



Odour wheel – A new supporting tool for the assessment of odours in indoor environments

L. Brosig^{a,*}, L. Strasser^{a,1}, B. Maxeiner^a, A. Beier^a, S. Senkale^a, R. Kolodziejczyk^a, J. Hameister^c, F. Gerull^d, K. Schröder^e, K. Sucker^f, A.M. Scutaru^b, C. Röhl^{b,g}, M. Debiak^h, M. Kolossa-Gehring^b, M. David^{b,1}

^a Olfasense GmbH, Schauenburgerstraße 116, Kiel, 24118, Germany

^b German Environment Agency (UBA), Corrensplatz 1, Berlin, 14195, Germany

^c State office of Health and Social Affairs Mecklenburg West Pomerania, Postfach 161161, Rostock, 18024, Germany

^d Berlin-Brandenburg State Laboratory, Department of Environmental Health Protection, Rudower Chaussee 39, Berlin, 12489, Germany

^e Free and Hanseatic City of Hamburg, Ministry of Justice and Consumer Protection, Unit Environmental Health Protection, Billstraße 80a, Hamburg, 20539, Germany

^f Institute for Occupational Safety and Health of the German Social Accident Insurance, (IFA), Alte Heerstraße 111, Sankt Augustin, 53757, Germany

^g Institute of Toxicology and Pharmacology for Natural Scientists, Christiana Albertina University of Kiel, Kiel, 24105, Germany

^h Federal Ministry for the Environment, Climate Action, Nature Conservation and Nuclear Safety, Köthener Str. 2-3, Berlin, 10963, Germany

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ABSTRACT

The presence of unusual or unexpected odours in indoor environments often causes concern among occupants about potential health effects of exposure to chemical substances. Accurately describing an odour in order to determine appropriate measurement strategies can be challenging, highlighting the need for supporting tools. An odour wheel can help to describe the perceived odour using odour-descriptive words. By providing a standardised vocabulary, an odour wheel may improve communication between affected persons and indoor air consultants, combining information from sensory perception with the need for analytical measurements. The aim of this study was to develop an odour wheel for the description of odours in indoor air. A literature review was conducted to identify odour-active substances and corresponding odour-descriptive words most commonly reported in indoor environments. These substances were prioritised through a multi-stage process involving expert consultations. Based on these results, a preliminary odour wheel was created and applied in 21 rooms, where panellists used it to describe the present odour. The results were compared with chemical and chemical-sensory analysis, including GC-MS for identification and quantification of VOC, HPLC for aldehydes and ketones, as well as GC-MS-sniffing for explicit identification of odours and odour-active substances. A final validation was conducted in artificially scented rooms using defined substance mixtures. The final odour wheel includes 66 single substances, mainly comprising the chemical groups of aldehydes, aromatic compounds, terpenes and alcohols. The odour wheel can support communication between occupants and indoor air consultants, selection of appropriate measurement methods, and source identification in indoor environments.

1. Introduction

The perception of unusual or unexpected odours in indoor environments such as homes or offices can give rise to concerns about potential

harmful health effects of exposure to contaminants or chemical substances in the air, particularly when the odour cannot be identified or traced to a specific source. To examine health complaints and the plausibility of complaints about odour annoyance, a general approach is:

Abbreviations: AIR, Ausschuss für Innenraumrichtwerte German Committee on Indoor Air Guide Values; GC-MS, Gas Chromatography–Mass Spectrometry; GV, German indoor air guide values; HPLC, High-performance liquid chromatography; LiGaVa, Liquid-to-Gas Vaporiser; OEL, Occupational exposure limits; OGV, Odour Guide Value; OTV, Odour threshold value; PAH, Polycyclic aromatic hydrocarbons; TDS, Thermal desorption as part of the GC-MS assessment; UBA, Umweltbundesamt German Environment Agency; VDI, Verein Deutscher Ingenieure The Association of German Engineers; VOC, Volatile organic compounds.

* Corresponding author.

E-mail address: lbrosig@olfasense.com (L. Brosig).

¹ These authors contributed equally to this publication.

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- a) to carry out analytical measurements to determine concentrations of substances in indoor air,
- b) to compare analytical results with health-based guide values, and
- c) to assess the necessity and relevance for remediation measures.

In Germany, the Committee on Indoor Air Guide Values (AIR) sets health-based guide values for single chemical substances in indoor air that enable a systematic assessment of potential health risks for occupants [1]. Since odorous substances are very complex and behave differently, some odours can be perceived at concentrations below a toxicological guide value, while others can only be perceived above these values. This requires an assessment distinct from toxicologically-derived guide values. Therefore, the AIR has also developed a concept of odour guide values (OGV, in German 'Geruchsleitwerte') [2] to evaluate complaints about odour annoyance [3, 4]. The basic assumption of the concept is that complaints about odours are expressed when the corresponding annoyance has increased to such an extent that the intervention by a responsible person (e.g. building owner, landlord) is deemed necessary. The concept provides a practical guidance dealing with these complaints. If the concentration of an odorous substance in indoor air reveals that an OGV is reached or exceeded, it is assumed that the complaints about odour annoyance are reasonable. The odour exposure was probably mainly caused by this single substance, either alone or in combination with other substances. In this case, a graded approach of odour reduction measures is recommended. Nevertheless, it cannot be assumed that the complaints about odour annoyance are not reasonable, when no OGV is reached or exceeded. The odour could be related to a substance for which there is no OGV available, yet. However, the OGV concept is not applicable when the concentration of an odorous substance is so low that it cannot be measured analytically, even though the odour is clearly perceptible. Furthermore, most odours are complex mixtures rather than single substances which makes identification and analytical measurement even more difficult [5].

The human sense of smell can be used as a valuable additional tool. According to DIN ISO 16000-30 [6] groups of trained or untrained panellists can be used to evaluate indoor odours in terms of acceptability, intensity and hedonic tone. However, using an odour wheel, sensory assessment can also be complemented by the occupants affected by the odour. They perceive the odour in the context of daily use and might therefore provide important information for identifying the odour source.

Nevertheless, the descriptions provided by occupants often are not sufficiently detailed or accurate enough to provide insight into the nature and potential cause of an odour. Although most odour descriptions are derived directly (e. g. 'banana') or indirectly (e. g. 'fruity') from the physical object emitting the odour [7], it is surprisingly difficult to describe even common household odours [8]. It is still a matter of debate, whether this is a consequence of weak associations between odour and language processing pathways in the human brain [9] or due to the lack of an adequate olfactory vocabulary and the use of odour-descriptive words in everyday life in Western cultures [10]. Nevertheless, the ability to describe an odour is significantly influenced by how familiar the odour is. Commercial products are often named to describe familiar odours, whereas unfamiliar odours are described using non-specific terms such as 'chemical' [11].

Classification schemes for taste and odour have been developed to characterise products such as perfumes, beverages or food. These schemes provide a standardised vocabulary, facilitating and improving the perception and description. The so-called 'aroma or flavour wheels' are laid out like dartboards, with general categories (e.g. 'fruity') in the centre and specific examples of those categories (e.g. 'strawberry') on the outer rings.

Moreover, odour wheels were developed to classify odorous emissions from environmental sources, such as drinking water, wastewater, composting, landfills and urban environments and to link them to

potential odour-causing substances [12]. Combining chemical and olfactory measurements enables characterisation of the relevant odour quality notes and related odorous substances. Furthermore it allows association with process conditions [13]. This facilitates effective abatement and management practices. The inner ring of most specific odour wheels shows general odour categories (e.g. 'earthy/musty/mouldy'), the middle ring shows specific odour-descriptive words within each odour category (e.g. 'earthy/musty'), and an outer virtual ring lists the chemical compounds that are associated with the categories and descriptors on the inner and the middle rings (e.g. 'geosmin') [14,15].

This approach was applied, for example, in the development of the 'Historic Book Odour Wheel'. It enables book conservators to classify the degeneration of a book's material based on its smell. It allows them to identify the chemical compounds responsible for the perceived odour and to choose the appropriate conservation methods. Furfural, for example, is linked to the degradation of cellulose whereas benzaldehyde and vanillin are associated with the degradation of lignin [16].

Another application of an odour wheel was its use in a citizen science project in California to manage odour emissions near a wastewater treatment plant. By creating a 'Community Odour Wheel', both site workers and local residents had a shared way to describe and record the odours they perceived. This common language helped improve communication and transparency between the community and industry. It appears to have led to a reduction in odour complaints as well as to have helped operators to better document and understand the odours related to their processes [17].

Other examples are odour wheels that are used to identify unpleasant odours in wastewater technology [18] or in the food sector to precisely determine the aromas of wine [19] or whisky [20].

In the context of indoor odour problems an odour wheel could be a valuable aid, as it enables indoor air consultants and occupants to classify annoying odours and narrow down potential odour sources based on the odour notes identified. This might even hint to substance groups or single substances from which the odour might originate. The main aim is to provide a supporting tool for identification of odour sources or for selecting the appropriate measurement strategy. In this context an odour wheel would facilitate the communication between indoor air consultants and the occupants, as a precise description of the odour causing complaints is helpful when planning indoor air measurements and mitigation strategies.

Therefore, the German Environment Agency (UBA) initiated a project to develop an odour wheel for typical odours and the related odorous substances in indoor environments [21].

In a first step, the compilation of typical indoor odour-active substances and their related odour-descriptive words was achieved by literature review and expert consultations. Based on the results of the literature review and the weighting of most relevant substances in a second step, a preliminary odour wheel was developed and tested in 21 rooms that were described as having an unpleasant and annoying odour. During the assessments, panellists walked into the rooms and marked the odours perceived in the room on the odour wheel. In parallel, chemical analyses were carried out and finally the detected substances were compared with the sensory odour perception. In a third step, the odour wheel was tested in artificially scented rooms in order to check the correspondence between the sensory perception and vaporised chemical substances. After every sensory assessment, panellists were asked about their feedback on the handling and user-friendliness of the odour wheel. Finally, based on this feedback, further odour-descriptive words and substances identified during the assessments were considered in the final revision of the odour wheel.

2. Methods

2.1. General approach

The general approach taken in the project is illustrated in the following Fig. 1. Individual steps are detailed in the corresponding sections.

2.2. Selection of odour-active substances and odour-descriptive words

A first step was to systematically review literature on relevant odour-active substances typically found in indoor environments. Various databases and specialised research portals were used for this purpose (e. g. Elsevier, ScienceDirect, American Chemical Society Publications, Wiley Online Library, Google Scholar, Semantic Scholar, 'raumluft.org', website of the WHO Regional Office for Europe). The result of this search yielded 114 articles. A priority list was compiled based on the identified substances and their frequency of mention in the literature. Substances were included if they were mentioned at least twice in different sources of literature. The list comprised 205 substances.

