of odor identification, odor discrimination and olfactory threshold. Chem Senses 22:39–52.

Jacob TJ, Wang L, Jaffer S, McPhee S. 2006. Changes in the odor quality of androstadienone during exposure-induced sensitization. Chem Senses 31:3–8.

Kaviani H, Wilson GD, Checkley SA, Kumari V, Gray JA. 1998. Modulation of the human acoustic startle reflex by pleasant and unpleasant odors. J Psychophysiol 12:353–61.

Kobal G. 1981. Electrophysiologische Untersuchungen des menschlichen Geruchssinns. Stuttgart, Germany: Thieme Verlag.

Kobal G, Hummel T. 1989. Brain responses to chemical stimulation of the trigeminal nerve in man. In: Green BG, Mason JR, Kare MR, editors. Chem senses. New York: Marcel-Dekker. p 123–39.

Kobal G, Hummel T, Van Toller S. 1992. Differences in human chemosensory evoked potentials and somatosensory chemical stimuli presented to left and right nostril. Chem Senses 17:233–44.

Koch M. 1999. The neurobiology of startle. Prog Neurobiol 59:107.

Kok A. 1997. Event-related-potential (ERP) reflections of mental resources: a review and synthesis. Biol Psychol 45:19–56.

Koles ZJ. 1998. Trends in EEG source localization. Electroencephalogr Clin Neurophysiol 106:127–37.

Kraft P, Popaj K. 2004. Total synthesis and olfactory evaluation of 5 beta,10-dimethyl-des-A-18-nor-androstan-13 beta-ol: a potential human pheromone? Eur J Org Chem 24:4995–5002.

Krauel K, Pause BM, Mueller C, Sojka B, Mueller-Ruchholtz W, Ferstl R. 1998. Central nervous correlates of chemical communication in humans. Ann N Y Acad Sci 855:628–31.

Lundstrom JN, Hummel T, Olsson MJ. 2003. Individual differences in sensitivity to the odor of 4,16-androstadien-3-one. Chem Senses 28:643–50.

Miltner W, Matjak M, Braun C, Diekmann H, Brody S. 1994. Emotional qualities of odors and their influence on the startle reflex in humans. Psychophysiology 31:107–10.

Naumann E, Maier S, Diedrich O, Becker G, Bartussek D. 1997. Structural, semantic, and emotion-focused processing of neutral and negative nouns: event-related potential correlates. J Psychophysiol 11:158–72.

Oldfield RC. 1971. The assessment and analysis of handedness: the Edinburgh inventory. Neuropsychologia 9:97–113.

Pause BM, Krauel K. 2000. Chemosensory event-related potentials (CSERP) as a key to the psychology of odors. Int J Psychophysiol 36:105–22.

Pause BM, Krauel K, Sojka B, Ferstl R. 1999. Body odor evoked potentials: a new method to study the chemosensory perception of self and non-self in humans. Genetica 104:285–94.

Pause BM, Rogalski KP, Sojka B, Ferstl R. 1999. Sensitivity to androstenone in female subjects is associated with an altered brain response to male body odor. Physiol Behav 68:129–37.

Prelog V, Ruzicka L, Wieland P. 1944. Steroide und sexualhormone: Über die herstellung der beiden moschusartig riechenden 16-androstenole-(3) und verwandter verbindungen. Helvetica Chim Acta 27:66–71.

Royet JP, Hudry J, Zald DH, Godinot D, Gregoire MC, Lavenne F, Costes N, Holley A. 2001. Functional neuroanatomy of different olfactory judgments. Neuroimage 13:506–19.

Royet JP, Plailly J, Delon-Martin C, Kareken DA, Segebarth C. 2003. fMRI of emotional responses to odors: influence of hedonic valence and judgment, handedness, and gender. Neuroimage 20:713–28.

Royet JP, Zald D, Versace R, Costes N, Lavenne F, Koenig O, Gervais R. 2000. Emotional responses to pleasant and unpleasant olfactory, visual, and auditory stimuli: a positron emission tomography study. J Neurosci 20:7752–9.

Scheffers MK, Johnson R Jr, Ruchkin DS. 1991. P300 in patients with unilateral temporal lobectomies: the effects of reduced stimulus quality. Psychophysiology 28:274–84.

Vanderploeg RD, Brown WS, Marsh JT. 1987. Judgments of emotion in words and faces: ERP correlates. Int J Psychophysiol 5:193–205.

Winston JS, Gottfried JA, Kilner JM, Dolan RJ. 2005. Integrated neural representations of odor intensity and affective valence in human amygdala. J Neurosci 25:8903–7.

Wise PM, Olsson MJ, Cain WS. 2000. Quantification of odor quality. Chem Senses 25:429–43.

Wysocki CJ, Pierce JD, Gilbert AN. 1991. Geographic, cross-cultural, and individual variation in human olfaction. In: Getchell TV, Bartoshuk LM, Doty RL, Snow J, editors. Smell and taste in health and disease. New York: Raven Press. p 287–314.

Zald DH, Pardo JV. 1997. Emotion, olfaction, and the human amygdala: amygdala activation during aversive olfactory stimulation. Proc Natl Acad Sci USA 94:4119–24.

Zatorre RJ, Jones-Gotman M, Rouby C. 2000. Neural mechanisms involved in odor pleasantness and intensity judgments. Neuroreport 11:2711–6.

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