Int Arch Occup Environ Health (2008) 81:683–694
DOI 10.1007/s00420-007-0262-4

ORIGINAL ARTICLE

Odor frequency and odor annoyance Part II: dose–response associations and their modification by hedonic tone

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Received: 5 March 2007 / Accepted: 7 September 2007 / Published online: 29 September 2007

Abstract

Objective Risk-assessment for environmental odors and the development of an appropriate guideline for protection against undue odor annoyance have long been hampered by the difficulties of assessing odor exposure and community annoyance responses. In recent years, however, dose–response associations between frequency of odor events and odor annoyance level in the affected population were established. However, the influence of hedonic tone (pleasantness–unpleasantness) and perceived odor strength (intensity) on the degree of odor annoyance have long been neglected in such studies and accompanying guidelines. In order to close this gap a pertinent field study was conducted in the vicinity of six odor emitting plants, two with pleasant (sweets production, rusk bakery), with neutral (textile production, seed oil production), and with presumably unpleasant odor emissions (fat refinery, cast iron production).

Methods A standardized sensory method was developed (described in Part I in the accompanying paper) to quantify intensity and hedonic tone within the assessment of odor exposure by systematic field inspection with trained observers. Additionally, exposure-information, the degree of annoyance, and the frequency of general health complaints and irritation symptoms were collected from the exposed residents through direct interviews. Multiple logistic regression analysis was used to establish dose–response associations between odor frequency, intensity and hedonic tone as independent variables and annoyance or symptom reporting as the dependent variable.

Results It is shown that exposure-annoyance as well as exposure–symptom associations are strongly influenced by odor hedonic. Whereas pleasant odors induced little to no annoyance, both neutral and unpleasant ones did. Additional inclusion of odor intensity did not improve the prediction of odor annoyance. Frequency of reported symptoms was found to be exclusively mediated by annoyance. The results are discussed in terms of environmental stress emphasizing the WHO-definition of health.

Conclusions Based on these findings the existing German guideline against undue odor annoyance was modified.

Keywords Odor annoyance · Dose–response relationship · Intensity · Hedonic tone · Field study

Parts of these findings were presented at the 15th Congress of the European Chemoreception Research Organization in Erlangen (2002), at the 43rd Congress of the German Society of Psychology in Berlin (2002), and at the at the 9th Meeting of the International Neurotoxicology Association in Dresden (2003).

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Introduction

Environmental odors, though not life threatening, are nevertheless able to disrupt well being and behavior and may, thus, be considered to meet the criteria of neurobehavioral toxicants (McMillan 1999). People living in the vicinity of odor emitting sources typically express concerns about possible impact of hazardous air pollution on health and quality of life. Although ambient air quality has significantly improved in the last few decades, the tolerance of residents to odor impacts appears to be reduced (Dalton 2003). As the residential use of rural landscapes increases, the number of complaints due to odors from livestock facilities grows significantly. Therefore, many countries are faced with the challenge to balance the requirements of residential and economic use of the environment and develop effective odor regulations or guidelines. An overview of different approaches to regulate odors around the world is given by Mahin (2001).

In Germany, the Federal Protection Act for Ambient Air (1974/1990) is the legal basis for any requirement with respect to ambient air quality to date. According to Results, the general public or the neighborhood has to be protected against odors caused by installations if, according to their nature, extent or duration they are likely to cause undue annoyance. In order to define critical levels of odor exposure associated with undue annoyance, questionnaire-based investigations were conducted to relate ambient odor exposure in terms of odor frequency to the degree of odor annoyance of residents (Steinheider et al. 1993, 1998). Based on the outcome of such studies odor frequencies between 10 and 20% (percentage of hours with recognizable odors per year) were proposed as being associated with undue annoyance (Guideline on Odour in Ambient Air; GOAA 1998/1999; in former times also called Directive on Odour in Ambient Air; meanwhile revised in 2004; Both et al. 2001, 2004).

Since, however, different odors clearly differ in their potential to cause annoyance it is unlikely that the one-dimensional criterion of the mere frequency of odor occurrence is sufficient to safely protect against undue odor annoyance in affected communities. Additional attributes of environmental odors, namely their pleasantness/unpleasantness and their intensity must be taken into account, as well.

Definitions of annoyance vary and sometimes emphasize perceptual-cognitive and emotional aspects as well as aspects of interference with intended activities and perceived somatic symptoms (Clark 1984; Kastka 1976). However, experience from studies dealing with adverse psychological responses to sound from traffic or industrial activities suggests that annoyance can most comprehensively be defined as a negative evaluation of a situation, characterized by undesirable, externally induced sensations accompanied by feelings of anger about their interference with ongoing or planned desired activities (Guski 1987). This interference-based concept of annoyance together with the definition of Lindvall and Radford (1973) characterizing annoyance as a feeling of displeasure associated with any agent or condition believed to adversely affect an individual or a group provide the basis for annoyance measurement in this study.

Observations from studies on noise annoyance suggest that a classification of individuals into “not annoyed” and “highly annoyed” respondents may also help to define levels of undue odor annoyance. The so-called Miedema/Vos curves which show the percentage of “highly annoyed” persons as a function of noise exposure are the internationally accepted dose–response relationship for investigations on noise effects to date (Miedema and Vos 1998). For use in this conceptual framework, a certain cutoff point is chosen on a continuous global annoyance scale and those giving responses above the cutoff are defined as “highly annoyed”. Typically, a point at 72% of the original scale length is chosen as cutoff point (Miedema 2004), i.e., on an eleven point scale from zero to ten persons with ratings greater “7” are called “highly annoyed”. Hence, to assess the percentage of “highly annoyed” persons seem to provide a most stable indicator of the degree of undue annoyance in the community. As pointed out by Schultz (1978), a clearer and more meaningful relationship between ambient noise exposure and annoyance reaction of the residents can be expected by means of this criterion, because persons who perceive their exposure as being extremely annoying have little difficulty in separating their annoyance responses from those related to other non-exposure variables which tend to produce scatter of annoyance responses in surveys. Such variables include characteristics of the person, e.g., age (Cavalini 1994), coping styles (Cavalini et al. 1991), MCS-related hyper-responsiveness to odors (Papo et al. 2006), trait-annoyance (Winneke and Neuf 1992), and many more characteristics involving their perceived associations with risk (Dalton 1996).