In a second step, additional information was gathered for the respective odour-active substances:

- typical concentrations in indoor air
- odour threshold values
- corresponding odour-descriptive words

Subsequently, this list was reviewed by German experts in the field of indoor air (see Appendix A). The experts were asked to answer the following questions for each substance on the list: Is the odour-causing substance relevant to indoor environments? Does it regularly feature in your professional day-to-day practice? Is it a frequent cause of complaints from building occupants? Are the identified odour thresholds plausible? Are the odour-descriptive terms appropriate? Which odourants, in your opinion, belong on the odour wheel and which do not? Following the first round of expert consultations, the list was narrowed down to 89 substances; following the second round, it was narrowed down to 64.

As part of the streamlining process, the numerous odour-descriptive words identified were limited to a maximum of three odour-descriptive words per substance. Expert GC-sniffers from the Olfasense GmbH were used for this task. They regularly practice describing odours by use of sniffing sticks (felt-tip pens filled with odorous substances [22] that can be used for panellists training) and by taking part in GC-MS-sniffing tests (Gas Chromatography – Mass Spectrometry with olfactory analysis, see Sections 2.4.2.1 and 2.4.2.2). In the latter they have to smell single

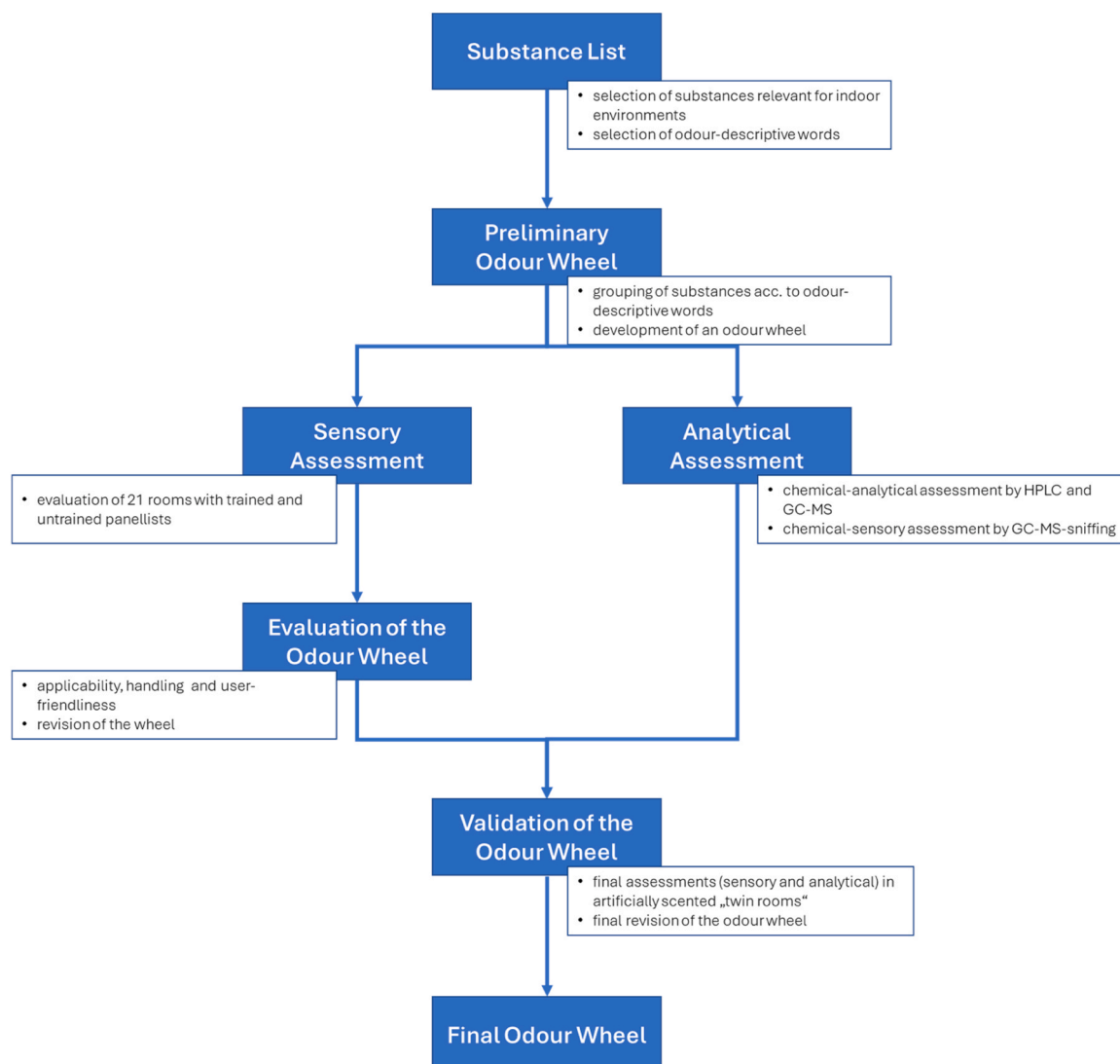


Fig. 1. General approach of the project.

substances, separated by the GC, by use of a nose mask (sniffing port). For each odorous single substance arriving at the nose, they provide suitable odour-descriptive words.

Expert GC-sniffers are best suited for adequately describing known and unknown odours from complex mixtures or caused by single substances. They are exceptionally sensitive, meaning that odours often can be detected even below the known odour threshold values.

Finally, a prioritisation list with the most important odorous substances in indoor air and their odour-descriptive words was the result of this process.

2.3. Development of the odour wheel

The development of the odour wheel was envisaged as a three-level structure wheel, expanding from a general central level to two further, more detailed levels of odour-descriptive words. To achieve this, the single substances from the final prioritisation list were first sorted according to their corresponding odour-descriptive words and grouped together in common odour categories, like 'burnt' or 'chemical'. These odour categories were placed in the first central level of the odour wheel. The second level includes more specific odour descriptors as respective odour categories, and the third level includes distinct so-called odour notes (see Fig. 2).

For each single substance the corresponding odour notes of the third level of the odour wheel are given in Table 3 in Appendix B.

As people interpret odour-descriptive words differently, depending on their experience and cultural background, a fourth level of images was added to the odour wheel to enable a visual association with the odour notes of the third level (see Fig. 6 in Section 3.2).

Finally, a handling and user-friendliness survey of the odour wheel was conducted (see Section 2.4). In addition to the option of adding personal comments on the applicability of the odour wheel, the survey included the following questions and possible answers.

The usage of the odour wheel:

- was very easy for me, I could find my way around the odour wheel straight away
- was easy for me, I could find my way around the odour wheel after a short time
- was not so easy for me
- was difficult for me

The design of the odour wheel:

- I like it very much and find it well designed
- I like it
- I don't like it very much, reasons are ...

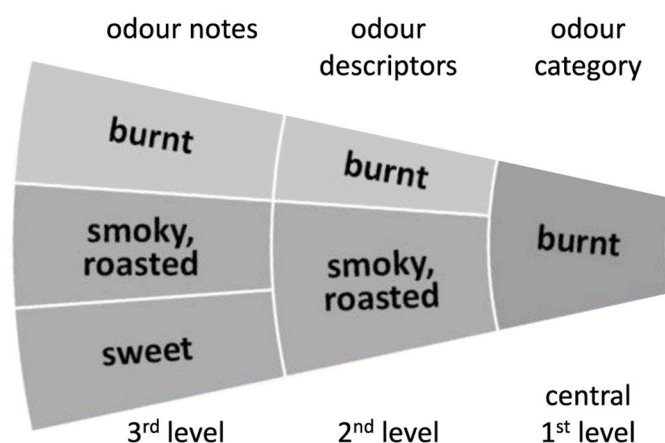


Fig. 2. Exemplary structure of the odour wheel.

A preliminary version of the odour wheel, containing the odour-descriptive words across all levels with images on the fourth level of the odour wheel, was used for the sensory assessments of the odorous rooms within the project (see Section 2.4). After practical testing and validation (see Section 2.4.3), the preliminary version of the odour wheel was updated and expanded to include additional single substances and odour notes resulting in a final version of the odour wheel (see Section 3.2).

2.4. Application and verification of the odour wheel

The odour wheel was tested in overall 21 rooms that were free of visible mould and had at least a clearly perceptible odour. The assessed rooms included offices, conference rooms, classrooms and corridors. They were reported by occupants or owners to have a persistent, annoying odour. Rooms were selected if the odour source was unknown to the occupants and not evident to the Olfasense staff as well. Furthermore, the odour needed to be at least clearly perceptible according to the assessment of the staff. The occupants predominantly described the odours as unpleasant, and sometimes more specifically as musty, pungent, chemical or synthetic.

Samples for the GC-MS and GC-MS-sniffing analysis as well as for HPLC analysis were taken directly in each room before the sensory odour assessment by panellists. After using the odour wheel, panellists were asked to complete a survey about its applicability and user-friendliness.

After assessing the 21 rooms and updating the odour wheel (see Section 3.2), a final test of the odour wheel was carried out in artificially scented so-called twin rooms (see Section 2.4.3).

2.4.1. Sensory odour assessment by panellists

Sensory odour assessment was carried out directly in the room based on VDI 4302-1 [4] and DIN ISO 16000 30:2014 [6]. In each of the 21 rooms, 20 untrained and 10 trained panellists described the odour using the odour wheel. Using both, trained and untrained panellists has the advantage of providing an impression of the extent to which untrained panellists, i.e. laypeople in the sense of affected room users, are able to use the odour wheel in the same way as trained panellists who have experience in evaluating and describing odours and can therefore be classified as more knowledgeable. The overall gender ratio of both groups was kept as evenly balanced as possible.

Trained panellists were selected in accordance with DIN EN 13725:2003/2022 [23,24] if they had an average odour sensitivity, with their individual odour threshold for n-butanol ranging between 20 and 80 ppb. Each trained panellist is regularly tested and excluded if their sense of smell does not meet the permissible limits.

Both trained and untrained panellists were generally excluded if they were smokers, had a cold or a notable disorder affecting their sense of smell. They were also excluded if they were using perfumes or fragrant body care products that might interfere with their own odour perception or that of other panellists. For untrained panellists no further selection criteria were applied. Some of the untrained panellists originated from the Olfasense GmbH pool of test subjects (volunteers without odour training according to DIN EN 13725:2003/2022 [23,24]) or were, for example, owners or employees of the companies or institutions that provided the odorous rooms with unknown odour source. Since the odour wheel is also intended for the communication with people who live or work in odour-polluted indoor environments, these individuals were not explicitly excluded from the study. This was rather seen as a realistic application scenario, which helped in the final validation of the odour wheel.