The conceptual framework for predicting odor annoyance from the sensory determinants of odor perception as opposed to the extraneous factors given above is stated in the acronym FIDO, which is the frequency of an odor, and its intensity, duration and offensiveness (Dalton 2003). Although one would expect odor intensity and offensiveness, often measured in terms of “hedonic tone”, i.e., the pleasantness–unpleasantness–dimension, to be powerful predictors of odor annoyance, only little evidence in this respect has been provided yet (Dravnieks et al. 1979; Steinheider et al. 1998). An indication for the importance of hedonic aspects of industrial odors has been reported by Winneke and Kastka (1987). They found different levels of annoyance in the vicinity of a chocolate factory, an insulation plant, a tar–oil refinery and a brewery, even though the four sources had similar odor exposure levels. In accordance with these findings odors from a grass drying plant and a food processing plant are rated as being less unpleasant and annoying than odors from chemical industry or tar processing (Hangartner and Wüst 1994). In a study on industrial odor sources, the prediction of percent "highly annoyed" improved if the pleasantness of the odor was taken into account. The degree of annoyance was found to be higher at a certain exposure level when the odor was less pleasant (Miedema et al. 2000). The pleasantness ratings were obtained through a supplementary laboratory study with samples from the sources concerned, and it was speculated that the effect of pleasantness on percent "highly annoyed" might have been caused by factors associated with the pleasantness of these odors. Offensiveness is the least sensory of the four elements of FIDO and it requires understanding not only the sensory attributes of an odor, but also the many non-sensory attributes, i.e., the cognitive and emotional factors which can increase, or in some cases decrease, a person's odor awareness and annoyance (Dalton 2003).

The general background and rationale behind dose–effect studies on the relationship between odor exposure and prevalence of annoyance in the community have been reported more extensively in previous studies (Cavalini et al. 1991; Miedema et al. 2000; Sucker et al. 2001).

In this context, the overarching aim of our study was to characterize and distinguish between pleasant, "neutral" und unpleasant odors in addition to their perceived intensity in order to determine if they differ according to the degree of induced annoyance. Therefore, the first step was to develop and validate methods for the assessment of odor intensity and offensiveness, quantified in terms of hedonic tone, as relevant attributes to characterize odor exposure in the field. This approach is described in the accompanying paper (Part I). The next step, described in the present paper, covers the modification of the dose–effect relationship by odor hedonic and intensity. It is shown that the newly validated method is applicable in the field, that external observers (panelists) and affected residents differ markedly in their hedonic judgment of the respective odor exposure (Part I), and that the pleasantness–unpleasantness dimension has a pronounced effect on the degree of odor annoyance of the residents living in the vicinity of six odor sources.

Materials and methods

Study area and odor sources

The investigations took place from 1999 until 2001 near industrial odor sources in six German cities in North Rhine-Westphalia and in Baden-Württemberg. Based on expert judgments of regional environmental agencies three types of odor emitting plants where chosen, pre-selected according to their likely hedonic tone: Two with presumably pleasant (sweets production, rusk bakery), two with presumably neutral (textile production, seed oil production) and two with presumably unpleasant odor emissions (fat refinery, cast iron production). Five of them were sources for a single odor, whereas the fat refinery plant was also producing washing powder, thus also emitting detergent odors.

Assessment of exposure

As details of odor impact assessment in terms of frequency, intensity and hedonic tone measured by systematic field inspection were already described (Part I), only a very brief description will be given here.

In order to measure odor impact in ambient air, the frequency of odor perception was recorded using trained and calibrated observers (panelists) according to the system of data acquisition, analysis and evaluation given in the GOAA (1998/1999) and in the Guideline VDI 3940 (1993; meanwhile revised Guideline VDI 3940, Part 1 2006).

Around each odor source an assessment area was defined and covered by a grid of equidistant observation points. The panelists visited each grid point according to a systematic sequence. During the assessment period (6 or 12 month) 13 or 26 odor measurements were carried out at each point. The panelists stayed at each observation point for 10 min recording the presence and duration of odors, as well as the type of perceived odors (e.g., nature/agriculture, household, traffic or other). Subsequently, they had to rate odor intensity and hedonic tone according to the method described in Part I. The panelists' ratings from a single measurement were considered, if more than five odor events with recognizable source-specific odors were identified during the observation time ("odor hour").

Survey strategy

Residential areas in the vicinity of the six odor emitting plants were chosen on the basis of the exposure measurements. Therefore, the grid of assessment squares was partitioned into four or five survey zones with different odor load. A net sample of approximately 200 (fat refinery) or rather 250 households (all other sources) was chosen in every assessment area by systematic sampling. Interviewers approached selected addresses until they reached equal numbers of residents in every survey zone. Within survey zones households being situated close to a street with a high traffic density were omitted.

Fully trained and supervised interviewers carried out face-to-face interviews at the resident's home. In order to reduce area confounding due to interviewer bias, care was taken to assign at least two study areas to each interviewer. In order to increase response rates, an initial letter was sent to every selected residence announcing the investigation. Subsequently, interviewers visited selected residences and tried to approach someone over 18 years of age. In a household with more than one eligible person the housekeeping person or someone else spending most of the time at home was contacted. If this person had an inadequate command of German, was sick, or was not a usual resident, the residence was classified as "out of range" and nobody else was interviewed. Similarly, if the target person refused to cooperate no one else was interviewed. If the target person was not at home, the residence had to be visited again up to three times on the same day after 5:00 p.m. or again the next day. When an eligible person agreed to participate, the structured interview was given, and the answers were recorded in written. The time needed to complete an interview was between 30 and 45 min.

Structure of the questionnaire

In order to reduce the probability of expectation biases, the residents were not told that the questionnaire was aimed at the assessment of odor annoyance. Therefore, the interview was introduced as part of a survey on health and living conditions in the neighborhood.

The questionnaire was mainly based on Likert-scales and covered the following aspects:

(1) *Living situation*: length of residence; quality of the residential area (6-point scale); environmental neighborhood disturbances (e.g., dust, noise, odors; 5-point scale).

Perceived health: Health satisfaction (5-point scale).

Frequency of somatic symptoms: 22 items (5-point scales), covering general health complaints (Difficulties falling asleep, Waking up during the night, Difficulties falling asleep after waking up, Not getting enough sleep, Headache, Cough, Stomach disorders, Breathing difficulties, Feeling miserable) and irritation symptoms (Nose irritation, Eye irritation), and two sham items (fever and asthma attacks) to control for response tendencies.