Each room was entered and assessed by approximately 30 panellists on the same day to ensure the same odour impression to be assessed. The assessments were conducted in groups of up to five persons at a time. Panellists stayed there for a maximum of five minutes. They were asked to mark all the odour-descriptive words on all levels of the odour wheel

that applied to the odour they perceived in the room. In approximately 15-minute intervals, the next group of five panellists entered the room.

The panellists were explicitly permitted to give multiple answers and were also asked to provide their own words for describing the odour if necessary.

2.4.2. Analytical odour assessment

In addition to sensory odour assessment by panellists, the odour-active substances in the respective rooms were examined using chemical-analytical assessments as gas chromatography-mass spectrometry (GC-MS, see Section 2.4.2.1) and high-performance liquid chromatography (HPLC, see Section 2.4.2.3). They were also assessed using GC-MS-sniffing (GC-MS-sniffing, see Section 2.4.2.2), which combines sensory and chemical-analytical assessment.

2.4.2.1. Chemical-analytical odour assessment (GC-MS). A common method of detecting volatile organic compounds (VOC) in indoor air is to use a gas chromatograph (GC) in conjunction with a thermal desorption unit (TDS) and Tenax® tubes to collect and provide the sample. Tenax® tubes (Fa. Markes) and automatic sampling pumps (GilAir® Plus; Fa. Gilian®) were used. Further details of the sampling process and the equipment used are provided below:

- Assessment: based on DIN ISO 16000–6:2012 [25]
- Sampling with automatic GilAir® Plus sampling pumps and a sampling volume flow of 100 ml/min
- Sampling position: 1–1.5 m above the floor, to simulate the height position of a sitting person in the room as closely as possible
- The following analytical instruments were used:
 - Gas chromatograph (TRACE 1310; Fa. Thermo Fisher Scientific)
 - Mass spectrometer (ISQ 7000; Fa. Thermo Fisher Scientific)
 - Thermodesorption unit (Unity-xr; Fa. Markes International)

After sampling on Tenax® tubes, the tubes were inserted into the thermal desorption unit and desorbed at temperatures ranging from 280

to 330 °C. Subsequently, the samples were concentrated in a cold trap using thermoelectric cooling at temperatures between 0 and 10 °C. The cold trap was then heated to 300–350 °C to release and focus all the volatile components for subsequent chromatographic separation. Different compounds reach the detector at different times, depending on their retention times in the GC column. Each compound exhibits a unique fragmentation pattern. These patterns are compared with those in the NIST 2017 spectrum database to identify single substances. A 5-point calibration curve was created using toluene-D8 to quantify all peaks obtained during sample analysis. Hence, the resulting concentrations are expressed in toluene equivalents (TE).

2.4.2.2. Sensory-analytical odour assessment (GC-MS-sniffing). Unlike standard GC-MS analysis, GC-MS-sniffing focuses specifically on evaluating odour-active substances. It is a technique that combines a gas chromatograph with the human nose as detector to evaluate the odour of single substances. The sampling, thermal desorption and separation processes in the chromatographic column are the same as in a standard GC-MS analysis. However, in the GC-MS-sniffing the sample flow is split via a splitter after leaving the chromatographic column. Only one part of the sample is then transferred into the mass spectrometer. The other part is transferred to a sniffing port. This enables trained subjects or ‘expert sniffers’ (following called ‘sniffers’) to directly detect and describe odorous substances contained in the sample flow (see Fig. 3).

These sniffers are characterised by exceptional sensitivity, particularly to the reference substance n-butanol. They therefore operate at or above the sensitivity limit specified in Section 2.4.1. They also exhibit this high sensitivity to other odorous substances and have a good ability to describe odours verbally.

These natural abilities are enhanced by training sessions from a pool of 160 odorous substances, which take place at least once a week. In addition, GC-MS sniffing runs are carried out for training purposes. As described, these involve smelling and describing the odours perceived. The words found are then compared with descriptions in the odour database and discussed in the group of participating sniffers.

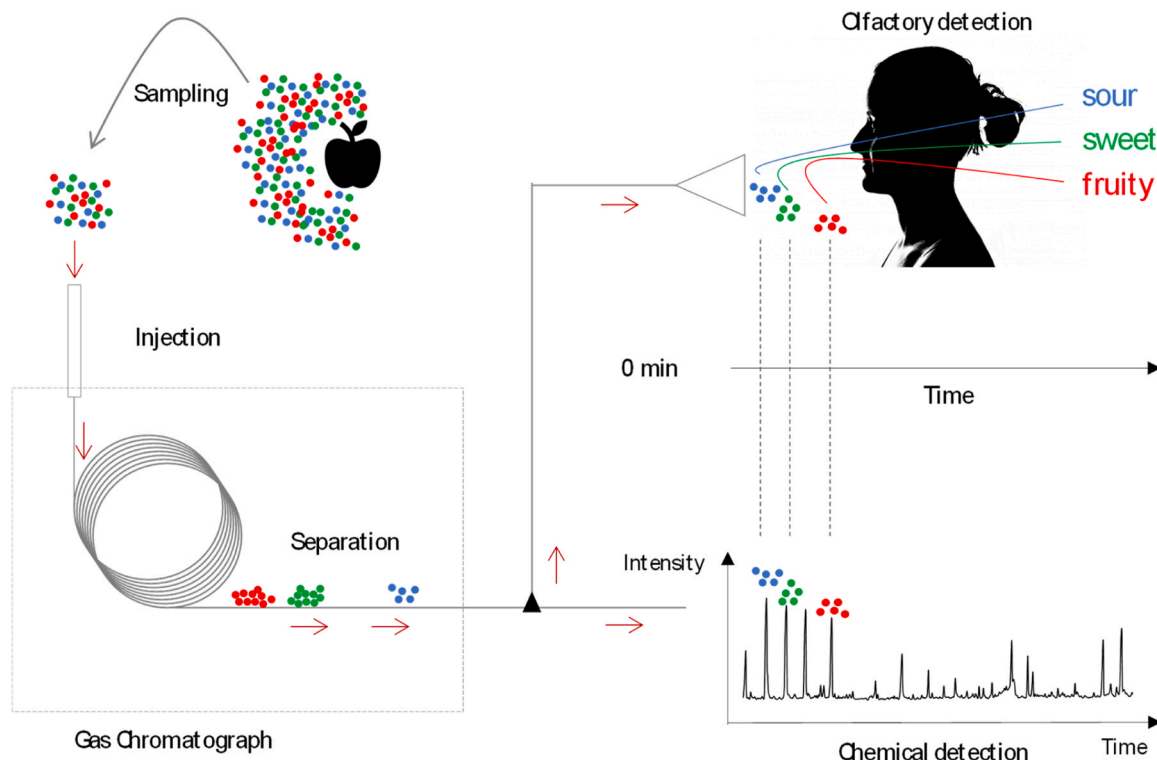


Fig. 3. Schematic process of the GC-MS-sniffing analysis.

As the molecules of the separated single substances reach the sniffing port, the sniffer assesses the character and intensity of the odour. The information is then communicated to a second sniffer, who is responsible for noting down the retention time and odour-descriptive words. Each 61-minute GC-MS run is divided into four sections, during which the sniffers alternate roles to avoid fatigue of their sense of smell (see Fig. 4). After the GC-MS-sniffing, the detected odours are overlaid with the GC-MS data using the retention times recorded by the mass spectrometer and the sniffers during a GC-MS run. The substances detected by sniffing are confirmed by overlapping odour perceptions with gas chromatographic retention times, data of the Olfasense GmbH odour database (combines GC-MS data, odour threshold levels and odour-descriptive words from literature, as well as the Olfasense GmbH odour vocabulary). The vocabulary has been established through the continuous training of sniffers using a library of reference odours.

This method makes it possible to see how well the odours, that are part of the odour wheel and could be found by the panellists, could also be found by sensory analysis (GC-MS-sniffing). Different sample volumes were first transferred to Tenax®-tubes to determine an appropriate volume for GC-MS-sniffing analysis of an odour-contaminated indoor environment. After evaluation, five litres were defined as a sufficient sample volume for the indoor environment assessments. Sniffers were also part of the sensory assessment of some rooms applying the odour wheel.

2.4.2.3. Chemical-analytical odour assessment for aldehydes and ketones (HPLC). Furthermore, assessments were carried out using HPLC² in accordance with ISO 16000-3:2013 [26] for formaldehyde and other carbonyl compounds. For this purpose, 40 litres of indoor air were drawn through a DNPH cartridge containing a collection medium of silica gel coated with 2,4-dinitrophenylhydrazine (DNPH). The aldehydes and ketones present in the indoor air react with the DNPH to form stable hydrazone derivatives. These derivatives could then be separated and identified using HPLC and analysed using an UV detector. The corresponding analysis was carried out by an external laboratory accredited according to ISO 17025 [27].

The results were also compared with the Olfasense GmbH odour database for further evaluation.

2.4.3. Validation of the odour wheel using twin rooms

In a further step, so-called twin rooms were artificially scented with specified mixtures of single substances, to test the odour wheel in practical use. The target substances were evaporated in quantities which, from a purely mathematical point of view, was aimed to reach concentrations above the odour threshold (by a factor of approximately 2–3) while ensuring that health-based guide values, in particular occupational exposure limits, were not exceeded. A total of 13 different substances were vaporised in four identical twin rooms, each with a floor area of 10.4 m² and an approximate volume of 27 m³. CO₂ was used as a tracer gas to determine the air exchange rate, and the decrease was measured repeatedly over an hour. This resulted in an average air exchange rate of 0.5 per hour for all rooms, ranging from 0.46 to 0.55 per hour. The temperature was kept at approximately 23 °C and the relative humidity varied between 39 and 52%. The twin rooms were specifically constructed to minimise emissions from building materials and to maintain an almost contamination-free environment. These conditions provide an optimal setting for controlled studies on odorous substances and mixtures.

The selection of substances to be vaporised was done in close collaboration with the expert group accompanying the study and was based on different criteria, like e.g. their relevance from the prioritisation list, their lack in the already conducted room experiments, or their

availability in procurement.

Each odour mixture contained three to four single substances. Each substance was included at least once in the odour wheel (see Table 2). To evaporate the substances under controlled conditions, a LiGaVa system (liquid-to-gas vaporiser, i.e. a heated vaporisation system) was used (see Fig. 5). Fans were operated to distribute the substances evenly throughout the rooms.

As before, samples were taken from all four twin rooms for GC-MS and GC-MS-sniffing analysis. Where appropriate, additional samples were taken for HPLC analysis. Following the sampling, the odour was evaluated by at least 10 untrained and 10 trained panellists using the odour wheel (see Section 2.4.1). This panel as well as gender-balanced as possible.