(2) *Odor (noise) annoyance*: degree of disturbance by odors/noise in your environment (11-point graphic scale, so-called "thermometer scale", from "0-no disturbance at all" to "10-extremely disturbed"), and degree of annoyance (7-point verbal scale from "0-not annoyed" to "6-extremely annoyed"); unacceptability judgments: "0-annoyance is acceptable" or "1-annoyance is unacceptable"

Odor perception: odor quality (up to three descriptions of smell outside the home, e.g., burned, like sulphur, sweet; up to three suspected main source of the smell described above, e.g., car, industry, agriculture; frequency of occurrence (6-point scale from "1-once a month or less" to "6-several times during the day" for the past year); intensity of the average and the strongest odor perception (6-point scale from "1-just perceptible" to "6-unbearably strong"); hedonic tone of the average and extreme (most unpleasant/pleasant) odor perception (9-point scale from "−4-extremely unpleasant" through "0-neither/nor" to "+4-extremely pleasant").

(3) *Socio-emotional effects*: seven items on 5-point scales from "0-never" to "4-always", covering impaired activities and emotions (e.g., being teased, disturbance while doing outdoor leisure activities/sitting in the garden).

(4) *Socio-demographic variables*: age, gender, marital status, smoking habits, housing situation (single family vs. multi-apartment as either tenant or owner) education (type of schooling), occupation (unemployed, employed), average time spent at home, participation ever in protest activities against source, economic dependence on the odor source (self or family member).

Data analysis

Data were analyzed both descriptively and analytically using the SAS-package (version 9.1.3).

Differences between the six samples in terms of the distribution of gender, age, perceived health, level of education, hours/day spent at home, years of residence, perceived quality of the neighborhood were tested by means of Chi square.

In order to describe respondents' odor annoyance, arithmetic means and 95%-confidence intervals were calculated. The degree of association between measures was calculated using Pearson's product-moment correlation coefficient. Although data from category scales are ordinal, at least in principle, their treatment by parametric statistics is adequate; deviations from the interval quality of such data are of only marginal relevance in this area of research (Steinheider and Winneke 1993).

Residents were counted as being exposed by the intended odor if they were able to name or describe the plant as the main source (e.g., rusk bakery in the neighborhood) and/or describe the quality of the odor correctly (like cookies, sweet). They were given the opportunity to describe up to three different odors, but they were requested to choose the most important ones. Annoyance ratings as well as somatic symptoms were taken into account, if the intended plant odor was ranked first.

Due to the fact that annoyance was not normally distributed the total group of residents was divided into two subgroups (Fig. 1). One thousand one hundred and seven residents were not at all annoyed ("0" on the thermometer scale). Those with scale values "1" to "10" exhibited varying degrees of annoyance ($n = 301$). This group of annoyed residents was further subdivided into those with moderate degrees of annoyance (scale values 1–6) and those with higher degrees of annoyance (values 7–10). Residents who rated annoyance to be equal to or higher than "7" on the thermometer scale were assigned to the group of "seriously annoyed" residents ($n = 82$). In this group the percentage of respondents who rated annoyance to be unacceptable was higher than in the group of the "moderately annoyed" residents.

One thousand two hundred and sixty two residents reported any somatic symptoms (frequency of symptom reporting = "0"). Residents were assigned to the group of "residents with general health complaints" ($n = 145$) if the frequency of one of the general health complaints variables (Difficulties falling asleep, waking up during the night, difficulties falling asleep after waking up, not getting enough sleep, headache, cough, stomach disorders, breathing difficulties, feeling miserable) was rated as "3-often" or "4-always"; residents were assigned to the group of "residents with irritation symptoms" ($n = 37$) if the frequency of one of the irritation symptoms variables (nose irritation, eye irritation) was rated as "3-often" or "4-always".

The odor exposure of each resident was calculated using the odor measure from his or her assessment square. Therefore, as described in Part I, estimates from four observation points were combined to yield area-estimates of odor frequency and intensity.

For odor frequency the ratio of the total sum of odor hours to the total number of observations in percent characterizes the degree of odor exposure in a given assessment square.

For odor intensity area estimates were derived as arithmetic means of all log-transformed ratings of the panelists across the number of pertinent observations within the assessment square.

As shown in Part I, residents and panelists differed for mean hedonic ratings and for the rank order of the six industrial source odors. Only the hedonic classification into "pleasant" and "not-pleasant" odors was remarkably consistent, because a group of sources with "neutral" odors was not found. Therefore the "neutral" odors were combined with unpleasant odors to form the class of "not-pleasant" source odors. Consequently, and due to the fact that no significant variation of hedonic tone with odor dispersion across the respective assessment area was observed, hedonic ratings were recoded as "1" for the sweets and the rusk bakery and as "2" for the other four odor sources (textile, seed oil, fat refinery, cast iron).

Multiple logistic regression analysis was used to establish dose–response associations between odor frequency, intensity and hedonic tone as independent variables and binary coded annoyance (e.g., not annoyed vs. annoyed; see Fig. 1) as well as binary coded somatic symptoms (e.g., no somatic symptoms vs. somatic symptoms) as the dependent variable. In order to investigate the influence of degree of annoyance on the frequency of somatic symptoms, further regression analysis were done with odor frequency, intensity, hedonic tone and annoyance as independent variables and somatic symptoms as dependent variables, respectively.

Odor frequencies were transformed into log values (logarithm to the basis 2 ($\log_2$)), because the linear fit between odor frequency and annoyance has previously been found to be closer on a log than on a linear scale (Steinheider and Winneke 1993). In order to avoid zero values, an additive constant "1" was added to the scale values.