2.4.4. Assessment of the applicability of the odour wheel

The applicability of the odour wheel was reviewed by comparing the sensory odour assessment results with the chemical-analytical (GC-MS and HPLC) and sensory-analytical results (GC-MS-sniffing) (see Section 3.3.1).

If an odour could be identified in the room using both the odour wheel and analytical methods such as HPLC, GC-MS or GC-MS-sniffing, this confirmed that the odour wheel could be used for describing the respective odour and the corresponding single substances.

The results from GC-MS and GC-MS-sniffing were compared to confirm on the one hand the presence of substances or odours already included in the odour wheel, and on the other hand to detect substances or odours not yet included.

3. Results

3.1. Selection of substances and odour-descriptive words

Through literature review and expert consultations, the priority list of over 200 substances could be reduced to 64 single substances relevant to indoor odours. These 64 substances were initially selected for the development of the odour wheel. The odour-descriptive words were refined in collaboration with the sniffers of Olfasense GmbH, to a maximum of three odour notes to be included in the third level of the odour wheel. The complete list of respective substances from the odour wheel is presented in Appendix B. The substances can mainly be assigned to the groups of aldehydes, aromatics, terpenes and alcohols.

During the investigation of 21 odorous rooms all panellists were asked to add their own odour-descriptive words on the odour wheel, if no suitable description could be found on the odour wheel. Thus, finalising the odour wheel, additional odour notes and corresponding odorous substances were added to the odour wheel, expanding the list to a total of 66 substances.

3.2. Final odour wheel

The final version of the odour wheel consists of three levels containing odour-descriptive words, as well as a fourth level containing illustrative images that are linked to the corresponding odours and shall support odour associations.

The first central level of the odour wheel contains the four odour categories 'chemical', 'organic', 'musty' and 'burnt'. These are divided into a total of 17 odour descriptors in the second level. The third and most detailed level consist of 45 odour notes to which a total of 66 single substances are assigned (see Appendix B). The final odour wheel is shown in Fig. 6 below.

It should be noted that some of the odour notes on the third level appear more than once, e.g. 'citrus' like in organic-fruity-citrus and chemical-cleaning products-citrus. In both cases the three corresponding single substances are the same: limonene, R-limonene and DL-limonene.

Additionally, most of the odour notes on the third level are associated with one, two or three single substances. But in some cases, four

² HPLC sampling and measurement for aldehydes and ketones were not carried out in the first five rooms.

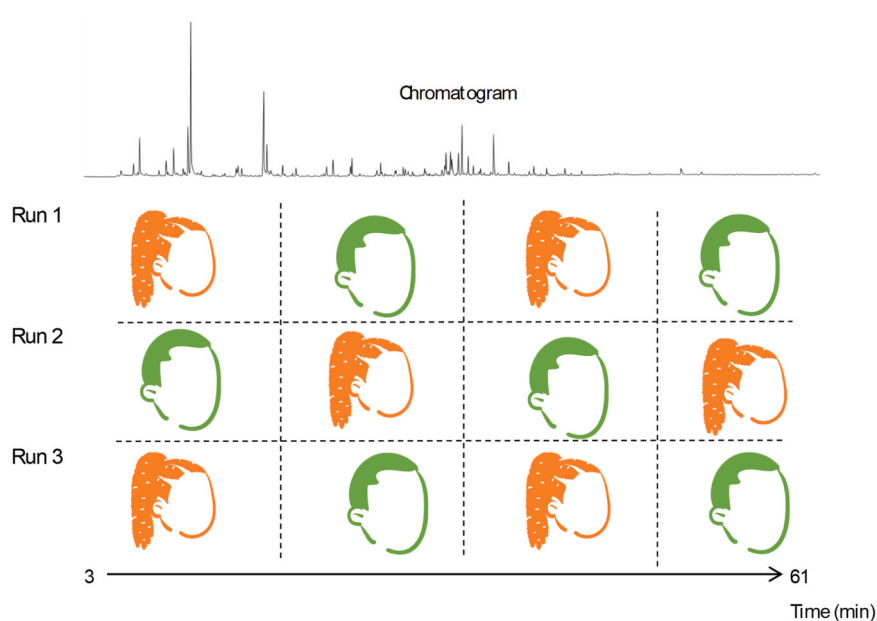


Fig. 4. Schematic GC-MS-sniffing process.



Fig. 5. LiGaVa 4.0 with heating block.

(‘rubber’; ‘mothball, old, old building’; ‘conifer, woody’; ‘pungent, acrid’) or more single substances are associated, e.g. ‘musty’ with five substances; ‘earthy, mouldy’ with six substances; ‘citrus’ with seven substances; ‘sweet’ with eleven substances. Therefore, it is possible that five odour notes are associated with 29 substances.

3.3. Applicability of the odour wheel

The survey on user-friendliness among panellists revealed that the odour wheel was perceived as mostly positive. 96% of the panellists commented the odour wheel to be well or very well designed, and were able to use it easily, either immediately or after a brief period of familiarisation. Thus, only minor design changes were made to the odour wheel, like changes in contrast, colours and the change in font colour from white to black.

Looking at the group of trained panellists, 100% of women and 97% of men rated the application as easy to very easy, while in the untrained group, 10% of women and 4% of men found the application to be at least not so easy.

3.3.1. Comparison of sensory, chemical-analytical and sensory-analytical odour assessment

There was a maximum of 66 possible agreements between the

sensory assessment by panellists using the odour wheel and the chemical-analytical (GC-MS and HPLC) / sensory-analytical (GC-MS-sniffing) data. It should be noted that the identification of only five odour notes can be associated with up to 29 single compounds (see Section 3.2). Taking into account that one aim of the odour wheel is to help narrow down potential odorous substances or substance groups, single substances were only counted once in the comparison of sensory and analytical assessment. There are two ways to determine the degree of agreement between analytical and sensory assessments. Either the number of analytically determined single substances in a room that can be confirmed by the panellists naming an odour note on the odour wheel can be determined or vice versa. It was decided to go with the second method. In each of the 21 rooms the number of single substances associated with the odour notes named by the panellists were counted. Then it was determined how many of these substances were analytically detected by GC-MS, HPLC or GC-MS sniffing (see Table 1).

On average 25% of the single substances associated with the odour notes named by panellists could be confirmed analytically. Both trained and untrained panellists identified the same number of substances on average. However, when looking at individual rooms, there were differences in the number of single substances associated with odour notes named by trained and untrained panellists.

A full list of the single substances included in the odour wheel and



Fig. 6. Final odour wheel developed by Olfasense GmbH on behalf of the German Environment Agency.

the corresponding odour categories, descriptors and notes is shown in Appendix C. It also contains the number of rooms in which the respective substance could be detected using GC-MS, HPLC or GC-MS-sniffing analysis, or in which the third-level odour note was named by panellists. In the last column, the number of agreements between GC-MS/HPLC /GC-MS-sniffing and the sensory assessment using the odour wheel are listed.

For some substances, sensory perception always occurred whenever they were analytically detected, like for 1-methylnaphthalene with the odour note 'mouldy' or 2-ethylhexanol with the odour note 'PVC', 'rubber' or 'menthol, fresh'. However, it was not always possible to obtain clear correlations between analytical and sensory assessment. For example, acetaldehyde could be detected in all 21 rooms using GC-MS/HPLC. Exposure concentrations were found both above and below the odour threshold value of $2.7 \mu\text{g}/\text{m}^3$. However, it could only be detected in five rooms using GC-MS-sniffing (3 rooms with concentrations clearly above the OTV and two with a concentration about factor 4 below the OTV). In 19 of 21 rooms, panellists selected the odour note 'pungent' in the third level. This resulted in a total of 19 agreements for acetaldehyde on the odour wheel. Acetaldehyde additionally is assigned to the odour note 'flowery, floral'. In comparison to 'pungent', this odour note was only selected in 12 rooms, resulting in 12 agreements on the odour wheel. Another example is n-butyl acetate with an OTV between 10 and $77 \mu\text{g}/\text{m}^3$, which corresponds to odour notes like 'paint, adhesive' as well as 'banana'. Using GC-MS, n-butyl acetate could only be detected in two rooms. In both rooms, the exposure concentration was below the

OTV ($1.7\text{--}1.8 \mu\text{g}/\text{m}^3$). No findings could be obtained using GC-MS-sniffing. The odour note 'paint, adhesive' was chosen by panellists in 18 rooms, while 'banana' was chosen by panellists in only two rooms. Overall, there are no agreements for n-butyl acetate for 'banana' and only one agreement for 'paint, adhesive'. Last but not least, panellists also identified a number of substances with the odour wheel that could not be detected analytically, like e.g. naphthalene- or chloroanisole-like substances, 2-butanone, 2-butoxyethanol, or 2-phenoxyethanol.

3.3.2. Twin rooms

Another approach to test the applicability of the odour wheel was to evaluate specifically scented rooms also using human-sensory assessment and analytical sampling for GC-MS and HPLC measurements. The general aim was to generate concentrations of odorous substance above the known odour threshold values in four so-called twin rooms. In order to achieve the required concentrations, partly relatively high concentrations were used in some cases, which from a purely mathematical point of view already exceeded health-based guide values. However, due to dilution and wall effects in the rooms, the analytically detected concentrations were within the range that is not considered to affect health, especially considering occupational exposure limits (OEL).

Table 2 comprises the information about the vaporised substances in the twin rooms, their respective OEL and health-based guide values, their dosage, calculated concentrations and analytically detected concentrations such as the number of panellists who identified the corresponding odour by naming odour notes using the odour wheel. Overall,

Table 1

Comparison of the number of single substances associated with odour notes identified by panellists using the odour wheel and the number of single substances analytically detected in the room using GC-MS, HPLC or GC-MS-sniffing, broken down by untrained and trained panellists as well as for the entire group of panellists.