Following a data-driven procedure based on correlations with both exposure and annoyance, variables were included in the regression model as confounders, if they met the significance level of $P \leq 0.20$. Thus, age, gender, smoking

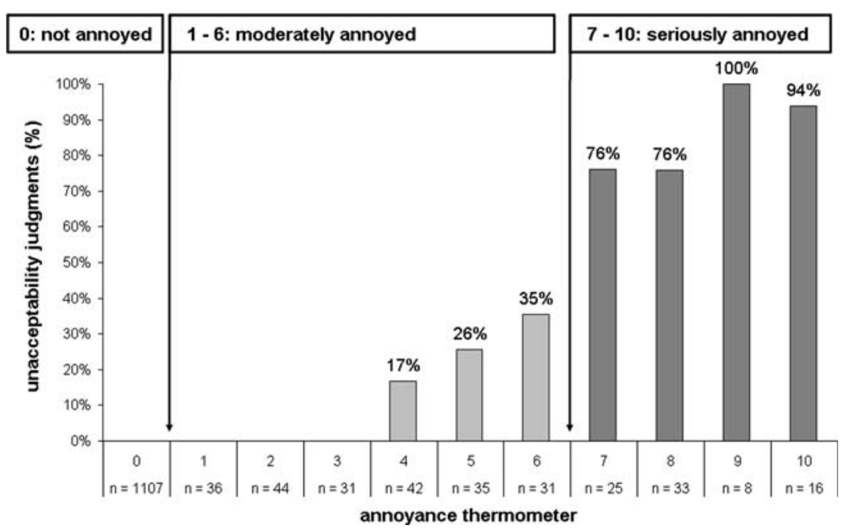


Fig. 1 Percent frequency of unacceptability judgments in relation to odor annoyance (thermometer scale) for "unpleasant" or "neutral" odors; in the vicinity of the pleasant odor emitting plants only one person rated odor annoyance to be unacceptable

habit, level of education, marital status, perceived health, quality of the residential area, noise disturbance (annoyance thermometer), average time at home, residential situation (owner or tenant; single or multiple house) and length of residence were included in the full regression model, plus frequency of odor exposure, hedonic and intensity measures alone or in combination. The six samples were analyzed together.

A *P* value of 0·05 was taken as the level of significance, throughout.

Results

Response rates

The response rate is given as the ratio of the number of individuals who were successfully interviewed (responders) to the total number of attempted contacts. Non-responders are those who could not be interviewed, either owing to absence or to refusal, or who broke off the interview. Response rates varied between 29 and 43% (Table 1).

The distribution of socio-demographic variables exhibited few significant differences between the six samples in terms of age, education and time spent at home. The sweets production sample consisted of younger and better-educated people, who stay less time at home relative to the other samples. Length of residence was significantly higher in the vicinity of the sweets, seed oil and cast iron plant as opposed to the other three odor sources. Perceived living quality was significantly lower in the vicinity of the textile plant and the fat refinery as opposed to the other four odor sources. Residents in the vicinity of the seed oil plant were predominantly living in single-family houses as owners as opposed to the residents of the other five odor sources. The distribution in terms of perceived health and gender was fairly equal. Since the variables given above were considered in regression modeling, they have no influence on the association between odor frequency and annoyance and its modification by hedonic tone.

Comparison of verbal annoyance and graphic disturbance scale

The comparison of verbal annoyance and graphic disturbance scales revealed good correspondence ($r = 0.88$, $N = 1{,}456$, $P < 0.001$). A strong deviation between the responses on the two scales (high values on the one scale and low on the other) was found for 48 interviews. Hence, the intraindividual consistency of responding (reliability) was questionable and these interviews were omitted. Finally the total sample for the six odor sources consisted of 1,408 interviews. In accordance with previous findings (Steinheider and Winneke 1993) both scales were highly correlated ($r = 0.94$, $N = 1{,}408$, $P < 0.001$) and seem to measure the same construct (Fig. 2). The category "4-serious" (annoyed) on the verbal scale is roughly equivalent to the category "7" on the graphic scale.

Odor annoyance

In Fig. 3 the average annoyance ratings of the residents' responses on the graphic disturbance scale across the six odor sources is shown. The rusk and the sweets odors were significantly less annoying than the other four odors. They were rated as between "0" and below "4" on the annoyance

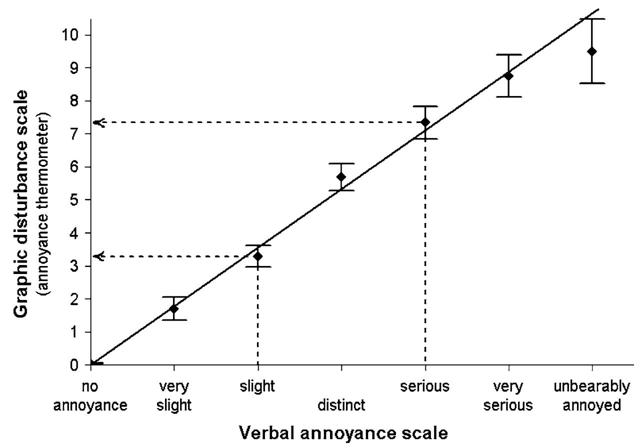


Fig. 2 The relationship between verbal annoyance scale and graphic disturbance scale for the total sample ($N = 1{,}408$)

Table 1 Response rates

Response category	Rusk bakery	Sweets production	Seed oil production	Textile production	Cast iron production	Fat refinery
Target sample	789	619	872	849	744	–[a]
Successful interviews	261	266	252	248	252	155
Response rate	33%	43%	29%	29%	34%	–[a]
Interview failures	528	353	620	601	492	–[a]
Refusals	214	135	235	217	226	–[a]
No contact	287	208	336	349	251	–[a]
Break off	27	10	49	35	15	–[a]

[a] Not available

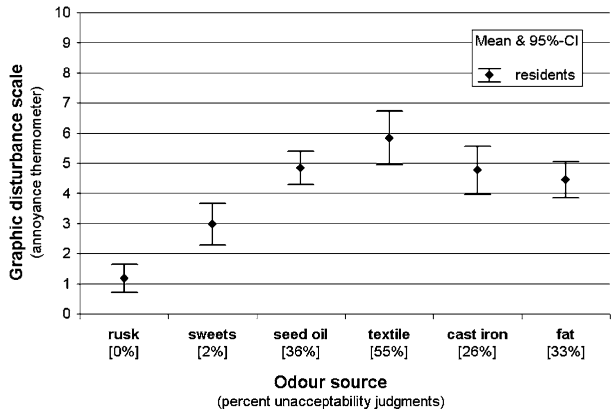


Fig. 3 Mean rating values and their 95%-confidence interval *asterisks* for the residents' annoyance response on the thermometer scale for the six industrial odors

scale. The mean annoyance ratings for the other four odors varied between "4" and "6", but were not significantly different. The rough hedonic classification into the two categories of "pleasant" or "not-pleasant" odors is seen again. Examination of the unacceptability judgments confirms this. In the vicinity of the rusk and the sweets production plant only one person of a total of 500 respondents considered annoyance to be unacceptable. In the neighborhood of the other four plants the percent of unacceptability judgments was much higher and varied between 26% (cast iron) and 55% (textile) ($n = 908$).