Room	No. of single substances analytically detected by GC-MS, HPLC, GC-MS-sniffing ^a	untrained panellists (n = 20)		trained panellists (n = 10)		all panellists (n = 30)	
		No. of single substances associated with odour notes	No. of single substances analytically confirmed (%) ^a	No. of single substances associated with odour notes	No. of single substances analytically confirmed (%) ^a	No. of single substances associated with odour notes	No. of single substances analytically confirmed (%) ^a
1	21	33	11 (33%)	37	10 (27%)	41	11 (27%)
2	18	37	11 (30%)	26	7 (27%)	40	12 (30%)
3	18	44	10 (23%)	42	12 (29%)	56	14 (25%)
4	11	41	6 (15%)	36	4 (11%)	54	9 (17%)
5	10	45	5 (11%)	45	8 (18%)	54	8 (15%)
6	14	25	3 (12%)	33	6 (18%)	37	7 (19%)
7	15	32	4 (13%)	8	1 (13%)	35	4 (11%)
8	13	46	9 (20%)	38	6 (16%)	48	9 (19%)
9	15	34	9 (26%)	38	6 (16%)	43	9 (21%)
10	13	26	5 (19%)	39	8 (21%)	40	8 (20%)
11	18	34	13 (38%)	40	12 (30%)	46	15 (33%)
12	18	36	8 (22%)	39	10 (26%)	45	12 (27%)
13	20	37	13 (35%)	28	10 (36%)	40	14 (35%)
14	19	33	12 (36%)	41	12 (29%)	52	17 (33%)
15	15	37	9 (24%)	36	8 (22%)	42	10 (24%)
16	19	25	9 (36%)	40	10 (25%)	50	14 (28%)
17	15	40	7 (18%)	37	13 (35%)	50	13 (26%)
18	16	37	8 (22%)	19	3 (16%)	38	9 (24%)
19	14	30	6 (20%)	28	6 (21%)	35	6 (17%)
20	24	37	14 (38%)	34	11 (32%)	39	14 (36%)
21	20	44	16 (36%)	39	11 (28%)	46	16 (35%)
Ø	17		(25%)		(24%)		(25%)

^a Only substances with an exposure concentration not lower than 10-times below the odour threshold were included. This is because the probability of panellists detecting these substances in indoor air below this threshold is virtually zero.

in four twin rooms mixtures of single substances (in total 15 single substances) were vaporised. However, for two substances (2-phenoxyethanol in room 1 and limonene in room 2), the final concentrations in the twin rooms were below the given odour threshold values. However, the substances were still confirmed by the odour notes chosen by panellists. Moreover, the dosing of caproic acid was not successful, so that this substance could not be detected either analytically or by sensory assessment.

The sensory assessment with the odour wheel was conducted by trained and untrained panellists, including eleven men and eleven to twelve women. Twelve of the 15 vaporised substances were identified by the group of panellists selecting the appropriate odour notes of the odour wheel. These findings confirm that the use of the odour wheel by panellists can provide indications of substances present in indoor air and thus assist in identifying the odour source.

In particular, the characteristic 'organic – animal – horse stable' was selected by panellists which can be correlated to p-cresol, which was vaporised into one of the twin rooms. GC-MS analysis resulted in concentrations of p-cresol approximately by a factor of three above the odour threshold value. Also, GC-MS-sniffing confirmed the presence of p-cresol.

In most rooms, the substance concentration and the results of the chemical analysis and sensory evaluation by panellists correlated well with each other. However, sometimes a concentration above the odour threshold value did not necessarily lead to naming the corresponding odour note on the odour wheel. This can be seen e.g. for alpha-pinene (dimer) in twin room 1 or benzaldehyde in twin room 3. For alpha-pinene, a smell of coniferous wood or resin would have been expected, but this was not detected by the panellists. After dosing with benzaldehyde, a nutty odour with a specific 'almond, marzipan' note should have developed in the room, but this could also not be detected by the panellists. The analytically determined concentrations were between 1.5 and 2 times higher than the respective odour threshold value and detection was also possible in GC-MS-sniffing. It is known that odour identification often occurs at concentrations several times higher than

the reported odour detection threshold, frequently around a factor of three to ten [44]. Therefore, the measured concentration range may not have been sufficient to reliably identify and name the expected odour notes. Additionally, expectations may also have influenced the perception of these two specific odour notes. Without features in the room to provide clues, such as a wooden ceiling for example, it might be difficult to identify these particular odours.

However, in twin room 1 containing alpha-pinene, 17 out of a total of 23 panellists predominantly evaluated the indoor air as having an 'organic' odour character, according to the first level of the odour wheel. This category includes all vaporised single substances in twin room 1 (1-butanol, hexanal, alpha-pinene, 2-phenoxyethanol), which are further specified on the third level. The 'organic' odour character was identified more frequently than any of the other odour categories on the odour wheel. This may indicate that the panellists were able to correctly identify the basic odour character given by the central level of the odour wheel but were unable to further differentiate it into specific odour descriptors or odour notes. In contrast to this, however, during the validation of the odour wheel benzaldehyde could only be found twice within the overall 21 rooms using GC-MS-sniffing but not in relevant concentrations using GC-MS only. Sniffers, that are used for GC-MS-sniffing, are selected for the high sensitivity of their sense of smell, which enables them to detect odours at very low concentrations and are trained to describe them accurately. In contrast, trained or untrained panellists typically have an average sense of smell, representing the average odour perception of the general population.

However, also the detection of single substances above the odour threshold value using GC-MS-sniffing was not always successful in the twin rooms. Despite concentrations three to ten times above the odour threshold value, 1-butanol in twin room 1, pentanal in twin room 2 and 2-ethylhexanol in twin room 4 could not be detected with GC-MS-sniffing.

In summary, a group of trained and untrained panellists could successfully identify all but three of the 15 substances in the four twin rooms using the odour wheel.

Table 2

Overview of the scenting in twin rooms: substances, dosage, concentrations, detection and recovery.

Room	Substances	CAS No.	Occupational Exposure Limit (OEL) in µg /m ³	German indoor air guide values (GV) ^c in µg /m ³	Dosage in µL	Purity of substance in %	Calculated concentration in µg/m ³	Concentration determined by GC-MS / HPLC in µg/m ³	Odour threshold value in µg/m ³	Single substance identified by GC-MS-sniffing	Associated odour note(s) on the odour wheel (number of panellists that identified the odour/overall number of panellists)
Twin room 1	1-butanol	71-36-3	310,000 [28]	GV I: 700 GV II: 2000 [28]	300	100	9000	1915	123 [23]	no	yes (3/23 - pungent) yes (3/23 - pungent, acrid) yes (2/23 - sweet) overall match 8/23
	hexanal	66-25-1	/	/	0.2	98	8.6	4.5 / 6.4	1.4 [29]	yes	yes (3/23 - rancid) yes (1/23 - grass, herb) overall match 4/23
	alpha-pinene (dimer) 2-phenoxyethanol	80-56-8 122-99-6	/ 5700 [31]	/ GV I: 30 GV II: 100 [32]	5 130	97 100	150 5344	142 53.6	100 [30] 4200 [33]	yes no	no (0/23 - conifer, woody) overall match 0/23 yes (3/23 - pungent) no (0/23 - rubber) yes (3/23 - acrid) overall match 6/23
Twin room 2	pentanal	110-62-3	/	/	0.5	97	10	4.5	1.5 [30]	no	yes (6/23 - fruity) yes (1/23 - musty) overall match 7/23
	hexanal	66-25-1	/	/	0.2	98	8.6	3.3 / 5.3	1.4 [29]	yes	yes (1/23 - grass, herb) yes (2/23 - rancid) overall match 3/23
	limonene	138-86-3	/	/	20	95	590	20.5	210 [30]	yes	yes (3/23 - organic, citrus) yes (3/23 - chemical, citrus) overall match 6/23
Twin room 3	acetophenone	98-86-2	/	GV I: 66 GV II: 220 [34]	5	100	190	44.5	1.2 [35]	yes	yes (7/23 - chemical sweet) overall match 7/23
	ethyl acetate	141-78-6	750,000 [36]	GV I: 600 GV II: 6000 [36]	500	100	16,560	1242.6	880 [37]	yes	yes (4/22 nail polish) overall match 4/22
	benzaldehyde	100-52-7	/	GV I: 20 GV II: 200 [38]	15	100	600	159	85 [39]	yes	no (0/22 - almond, marzipan) overall match 0/22
Twin room 4	p-cresol ^a	106-44-5	4500 [40]	GV I: 5 GV II: 50 for the sum of methyl-phenols ^d [41]	20	-	0.86	0.6	0.24 [30]	yes	yes (2/22 - horse stable) overall match 2/22
	caproic acid	142-62-1	/	/	1	98	30	-	2.9 [30]	no	no (0/22 - goat) no (0/22 - sweaty, cheesy) no (0/22 - sour) overall match 0/22
	2-ethylhexanol	104-76-7	54,000 [42]	GV I: 100 GV II: 1000 [43]	30	100	900	230	50 [30]	no	yes (1/22 - menthol, fresh) no (0/22 - rubber) no (0/22 - PVC) overall match 1/22
	2-methyl-naphthalene ^b	91-57-6	/	/	90	-	20.7	9.0	1.6 [33]	yes	yes (1/22 - mouldy) yes (1/22 - mothball, old, old building) no (0/22 - musty) overall match 2/22
	acetophenone	98-86-2	/	GV I: 66 GV II: 220 [34]	5	100	190	46.0	1.2 [35]	yes	yes (6/22 - sweet) overall match 6/22

^a Sample solution containing 11.6 mg in 10 ml isopropanol, resulting in a concentration of 1.16 mg/ml.^b Sample solution containing 62 mg in 10 ml isopropanol, resulting in a concentration of 6.2 mg/ml.^c retrieved from <https://www.umweltbundesamt.de/en/topics/health/commissions-working-groups/german-committee-on-indoor-air-guide-values>. GV I describes the concentration of a pollutant in indoor air which, according to current knowledge, is not expected to cause any adverse health effects, even in the case of lifelong exposure of sensitive persons. GV II is an effect-related value, based on current toxicological and epidemiological knowledge of a substance's effect threshold. It represents the concentration of a pollutant in indoor air at which immediate action is required if it is reached or exceeded. This concentration is particularly likely to affect the health of sensitive persons, including children, especially if they spend long periods of time indoors.^d details on substance spectrum see in the respective publication [40].

3.3.3. Comparison of panellist's sensory assessment

Both trained and untrained panellists were selected for participation in the study, with attention given to achieving a balanced gender distribution. Differences related to gender and the level of sensory experience are briefly addressed here. On average, each panellist selected six odour descriptors or fields on the odour wheel. Female panellists provided on average one additional odour descriptor compared with male panellists. Moreover, trained panellists (including sniffers) identified approximately two more odour descriptors per session than untrained panellists, indicating a higher level of sensitivity and discrimination ability among the trained group. However, this increased sensitivity did not lead to a higher number of matches between analytical and sensory assessment, neither across the 21 rooms nor within the twin room experiments.

4. Discussion

Based on a review of odour-active substances relevant for indoor environments, more than 200 single substances were collected and listed if they were mentioned in more than one paper or explicitly identified as relevant by expert consultations. Reduction to the most odour-relevant 64 single substances was achieved by

- comparing single substances of the first list with the Olfasense internal odour database,
- through additional research on detailed information for odour parameters (like OTV, typical indoor concentrations, hedonics, odour-descriptive words) for the listed substances and
- through repeated expert consultations.