Odor frequency and annoyance

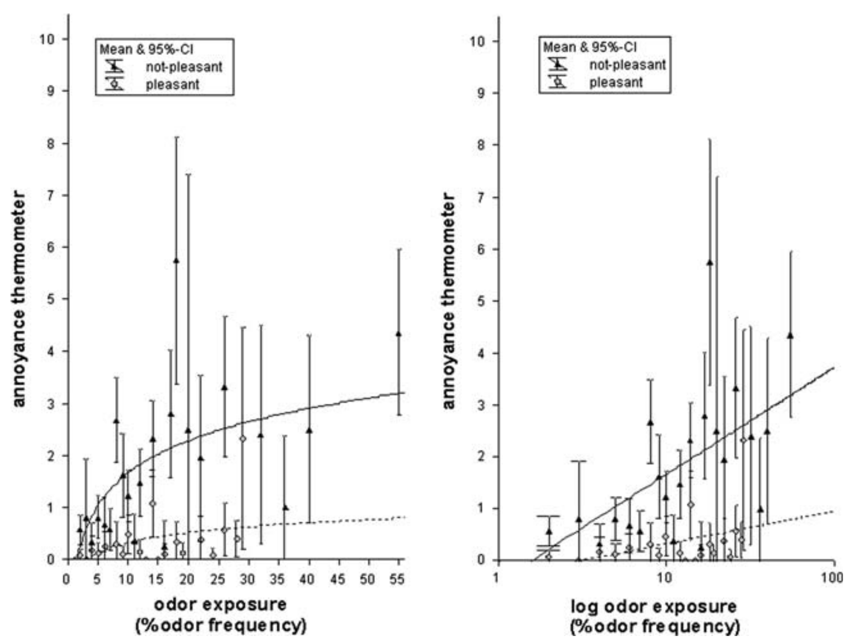
Based on previous experience (Steinheider and Winneke 1993) the present paper emphasizes the graphic annoyance scale (thermometer) rather than the verbal scale, partly because of its better association with exposure and partly because both are well correlated (see Fig. 1). Figure 4 depicts the relationship between mean unadjusted annoyance response for "pleasant" and combined "neutral/unpleasant" odors and odor frequency. A model with linear odor frequencies was compared with a log model. The correlation between annoyance and the linear odor exposure measure (% odor frequency) was $r = 0.11$ ($r^2 = 0.01$, $P = 0.002$; pleasant odors) and $r = 0.28$ ($r^2 = 0.08$, $P < 0.001$; not-pleasant odors); between annoyance and the log-transformed odor measure $r = 0.11$ ($r^2 = 0.01$, $P = 0.002$; pleasant odors) and $r = 0.29$ ($r^2 = 0.08$, $P < 0.001$; not-pleasant odors). Thus, the differences of fit between both models are only marginal here, contrary to previous experience (Steinheider and Winneke 1993). The logarithmic model was chosen for subsequent analyses. As can be seen, the degree of annoyance increases with increasing exposure.

This relationship is linear with log-transformed odor impact. For the same levels of exposure much lower degrees of annoyance were found in the vicinity of the "pleasant" odor sources in comparison to the "not-pleasant" odor sources.

Dose–response associations between odor frequency and annoyance

Multivariate logistic regression analysis was used to test the significance of the dose–response associations between odor frequency (%), odor intensity and hedonic tone (pleasant (0) vs. not-pleasant (1)) on the one hand and annoyance (% "annoyed" or % "seriously annoyed") on the other, including adjustment for significant confounders.

Fig. 4 Relationship between mean annoyance response of residents for "pleasant" and combined "neutral/unpleasant" odors and % odor frequency (odor hours). *Left* Linear exposure data. *Right* Log exposure data unadjusted (raw) data are given



The full model (Table 2; Fig. 5) confirmed a highly significant dose–response association between odor frequency and percentage of "annoyed" Ss (OR = 1.6; 1.3–2.0) and "seriously annoyed" Ss (OR = 1.9; 1.3–2.6). This model was expanded by hedonic tone as second independent exposure variable. An additional strong impact of odor hedonic ("annoyed": OR = 4.9; 3.4–7.2; "seriously annoyed": OR = 17.6; 6.7–46.5) was recognizable as well.

The dose–response association between log odor frequency and percentage of "annoyed" and "seriously annoyed" Ss can be graphically represented by an S-shaped curve as illustrated in Fig. 5. Therefore, three logistic regression analysis were conducted separately for the pleasant odor group ($n = 500$) and the not-pleasant odor group ($n = 908$). The conduction of the fourth logistic regression analysis for the "pleasant" odors was not possible, because the group of "seriously annoyed" Ss only contained five persons.

It is obvious that hedonic tone has an abundantly clear effect on the dose–response relationship between odor frequency and annoyance. Pleasant odors have a significant lower annoyance potential than unpleasant/neutral odors. The exposure level "odor frequency" based on the system of "odor hours" is suitable and sufficient to predict odor annoyance caused by not-pleasant odors in this investigation.

Including odor intensity as independent variable to the full regression model exhibits again a highly significant effect on the percentage of "annoyed" Ss (OR = 1.3; 1.1–1.5) and "seriously annoyed" Ss (OR = 1.5; 1.1–2.0), but the additional influence is much weaker compared to hedonic tone. If odors are recognizable in the field (mean odor intensity ≥ "1") they can cause annoyance.

Table 2 Results of two logistic regression analysis of the dose–effect association between (a) "percent annoyed" residents (thermometer scale: 1–10) and (b) "percent seriously annoyed" residents (thermometer scale: 7–10) as dependent variable (effect) and odor frequency (log), intensity and hedonic tone (pleasant vs. not-pleasant) as independent variables (dose) for the total sample of six odor sources

Dependent variables	Independent variables	OR*	Odds, 95%-CI
(a) Annoyed residents	Odor frequency	1.6	1.3–2.0[a]
	Intensity	1.3	1.1–1.5[b]
	Hedonic tone	4.9	3.4–7.2[a]
(b) % Seriously annoyed residents	Odor frequency	1.9	1.3–2.6[a]
	Intensity	1.5	1.1–2.0[b]
	Hedonic tone	17.5	6.7–46.5[a]

[a] $P < 0.001$; [b] $P < 0.01$; [c] $P < 0.05$

*(a) Adjusted f noise disturbance: 1.0 (1.0–1.1), length of residence: 1.3 (1.1–1.6)[b], quality of the residential area: 1.2 (1.0–1.3)[b], tenant owner: 0.6 (0.4–0.8)[b], single/multiple house : 1.2 (0.8–1.7), average time at home: 1.0 (0.9–1.0), perceived health: 1.0 (0.9–1.1), smoking habit: 0.7 (0.5–1.0)[c], gender: 0.7 (0.5–1.0)[c], age: 0.8 (0.7–0.9)[b], marital status: 1.2 (0.8–1.6), level of education: 1.2 (1.0–1.4)

(b) Adjusted f noise disturbance: 1.2 (1.1–1.3)[a], length of residence: 1.1 (0.8–1.5), quality of the residential area: 1.5 (1.2–1.9)[b], tenant owner: 0.5 (0.3–1.0), single/multiple house: 0.9 (0.5–1.9), average time at home: 1.0 (0.9–1.1), perceived health: 1.1 (0.8–1.4), smoking habit: 0.7 (0.4–1.2), gender: 1.0 (0.6–1.7), age: 0.9 (0.7–1.1), marital status: 0.9 (0.5–1.5), level of education: 1.2 (0.8–1.6)

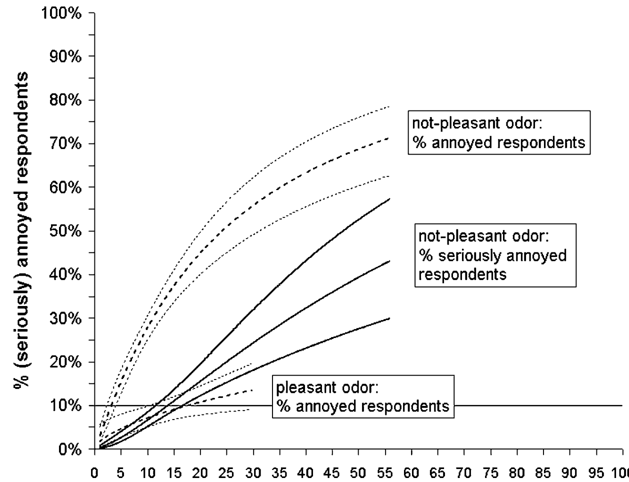


Fig. 5 Percentage of "annoyed" (thermometer scale: 1–10) and "seriously annoyed" (thermometer scale: 7–10) persons as related to odor exposure (log % odor frequency) after adjustment for confounding (noise disturbance, quality of residential area, tenant or owner, single/multiple house, average time at home, perceived health, smoking habit, gender, age, marital status, level of education)

Besides the expected positive relationship between odor exposure and annoyance, personal factors strengthen or weaken the annoyance response in the following manner: with respect to the percentage of "seriously annoyed" Ss increasing noise annoyance and quality of the residential area is always associated with increasing odor annoyance. The influence of other variables on odor annoyance is less consistent, but in all of the regression models confounder variables describing aspects of the residential satisfaction had a significant effect on annoyance.

Dose–response associations between odor frequency, intensity, hedonic tone and somatic symptoms

As described above multivariate logistic regression analysis was used to test the significance of the dose–response associations between odor frequency (%), odor intensity and hedonic tone [pleasant (0) vs. not-pleasant (1)] on the one hand and somatic symptom reporting (% "residents with general health complaints" or % "residents with irritation symptoms") on the other, including adjustment for confounders.

The full model (Table 3) shows that the percentage of "residents with general health complaints" was significantly increased with increasing odor exposure (OR = 1.8; 1.4–2.3). Hence, the dose–response association between odor frequency and percentage of "residents with irritation

Table 3 Results of two logistic regression analysis of the dose–effect association between (a) "percent residents with general health complaints" and (b) "percent residents with irritation symptoms" as dependent variable (effect) and odor frequency (log), intensity and hedonic tone (pleasant vs. not-pleasant) as independent variables (dose) for the total sample of six odor sources

Dependent variables	Independent variables	OR*	Odds, 95%-CI
(a) % Residents with general health complaints **	Odor frequency	1.8	1.4–2.3[a]
	Intensity	1.1	0.9–1.4
	Hedonic tone	3.2	2.0–5.0[a]
(b) % Residents with irritation symptoms **	Odor frequency	1.1	0.7–1.6
	Intensity	1.4	1.0–2.0
	Hedonic tone	4.3	1.7–11.3[b]

[a] $P < 0.001$; [b] $P < 0.01$; [c] $P < 0.05$

*(a) Adjusted for noise disturbance: 1.0 (1.0–1.1), length of residence: 1.1 (0.9–1.5), quality of the residential area: 1.2 (1.0–1.4)[c], tenant or owner: 0.6 (0.4–1.0), single/multiple house: 1.0 (0.6–1.6), average time at home: 1.0 (0.9–1.0), perceived health: 1.4 (1.2–1.7)[a], smoking habit: 0.9 (0.6–1.3), gender: 1.3 (0.9–1.9), age: 0.9 (0.8–1.1), marital status: 1.0 (0.7–1.5), level of education: 1.0 (0.8–1.3)

(b) Adjusted for noise disturbance: 1.1 (1.0–1.2), length of residence: 1.7 (1.1–2.8)[c], quality of the residential area: 1.1 (0.8–1.5), tenant or owner: 0.2 (0.1–0.6)[b], single/multiple house: 1.4 (0.5–3.7), average time at home: 1.1 (1.0–1.2), perceived health: 1.6 (1.2–2.2)[b], smoking habit: 0.8 (0.4–1.7), gender: 0.8 (0.4–1.6), age: 0.7 (0.5–1.0)[c], marital status: 0.6 (0.3–1.3), level of education: 1.5 (0.9–2.4)

**Sum of general health complaints symptoms (Difficulties falling asleep, Waking up during the night, Difficulties falling asleep after waking up, Not getting enough sleep, Headache, Cough, Stomach disorders, Breathing difficulties, Feeling miserable);

Sum of irritant symptoms (Nose, Eye);

The variables equal "1", if the frequency of one of the symptoms was rated as 3 "often" or 4 "always"

symptoms" was not significant. This model was expanded by intensity as second and hedonic tone as third independent exposure variable. An additional strong impact of odor hedonic ("residents with general health complaints": OR = 3.2; 2.0–5.0; "residents with irritation symptoms": OR = 4.3; 1.7–11.3) was recognizable as well, but intensity had no further influence.