In order to develop an easy-to-use odour wheel, general descriptions of odours were placed as so-called 'odour categories' in the centre of the odour wheel, while more detailed descriptions were defined on a middle level as 'odour descriptors' and on an outer level as 'odour notes'. Between one and up to 11 single substances were then assigned to the respective odour notes. Additions to the odour wheel could be made during the course of the project. Hence, the final odour wheel includes 66 single substances. It should be noted, however, that the odour wheel does not claim to include all possible odour notes and odorous substances. To ensure a clear and functional visualisation, the inclusion of further odour notes was deliberately limited. Consequently, the odour wheel represents the odour notes identified as most relevant for odour perception in indoor environments. For example, the odour note 'cigarette smoke' was not included in the odour wheel, as this was considered through the expert consultation as an easy to identify odour which needs no further evaluation using an odour wheel. Nevertheless, the odour wheel keeps the option to assign further odorous substances to the odour notes, if required or beneficial.

Evaluating the practical use of the odour wheel by trained and untrained panellists, and considering fundamental differences and weaknesses of analytics and sensory evaluation, good agreement was found between the odour notes chosen through the sensory assessment with the odour wheel and single substances identified by GC-MS, HPLC or GC-MS-sniffing. However, there were also substances included in the odour wheel that could not be confirmed analytically. For example, single substances such as 2-butanone, 2-butoxyethanol, (+) alpha-pinene and ethyl acetate were not found in relevant concentrations analytically at all but respective odour notes were marked on the odour wheel. Hence, e.g. a 'conifer, woody' odour note for (+) alpha-pinene could not be confirmed analytically. With 2-butanone not being analytically detected, the odour note 'sweet', within the descriptor 'fruity' and the category 'organic', could also not be verified. With ethyl acetate not being detected analytically at all and acetone being detected only once analytically and with no matches to be found between chemical analysis and human sensory assessment, the verification of the odour note 'nail polish', which is part of the descriptor 'solvent' and the category

'chemical', could also not be verified analytically. The same applies e.g. for benzaldehyde with an 'almond, marzipan' odour note which could not be confirmed via GC-MS. In contrast, acetaldehyde was detected in all rooms using GC-MS but could only be identified in five rooms using GC-MS sniffing. More examples can be seen in Table 4 in Appendix C.

There may be various reasons for single substances or odour notes not being found in the assessed rooms:

- Some of the 66 substances were not present in any of the assessed rooms (limited number of 21 rooms).
- The rooms were primarily offices, conference rooms and corridors. For example, no living rooms or rooms used mainly for private purposes were assessed.
- The measured substance concentrations were below or only slightly above their actual OTV, so they could not be detected either by the panellists or by GC-MS sniffing.
- OTVs in the literature like from Devos et al. [45], Van Gemert [35] or Cain and Schmidt [46] can differ by several orders of magnitude and are not always reliable [47].
- The odour character of the respective substance might be difficult to identify within the corresponding odour mixture and does not lead to a clear perception [47,48]. Effects such as amplification, attenuation, or complete masking of specific odorous substances may have influenced the identification of some of the odour notes.

Due to the relatively homogeneous characteristics of the selected rooms, the odour impressions most frequently chosen by panellists were predominantly assigned to the first level categories 'chemical' and 'musty', which are related mainly to the substance groups of aromatic compounds, alcohols, terpenes and polycyclic aromatic compounds (PAH). The odour category 'organic' assigned mainly to the substance groups of aldehydes, alcohols, terpenes and organic acids was only in one room predominantly chosen by panellists, while 'burnt' or 'pungent' mainly assigned to the substance group of aldehydes were rarely chosen compared to the overall answers. The frequent occurrence of aldehydes, alcohols, terpenes, PAH and organic acids in indoor environments likely reflects their widespread origin from building materials, cleaning agents, and occupant activities. Some odour impressions, especially those from the third level of the odour wheel and the related single substances, showed little or no agreement between sensory assessment and chemical analysis. This can be explained by the fact that the interaction of single substances within a multicomponent mixture in indoor air may lead to various perceptual effects such as amplification, attenuation, or complete masking of odorous substances. In some cases, such interactions may lead to a fundamental change in the perception of the odour of a single substance [49,50]. Changes in odour characteristics can also result from differences in the concentration of single substances. Examples are skatole or indole: at high concentrations, they have a faecal odour, but at very low concentrations, they contribute a flowery note to perfumes [51,52].

With regard to the analytical limits, it must be mentioned that not all substances that may be the cause of a certain odour perception in rooms can be detected due to existing detection and determination limits or a lack of appropriate measurement methods. Furthermore, detection of single substances above the odour threshold value in GC-MS does not always result in odour detection in GC-MS-sniffing and vice versa. The perceptibility of substances in the GC-MS-sniffing analysis depends on several factors, such as the volatility of substances, losses due to condensation, the dilution effect through sniffing ports and the sniffer's breathing intervals especially during the exhalation phase, during which no odours can be perceived [53]. Therefore, inhalation is done very consciously, and the exhalation phase shall be kept as short as possible. Another aim is to reduce the risk of olfactory fatigue [54] and to minimise or even eliminate the possible influence of (partial) anosmia for single substances [55,56]. To achieve this, several rounds of GC-MS-sniffing are performed per sample, using multiple sniffers [57]

and changing the order of sniffers during each GC-MS-sniffing run.

The evaluation of the twin rooms showed that substances detected analytically above the OTV do not necessarily result in the perception of the corresponding odour notes. It has been shown in some cases that characteristic odours that are vaporised into a room as a multi-component mixture were not necessarily found in the room with the same odour characteristics that they had as single substances. A relevant factor here may be the proportion of the single substance in the total concentration of the mixture and its odour intensity. It can be assumed that the greater the odour intensity of a single substance and the higher its concentration compared to other substances in a mixture, the more clearly it is perceived [58]. Dealing with mixed odours in indoor environments and the associated challenges in analytical detection, like sampling and instrumental detection limits, remain the subject of further research. Another discrepancy was the differences of calculated and measured concentrations of the substance mixtures in the twin rooms. At the beginning of the experiment, substance concentrations were calculated and vaporised in the twin rooms in a corresponding mixing ratio. The recovery rate of the single substance concentrations using the analytical measurement methods varies depending on the substance. This is primarily due to dilution effects and wall effects due to surface adsorption, which must be taken into account before planning such a study.

Despite the peculiarities of odour perception and the associated challenges, an average of 25% of the single substances identified by panellists using the odour wheel could be analytically confirmed by GC-MS, HPLC and/or GC-MS-sniffing in the 21 rooms. In the four twin rooms, a group of trained and untrained panellists successfully identified all but three of the 15 substances using the odour wheel.

However, there were two odour-descriptive words, repeatedly named by panellists in several rooms that were not part of the preliminary odour wheel. These were assigned to caprolactam and 4-phenylcyclohexene. In the final revision of the odour wheel, both were included. Caprolactam was added to the first level category 'chemical' and the descriptor 'cleaning products' and was then assigned to the newly added odour note 'chlorine'. 4-phenylcyclohexene was assigned to 'chemical', 'plastic' and in the third level to the also new odour note 'carpet, textile'.

Based on the latest changes, the final odour wheel is now available. The practical benefits of the odour wheel must be demonstrated in long-term use of the odour wheel. Important user groups for the application of the odour wheel are health authorities, expert consultants, and analysis laboratories that deal with indoor air and indoor hygiene. It has to be noted that odour perception is influenced by individual factors such as personal sensitivity, prior experience, and associative memory [59]. This individuality should be considered when interpreting results based on an odour wheel, as users may differ in their personal ability to assign specific odour qualities. The minor differences observed in our study between trained and untrained panellists, as well as between male and female participants, may indicate the influence of sensory experience and gender on odour perception and characterisation. Trained panellists (including sniffers) tended to identify a slightly broader range of odour descriptors, consistent with enhanced discrimination ability associated with training. Female participants provided more responses than male participants, which may align with previous reports of sex differences in olfactory sensitivity [60,61]. These results highlight the need for balanced panel composition in odour assessments. The results also increase the relevance for guided use of the odour wheel. Therefore, odour wheels are best used by indoor air consultants who are familiar with typical odorous substances to ensure consistent interpretations.

Other odour wheels with their focus on industrial or environmental odours have already been successfully used to analyse the causes of odour emissions during e.g. the processing of wastewater biosolids or to identify and localise odour emissions in industrial facilities [50,62,63]. As a result, perceived odour problems and a standardised vocabulary could contribute to odour management and emission control for these

cases [62]. This demonstrates that odour wheels, when used alongside chemical analyses, can be a useful tool for identifying and tracing odour sources.

Another option for identifying causes for an unpleasant odour is to combine the odour wheel with questionnaires focusing on the described problems regarding the indoor air quality, environmental disturbing factors and ventilation conditions of occupants. This could help to additionally determine how indoor air quality affects the satisfaction of occupants. Standardised questionnaires like the ones given by VDI 4302-3 'Odour testing of indoor air and emissions from indoor materials - Survey of satisfaction with indoor air quality in homes and offices by means of questionnaires' [64], specifically support to investigate health problems and discomfort in indoor environments and help to find practical solutions.

Analytical measurements in indoor environments are essential for a systematic assessment of odour-related problems, as they provide objective data beyond subjective human perception. In many cases, however, it is not necessary to capture the entire spectrum of potentially present substances, but rather to focus on those substance groups that are most relevant to the perceived odour and the underlying question. The odour wheel can support this process by facilitating a structured classification of the perceived odour prior to indoor air measurements. By assigning the odour to specific odour categories, descriptors, and notes, the odour wheel can guide the targeted selection of appropriate analytical methods and substance groups. Thus, the odour wheel does not only serve as a descriptive tool but also as a practical instrument for designing efficient and problem-oriented measurement strategies in indoor environments.

In summary, the odour wheel can be effectively used alongside the procedure for evaluating complaints about odour annoyance to assist in communication between occupants and experts, planning the appropriate measurement strategy, and source identification [2].

5. Conclusion

The odour wheel developed in this project is an innovative tool that establishes a common language for characterising odours in indoor environments. By providing odour-descriptive words it supports the communication between occupants and indoor air consultants and assists in planning indoor air measurements. As it links odour perception to specific single substances or substance groups, it might also support source identification. However, expert involvement still remains essential for identifying odour sources.

In some cases, the concentration of an odorous substance is so low that it cannot be measured analytically, even though the odour is clearly perceptible. Here, the odour wheel complements well-established standard methods such as GC-MS, HPLC, or GC-MS sniffing. Neither of these methods can be regarded as 'gold standard' that yields a correct result against which the other method can be assessed. Both analytical and sensory methods have advantages and disadvantages and each identifies different quantities of single substances in indoor air. However, the approaches can complement each other effectively.

The strong interest signalled from German federal health authorities reflects the odour wheel's practical value. Its use by indoor air consultants to communicate with occupants improves handling of odour complaints in both public and private indoor environments and represents a significant step toward better management of indoor odour issues.