With respect to the percentage of "residents with general health complaints" quality of the residential area and perceived health was associated with higher frequency of symptom reporting. Accordingly, regarding the percentage of "residents with irritation symptoms" length of residence, being a tenant or owner, age and perceived health was associated with higher frequency of symptom reporting.

Odor annoyance as a mediator for symptom reporting

After adjustment for annoyance (values on the thermometer scale between 0 and 10), however, regression analysis revealed only a significant link between odor exposure and general health complaints, but not with irritation symptoms. The results are summarized in Table 4.

Discussion

We have shown here, that the frequency of odor events assessed by trained and selected observer panels within systematic observation strategies predicts odor annoyance in the affected population. Furthermore, the hedonic odor quality, namely the location of environmental odors of industrial origin on the pleasantness–unpleasantness (hedonic) dimension adds substantially to the degree of population annoyance. Whereas the former finding confirms previous observations (e.g., Cavalini et al. 1991; Steinheider and Winneke 1993; Hangartner and Wüst 1994), the latter, to the best of our knowledge, has not been reported before outside experimental settings. With regard

Table 4 Results of two logistic regression analysis of the dose–effect association between (a) "percent residents with general health complaints" and (b) "percent residents with irritation symptoms" as dependent variable (effect) and odor frequency (log), intensity, hedonic tone (pleasant vs. not-pleasant) and annoyance (thermometer scale: 0–10) as independent variables (dose) for the total sample of six odor sources

Dependent variables	Independent variables	OR*	Odds, 95%-CI
(a) % Residents with general health complaints**	Odor frequency	1.4	1.0–1.9[c]
	Intensity	0.9	0.7–1.2
	Hedonic tone	0.9	0.5–1.5
	Annoyance	1.7	1.6–1.8[a]
(b) % Residents with irritation symptoms**	Odor frequency	0.8	0.5–1.2
	Intensity	1.1	0.7–1.6
	Hedonic tone	1.2	0.4–3.6
	Annoyance	1.5	1.4–1.7[a]

[a] $P < 0.001$; [b] $P < 0.01$; [c] $P < 0.05$

*(a) Adjusted for noise disturbance: 0.9 (0.8–1.0), length of residence: 1.1 (0.8–1.4), quality of the residential area: 1.1 (0.9–1.4), tenant or owner: 0.9 (0.5–1.7), single/multiple house: 0.8 (0.4–1.5), average time at home: 1.0 (0.9–1.1), perceived health: 1.6 (1.3–2.0)[a], smoking habit: 1.1 (0.7–1.8), gender: 1.6 (1.0–2.5)[c], age: 1.0 (0.8–1.2), marital status: 1.1 (0.7–1.8), level of education: 1.0 (0.7–1.3)

(b) Adjusted for noise disturbance: 1.0 (0.9–1.2), length of residence: 1.7 (1.0–2.9), quality of the residential area: 1.0 (0.7–1.4), tenant or owner: 0.3 (0.1–0.9)[c], single/multiple house: 1.6 (0.5–4.8), average time at home: 1.1 (1.0–1.2), perceived health: 1.6 (1.2–2.3)[b], smoking habit: 1.1 (0.5–2.4), gender: 0.8 (0.4–1.8), age: 0.8 (0.5–1.1), marital status: 0.6 (0.3–1.3), level of education: 1.3 (0.8–2.2)

**Sum of General Health Complaints (Difficulties falling asleep, Waking up during the night, Difficulties falling asleep after waking up, Not getting enough sleep, Headache, Cough, Stomach disorders, Breathing difficulties, Feeling miserable)

Sum of irritant symptoms (Nose, Eye)

The two variables equal "1", if the frequency of one of the symptoms was rated as 3 "often" or 4 "always" to the frequency of pronounced somatic complaints, odor exposure was also found to be associated with the occurrence of general health complaints or irritating symptoms. Hence, after adding odor annoyance to the regression model, no correlation remained significant. These findings will be considered in the context of the differential health-based regulation of chemicals eliciting adverse chemosensory responses in occupational settings on the one hand, and in environmental settings, on the other.

The regulation of chemical exposure in the workplace, if associated with chemosensory information processing, is typically based on irritations rather than on olfaction per se (Van Thriel et al. 2006). Irritation thresholds often exceed odor thresholds by orders of magnitude (Shusterman 1992). In contrast to workplace regulation of odorant/irritant chemicals in Germany, which is based on "Maximum Allowable Concentrations" (Maximale Arbeitsplatzkonzentrationen = MAK-values) for irritation potential, the regulation of airborne chemicals or chemical mixtures eliciting chemosensory responses in the general environment is based on odor annoyance using odor frequency as the critical exposure measure (Both 2001). According to the "Federal Protection Act for Ambient Air" (Bundes-Immissionschutzgesetz 1974/1990) odor- or noise-emitting premises must be operated in such a manner that the population is protected against "undue" or "substantial" annoyance ("erhebliche Belästigung"). In the case of odorant chemicals in ambient air the frequency of odor-events, i.e., concentrations exceeding the odor threshold according to trained and selected observers or dispersion calculations, is the relevant exposure parameter; thus, olfaction and associated annoyance rather than irritation is the guiding principle (Both 2001).

It is worthwhile to briefly discuss these discrepancies between workplace and environmental regulations of airborne chemicals with inherent chemosensory properties and their underlying philosophy. Chemical exposure at the workplace is limited to an 8-h work shift and also limited to a healthy, age-restricted workforce under regular medical surveillance. In setting ambient odor exposure limits for the general population, however, all age groups as well as sensitive subgroups have to be protected, and duration of exposure can be prolonged, and may well exceed the 8-h workplace duration of exposure. It has also been argued (Campbell 1983) that, although environmental odors are certainly not life threatening and do not require immediate counteraction, they are unwanted, unpredictable, uncontrollable, require moderate adjustments, constitute a nearly continuous environmental background and, therefore, qualify as ambient stressors. Since, furthermore, stress coping styles and behavioral modifications have been shown to be effective in environmental odor settings, the term environmental stress has also been used to characterize the adversity of ambient odor exposure (Cavalini et al. 1991; Steinheider and Winneke 1993). Such adversity has even lead to the conclusion that a chemical with an unpleasant odor, due to its demonstrated capacity to modify behavior and to impair the quality of life, meets the criteria of a neurobehavioral toxicant (McMillan 1999).