CRedit authorship contribution statement

L. Brosig: Writing – review & editing, Writing – original draft, Visualization, Validation, Supervision, Software, Resources, Project administration, Methodology, Investigation, Funding acquisition, Formal analysis, Data curation, Conceptualization. **L. Strasser:** Writing – original draft, Validation, Investigation, Formal analysis. **B.**

Maxeiner: Funding acquisition. **A. Beier:** Methodology, Investigation. **S. Senkale:** Data curation. **R. Kolodziejczyk:** Data curation. **J. Hameister:** Writing – review & editing, Investigation. **F. Gerull:** Writing – review & editing. **K. Schröder:** Writing – review & editing. **K. Sucker:** Writing – review & editing. **A.M. Scutaru:** Writing – review & editing. **C. Röhl:** Writing – review & editing. **M. Debiak:** Conceptualization. **M. Kolossa-Gehring:** Writing – review & editing. **M. David:** Writing – review & editing, Writing – original draft, Supervision, Methodology, Investigation, Conceptualization.

Declaration of Competing Interest

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Appendix A. Experts

Prof. Dr. Claudia Röhl (German Environment Agency (UBA) and Christiana Albertina University of Kiel); Dipl.-Biol., Dipl.-Ing. Roland Braun (Ingenieur- und Sachverständigenbüro Roland Braun, Hamburg); Dr. Kirsten Sucker (Institute for Occupational Safety and Health of the German Social Accident Insurance, (IFA)); Felicia Gerull (Landeslabor Berlin-Brandenburg LLBB); Dr. Jörn Hameister (State office of Health and Social Affairs Mecklenburg West Pomerania); Dr. Wolfgang Horn (Federal Institute for Materials Research and Testing (BAM)); Dr. rer. nat. Andrea Burdack-Freitag (Fraunhofer Institute for Building Physics IBP); Dr. Katrin Schröder (Hamburg's Ministry of Justice and Consumer Protection); Nadja von Hahn (German Social Accident Insurance (DGUV)); Dipl.-Ing. Jörg Brandes (GFI Gesellschaft für Innenraumhygiene mbH)

Appendix B. Single substances included in the odour wheel

Table 3

Final substance list with odour notes of the third level of the odour wheel, OTVs and typical indoor air concentrations

No.	Substances (CAS No.)	Odour notes (third level of the odour wheel)	OTV in $\mu\text{g}/\text{m}^3$	Typical indoor air concentration in $\mu\text{g}/\text{m}^3$
1	(+)-alpha-pinene (7785–70-8)	conifer, woody	5.3 [65]	/
2	(E)-2-nonenal / (E)-2-decanal (18829–56-6)	moist cardboard	0.09 [39]	/
3	1,2,3-trimethylbenzene (526–73-8)	rubber	/	1.01 – 1.25 [66]
4	1-butanol (71–36-3)	pungent, acrid, sweet	78 – 1400 [67,68]; 120 [23,24]	1 – 55.6 [69,70]
5	1-butoxy-2-propanol (5131–66-8)	fruity	870 [30]	/
6	1-chloronaphthalene (90–13-1)	musty, mothball, old, old building	2.7 [21]	/
7	1-methylnaphthalene (90–12-0)	mothball, old, old building, mouldy	1.9 [33]	/
8	1,4-dimethylnaphthalene (571–58-4)	musty, mouldy	4.2 [33]	/
9	2,3,4,5,6-pentachloroanisole (1825–21-4)	earthy, mouldy	1.6 [71] – 2.19 [35]	/
10	2,3,4,6-tetrachloroanisole (938–22-7)	earthy, mouldy	0.01 [35]	/
11	2,3,4-trichloroanisole (54135–80-7)	earthy, mouldy	30.38 [35]	/
12	2,3,6-trichloroanisole (50375–10-5)	earthy, mouldy	0.03 [35] – 1.6 [71]	/
13	2,4,6-trichloroanisole (87–40-1)	earthy, mouldy	1.6 [71]; 0.005 [35] – 0.08 [33]	/
14	2-butanone (78–93-3)	sweet	210 [72] – 1300 [30] 2650 [21]	1.09 – 5.38 [69]
15	2-butanone oxime (96–29-7)	paint, adhesive	270 [33]	/
16	2-butoxyethanol (111–76-2)	rancid, sweet	210 [30]	0.66 – 21.34 [69,73]
17	2-ethylhexanol (104–76-7)	menthol, fresh, rubber, PVC	127 [33]	3.9 – 4.7 [73]
18	2-methyl-1-propanol (78–83-1)	moist mineral based building products	33 [30]	/
19	2-methylnaphthalene (91–57-6)	mouldy, musty, mothball, old, old building	1.6 [33] – 4.0 [35]	/
20	2-phenoxyethanol (122–99-6)	rubber, pungent, acrid	4200 [33]	/
21	2-propanol (isopropanol) (67–63-0)	medicine, disinfectant	65,000 [30]	11.29 – 31.02 [69]
22	acetaldehyde (75–07-0)	flowery, floral, pungent	2.7 [30]	4.9 – 42.5 [66,70,73–75]
23	acetone (67–64-1)	nail polish	26,690 [33]	14.9 [70] – 36.04 [69]
24	acetophenone (98–86-2)	sweet	1.2 [35] – 2.9 [33]	/
25	acrolein (acrylic aldehyde) (107–02-8)	sweet, burnt	8.3 [30]	1.3 – 2.5 [73]
26	alpha-pinene (dimer) (80–56-8)	conifer, woody	100 [30]	4.2 – 232 [66,69,73,75]
27	benzaldehyde (100–52-7)	almond, marzipan	85 [39] 67.4 [21]	0.9 – 18.8 [66,69,70,73–75]
28	benzothiazole (95–16-9)	rubber	3.4 [33]	/
29	beta-pinene (127–91-3)	conifer, woody	187 [30]	1.81 – 73.9 [66,69,75]

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Table 3 (continued)

No.	Substances (CAS No.)	Odour notes (third level of the odour wheel)	OTV in $\mu\text{g}/\text{m}^3$	Typical indoor air concentration in $\mu\text{g}/\text{m}^3$
30	butanoic acid (107–92-6)	lactic, milky	0.35 – 0.94 [30] [50,76,77]	/
31	butyraldehyde (butanal) (123–72-8)	pungent	1.3 – 100 [29,78]	1.5 – 10.3 [70]
32	caproic acid (142–62-1)	goat, sweaty, cheesy, sour	4.7 – 10 [50,76,77]; 2.9 [30]	7.77 – 24.96 [69]
33	decanal (112–31-2)	citrus, grass, herb	2.6 [39] [30]	< 1 – 18 [70,79]
34	delta-3-carene (13466–78-9)	sweet, conifer, woody	9300 [80]	2.09 [66]
35	DL-limonene (7705–14-8)	citrus	/	3.46 – 9.9 [69]
36	acetic acid (64–19-7)	vinegar	13 [50] – 150 [81,82]; 21 [33]	10.4 – 153 [66,69]
37	ethyl acetate (141–78-6)	nail polish	4300 – 4700 [68]; 3100 [30]; 880 [37]; 4130 [21]	3.94 – 11.72 [69]
38	ethylbenzene (100–41-4)	petrol, gasoline	26 [83] – 730 [30]	0.15 – 5.01 [66,69,70,73]
39	formaldehyde (50–00-0)	disinfectant	140 [84] – 630 [30]	8.1 – 926 [66,70,73,75]
40	geosmin (19700–21-1)	earthy, mouldy	0.049 [30] – 0.21 [85]; 7.6 [86]	/
41	heptanal (111–71-7)	citrus	0.85 [30] – 0.9 [39]; 260 [78]	2.02 – 25.3 [69,75]
42	heptanoic acid (111–14-8)	rancid	22 [35]	/
43	hexanal (capronaldehyde) (66–25-1)	rancid, grass, herb	1.4 – 230 [29,78]; 3.1 [33]	5 – 267 [66,73–75]
44	limonene (138–86-3)	citrus	210 [30]	16 – 29 [79]
45	m/p-xylene (1330–20-7)	sweet	180 – 260 [30]	1.6 – 30.45 [69,70] [69]
46	m-cresol (108–39-4)	horse stable, woody, cork	0.28 [33] – 0.44 [30]	/
47	naphthalene (91–20-3)	musty, mothball, old, old building, tar	450 [35]; 2.3 $\pm$ 0.8 [86]; 1.0 [33]	0.03 [69]
48	n-butyl acetate (123–86-4)	paint, adhesive, banana	10 [46] – 77 [30]	6.75 – 24.78 [69]
49	nonanal (124–19-6)	citrus, grass, herb	2.7 [33] – 3.1 [29]	< 1 – 46.6 [70,75,87]
50	octanal (124–13-0)	fatty, citrus	0.052 [30] – 0.88 [29]; 170 [78]	1.97 – 44.3 [66,75]
51	o-xylene (95–47-6)	sweet	1600 [30]	1.5 [70]
52	phenol (108–95-2)	tar, sweet	21 [30]	18.3 – 58.6 [66]
53	p-cresol (106–44-5)	horse stable	0.24 [30] – 0.36 [30,33]	/
54	propionaldehyde (propanal) (123–38-6)	pungent	2.4 [30] – 4.8 [29]	1.4 – 2.8 [73]
55	R-limonene (5989–27-5)	citrus	45 [88]	/
56	styrene (100–42-5)	pungent, acrid, sweet, plastic	150 [30] – 26,400 [89]	0.32 – 25.4 [66,69,70,73]; 250 [90,91]
57	toluene (108–88-3)	sweet, pungent, acrid	300 [83] – 1300 [30]	0.5 – 130.55 [66,69,70,92]
58	trichloromonofluoromethane (75–69-4)	other cleaning products	/	/
59	trimethylamine (75–50-3)	fish	0.26 – 2100 [86]; 0.077 [30] – 630 [93]; 0.041 – 1.1 [94]	/
60	valeraldehyde (pentanal) (110–62-3)	fruity, musty	1.5 [30] – 850 [78]	2.9 – 72.9 [69,74,75]
61	3-methylbutanal (590–86-3)	smoky, roasted	0.35 – 1.6 [35]	2.8 [70]
62	2-methylpropanal (78–84-2)	smoky, roasted	1.0 [30]	/
63	2-ethylhexyl acetate (103–09-03)	smoky, roasted	50 [95]	/
64	1-pentanol (71–41-0)	plastic	367 [30]	/
65	caprolactam (105–60-2)	chlorine	399.2 [33]	300 [90]
66	4-phenylcyclohexene (4994–16-5)	carpet, textile	2.0 [96]	2.0 [97]

Appendix C. Detection of single substances of the third level of the odour wheel via sensory assessment using the odour wheel in comparison to findings in GC-MS, HPLC and GC-MS-sniffing in 21 rooms