According to the World Health Organization (WHO) health is not only absence of disease but a state of complete physical, mental and social well being. The characterization of environmental odors as ambient or environmental stressors clarifies that. Although such exposure is unlikely to induce clear-cut states of disease (Shusterman 1992) it is nevertheless compatible with the WHO-definition of health impairment. This is even clearer, if the pleasantness-unpleasantness (hedonic) aspect of odors as another important determinant of annoyance is taken into account. By classifying industrial odor sources into three categories, namely pleasant, neutral and unpleasant, we have clearly shown here, that pleasant odors do elicit annoyance responses in only an insignificant or marginal degree, whereas neutral and malodors have a rather strong impact in this respect. This has already been suggested in previous work (Winneke and Kastka 1987) but, to our knowledge, has not been demonstrated in systematic field studies with odor-frequency as the exposure-measure, before.

On the basis of laboratory studies it was suggested that annoyance responses can be predicted from the relation between hedonic tone and odor concentration in connection with the more simple relation between perceived intensity and odor concentration (Miedema et al. 2000; Van Harreveld 2004). Therefore, we expected to find different dose–effect curves for odors with distinct hedonic tone. However, our results do not fully agree with this expectation. Only the dose–response associations for the "pleasant" odors differed from those of the "neutral" and "unpleasant" ones, whereas the "neutral" and the "unpleasant" odors did not differ from each other. For not-pleasant odors the percentage of "seriously annoyed" residents was found to be much higher at a given exposure level. Additionally, the amount of unacceptability judgments in the vicinity of the two pleasant odor sources was nearly zero. These results are in accordance with psychophysical findings showing a greater increase in sensitivity and awareness for increased concentrations of malodors than for pleasant odors (Jacob et al. 2003).

Another significant conclusion of this study is that the degree of annoyance and the number of seriously annoyed subjects could adequately be predicted by measuring odor exposure in terms of frequency of odor-events per year. This largely confirms previous observations (Cavalini et al. 1991; Miedema et al. 2000; Hangartner and Wüst 1994; Steinheider and Winneke 1993), showing modest but statistically significant exposure–response association for odor annoyance. Furthermore, our results are in line with previous studies demonstrating that odor frequency usually explains more of the variance of the annoyance response than other non-sensory factors like e.g., personal factors such as age, perceived health or coping strategies (Steinheider and Winneke 1993). However, the overall contribution of ambient odor load measures in explaining annoyance variance was hardly found to exceed 15–20% in moderate exposure situations (Steinheider et al. 1998), whereas for noise annoyance the corresponding values are between 25 and 30% (Guski 1987). This is probably due to the less precise sensory measurement of odor exposure by means of trained observer panels in contrast to the purely physical sound pressure noise levels. Our observations clearly show that the prediction of odor annoyance can be increased if, in addition to odor frequency, odor hedonic is taken into account, as well.

It could be argued that the significant difference between the pleasant and not-pleasant odors might reflect the residents' positive or negative appraisal of the general odor exposure situation in terms of health risk, rather than odor offensiveness per se. It has been shown, for example, that different instructions concerning the health risk for the same odorous compound in a laboratory setting, i.e., presumably health-threatening versus not, alters the hedonic evaluation of the same stimulus significantly (Dalton 1996). Thus, according to this argument, it is not the hedonic stimulus quality but the fear of health risks associated with malodors, which determine the annoyance response.

Recent data from a clinical laboratory setting do not confirm this conclusion, however. Patients diagnosed as suffering from "Multiple Chemical Sensitivity (MCS)" or "Idiopathic Environmental Illness (IEI)" and non-patient controls were given the same set of odorants, namely peppermint and phenyl ethyl acetate (pleasant), *n*-butanol (neutral) and hydrogen sulphate (unpleasant) for olfactometric evaluation (Papo et al. 2006). The patients rated the whole set of odorants as being significantly less pleasant than the non-patient control group, although both groups did not differ for odor thresholds, intensity ratings or accuracy of odor identifications. However, the hedonic ranking of the four odorants was the same as that of the controls. This supports the conclusion that fear of odor-induced health impairment is not a relevant determinant of evaluations on the pleasantness-unpleasantness dimension and that, furthermore, hedonic odor quality is a stimulus rather than a pure response attribute.

This is supported by our findings on the associations between odor exposure and symptom reporting. After adding odor annoyance to the regression model, only the correlation between general health complaints and frequency of odor events remained significant, although in a less pronounced manner. The impact of odor hedonic was not recognizable any more. The identification of annoyance as a determinant for, or mediator of symptom reporting is in line with observations from other investigations (Cavalini 1994; Shusterman 1992; Steinheider et al. 1998). One likely possibility relates to the less offensive character of the industrial odors in our study as compared to another more extreme exposure scenario (e.g., manure from poultry- and horse-farming to produce mushroom–fertilizer), which was found to induce a serious amount of gastric symptoms, e.g., disgust, loss of appetite, vomiting, nausea or retching (Steinheider et al. 1998).

A first guideline effort towards defining "undue odor annoyance" for the regulation of environmental odors according to the German "Federal Protection Act for Ambient Air" (1974/1990) used existing exposure–response curves from population-based field studies, with frequency of odor events as the exposure measure. This approach (GOAA 1998/1999) was criticized for not taking odor hedonic and odor intensity into account (Junker 1998). The results of the present study partly support this argument. Odor hedonic in addition to odor frequency does indeed aggravate odor annoyance markedly; whereas the further consideration of rated odor intensity has no additional effect. Based on these observations the preliminary guideline version was modified to also include the pleasantness–unpleasantness dimension (Both et. al 2001, 2004).

Acknowledgments This research was partly supported by the Ministry of the Environment, Conservation, Agriculture and Consumer Protection of the State of North Rhine-Westphalia (MUNLV NRW) and the Ministry of the Environment and Traffic of the State of Baden-Württemberg (UVM BW), and by the German Chemical Industry Association (VCI). We would like to thank Dr. Ursula Krämer (IUF, Düsseldorf) for statistical and epidemiological advice, Frank Müller and Hans-Georg Bruder (LANUV, Essen) for their support in selecting adequate industrial odor sources and carrying out some of the field measurements, and Dr. Armin Junker (Troisdorf) for his critical contributions in the planning phase of this study.

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