Table 4

Substance list with odour notes and number of findings in the comparison of sensory and analytical assessment

Substance (CAS No.)	Category L ^a 1 – Descriptor L ^a 2 – Odour note L ^a 3	Number of rooms with findings in GC-MS, HPLC / GC-MS-sniffing	Overall number of rooms with analytical findings	Number of rooms with mentions of the odour note by panellists	Number of agreements between sensory and chemical assessment
(+)-alpha-pinene (7785–70-8)	organic – vegetal – conifer, woody	- / -	-	10	-
(E)-2-nonenal / (E)-2-decanal (18829–56-6)	musty – earthy, woody, moist – moist cardboard	2 / 2	3	16	2
1,2,3-trimethylbenzene (526–73-8)	chemical – plastic – rubber	- / 2	2	18	2
1-butanol (71–36-3)	organic – pungent – pungent	9 / 1	10	19	10

(continued on next page)

Table 4 (continued)

Substance (CAS No.)	Category L ¹ – Descriptor L ² – Odour note L³	Number of rooms with findings in GC-MS, HPLC / GC-MS-sniffing	Overall number of rooms with analytical findings	Number of rooms with mentions of the odour note by panellists	Number of agreements between sensory and chemical assessment
1-butanol (71–36-3)	chemical – solvent – pungent, acrid	9 / 1	10	7	4
1-butanol (71–36-3)	chemical – sweet – sweet	9 / 1	10	18	9
1-butoxy-2-propanol (5131–66-8)	organic – fruity – fruity	- / 6	6	14	4
1-chloronaphthalene (90–13-1)	musty – musty – musty	- / -	-	21	-
1-chloronaphthalene (90–13-1)	musty – old – mothball, old, old building	- / -	-	18	-
1-methylnaphthalene (90–12-0)	musty – old – mothball, old, old building	2 / 1	3	18	3
1-methylnaphthalene (90–12-0)	musty – musty – mouldy	2 / 1	3	21	3
1,4-dimethylnaphthalene (571–58-4)	musty – musty – musty	- / -	-	21	-
1,4-dimethylnaphthalene (571–58-4)	musty – musty – mouldy	- / -	-	21	-
2,3,4,5,6-pentachloroanisole (1825–21-4)	musty – earthy, woody, moist – earthy, mouldy	- / -	-	17	-
2,3,4,6-tetrachloroanisole (938–22-7)	musty – earthy, woody, moist – earthy, mouldy	- / -	-	17	-
2,3,4-trichloroanisole (54135–80-7)	musty – earthy, woody, moist – earthy, mouldy	- / -	-	17	-
2,3,6- trichloroanisoles (50375–10-5)	musty – earthy, woody, moist – earthy, mouldy	- / -	-	17	-
2,4,6-trichloroanisoles (87–40-1)	musty – earthy, woody, moist – earthy, mouldy	- / -	-	17	-
2-butanone (78–93-3)	chemical – sweet – sweet	- / -	-	18	-
2-butanone (78–93-3)	organic – fruity – sweet	- / -	-	18	-
2-butanone oxime (96–29-7)	chemical – solvent – paint, adhesive	- / -	-	18	-
2-butoxyethanol (111–76-2)	organic – fatty – rancid	- / -	-	11	-
2-butoxyethanol (111–76-2)	chemical – sweet – sweet	- / -	-	18	-
2-ethylhexanol (104–76-7)	organic – vegetal – menthol, fresh	9 / 1	9	7	2
2-ethylhexanol (104–76-7)	chemical – plastic – rubber	9 / 1	9	18	7
2-ethylhexanol (104–76-7)	chemical– plastic – PVC	9 / 1	9	20	9
2-methyl-1-propanol (78–83-1)	musty – earthy, woody, moist – moist mineral based building products	- / -	-	16	-

(continued on next page)

Table 4 (continued)

Substance (CAS No.)	Category L ^a 1 – Descriptor L ^a 2 – Odour note L^a3	Number of rooms with findings in GC-MS, HPLC / GC-MS-sniffing	Overall number of rooms with analytical findings	Number of rooms with mentions of the odour note by panellists	Number of agreements between sensory and chemical assessment
2-methylnaphthalene (91–57-6)	musty – musty – musty	2 / 1	2	21	2
2-methylnaphthalene (91–57-6)	musty – musty – mouldy	2 / 1	2	21	2
2-methylnaphthalene (91–57-6)	musty – old – mothball, old, old building	2 / 1	2	18	2
2-phenoxyethanol (122–99- 6)	chemical – plastic – rubber	- / -	-	18	-
2-phenoxyethanol (122–99- 6)	chemical – solvent – pungent, acrid	- / -	-	7	-
2-phenoxyethanol (122–99- 6)	organic – pungent – pungent	- / -	-	19	-
2-propanol (isopropanol) (67–63-0)	chemical – cleaning products – medicine	- / 1	1	14	-
2-propanol (isopropanol) (67–63-0)	chemical – cleaning products – disinfectant	- / 1	1	9	-
acetaldehyde (75–07-0)	organic – pungent – pungent	21 / 5	21	19	19
acetaldehyde (75–07-0)	organic – vegetal – flowery, floral	21 / 5	21	12	12
acetone (67–64-1)	chemical – solvent – nail polish	1 / 1	1	6	-
acetophenone (98–86-2)	chemical – sweet – sweet	14 / 5	14	18	11
acrolein (acrylic aldehyde) (107–02-8)	chemical – sweet – sweet	7 / 1	8	18	7
acrolein (acrylic aldehyde) (107–02-8)	burnt – burnt – burnt	7 / 1	8	5	4
alpha-pinene (dimer) (80–56-8)	organic – vegetal – conifer, woody	3 / 7	7	10	3
benzaldehyde (100–52-7)	organic – nutty – almond, marzipan	- / 2	2	2	-
benzothiazole (95–16-9)	chemical – plastic – rubber	- / 5	5	18	4
beta-pinene (127–91-3)	organic – vegetal – conifer, woody	- / 1	1	10	-
butanoic acid (107–92-6)	organic – sour – lactic, milky	4 / 3	6	2	-
butyraldehyde (butanal) (123–72-8)	organic – pungent – pungent	20 / 11	20	19	18
caproic acid (142–62-1)	organic – animal – goat	1 / -	1	6	-
caproic acid (142–62-1)	organic – sour – sweaty, cheesy	1 / -	1	15	1
caproic acid (142–62-1) ^b	organic – sour – sour	1 / -	1	^b	^b
decanal (112–31-2)	organic – fruity – citrus	20 / 3	20	7	6

(continued on next page)

Table 4 (continued)

Substance (CAS No.)	Category L ¹ – Descriptor L ² – Odour note L³	Number of rooms with findings in GC-MS, HPLC / GC-MS-sniffing	Overall number of rooms with analytical findings	Number of rooms with mentions of the odour note by panellists	Number of agreements between sensory and chemical assessment
decanal (112–31-2)	organic – vegetal – grass, herb	20 / 3	20	8	8
delta-3-carene (13466–78-9)	chemical – sweet – sweet	- / 1	1	18	1
delta-3-carene (13466–78-9)	organic – vegetal – conifer, woody	- / 1	1	10	-
DL-limonene (7705–14-8)	organic – fruity – citrus	- / -	-	7	-
DL-limonene (7705–14-8)	chemical – cleaning products – citrus	- / -	-	9	-
acetic acid (64–19-7)	organic – pungent – vinegar	13 / 12	19	9	7
ethyl acetate (141–78-6)	chemical – solvent – nail polish	- / -	-	6	-
ethylbenzene (100–41-4)	chemical – crude oil products – petrol, gasoline	2 / -	2	3	2
formaldehyde (50–00-0)	chemical – cleaning products – disinfectant	9 / -	9	9	6
geosmin (19700–21-1)	musty – earthy, woody, moist – earthy, mouldy	- / 1	1	17	1
heptanal (111–71-7)	organic – fruity – citrus	20 / 4	20	7	7
heptanoic acid (111–14-8)	organic – fatty – rancid	- / -	-	11	-
hexanal (capronaldehyde) (66–25-1)	organic – fatty – rancid	21 / 16	21	11	11
hexanal (capronaldehyde) (66–25-1)	organic – vegetal – grass, herb	21 / 16	21	8	8
limonene (138–86-3)	organic – fruity – citrus	1 / 2	2	7	1
limonene (138–86-3)	chemical – cleaning products – citrus	1 / 2	2	9	1
m/p-xylene (1330–20-7)	chemical – sweet – sweet	- / -	-	18	-
m-cresol (108–39-4)	organic – animal – horse stable	3 / 2	3	6	2
m-cresol (108–39-4)	musty – earthy, woody, moist – cork	3 / 2	3	16	2
m-cresol (108–39-4)	organic – vegetal – woody, cork	3 / 2	3	19	3
naphthalene (91–20-3)	musty – musty – musty	7 / 5	8	21	8
naphthalene (91–20-3)	musty – old – mothball, old, old	7 / 5	8	18	7
naphthalene (91–20-3)	chemical – crude oil products – tar	7 / 5	8	5	3
n-butyl acetate (123–86-4)	organic – fruity– banana	2 / -	2	2	-

(continued on next page)

Table 4 (continued)

Substance (CAS No.)	Category L ¹ – Descriptor L ² – Odour note L³	Number of rooms with findings in GC-MS, HPLC / GC-MS-sniffing	Overall number of rooms with analytical findings	Number of rooms with mentions of the odour note by panellists	Number of agreements between sensory and chemical assessment
n-butyl acetate (123–86-4)	chemical– plastic – paint, adhesive	2 / -	2	18	1
nonanal (124–19-6)	organic – vegetal – grass, herb	20 / 13	20	8	8
nonanal (124–19-6)	organic – fruity – citrus	20 / 13	20	7	7
octanal (124–13-0)	organic – fruity – citrus	20 / 13	20	7	6
octanal (124–13-0)	organic – fatty – fatty	20 / 13	20	6	6
o-xylene (95–47-6)	chemical – sweet – sweet	- / 4	4	18	3
o-xylene (95–47-6)	burnt – smoky, roasted – sweet	- / 4	4	10	2
phenol (108–95-2)	chemical – sweet – sweet	1 / 2	3	18	2
phenol (108–95-2)	chemical – crude oil products – tar	1 / 2	3	5	1
p-cresol (106–44-5)	organic – animal – horse stable	- / 1	1	6	-
propionaldehyde (propanal) (123–38-6)	organic – pungent – pungent	8 / -	8	19	8
R-limonene (5989–27-5)	chemical – cleaning products – citrus	3 / 3	4	9	2
R-limonene (5989–27-5)	organic – fruity – citrus	3 / 3	4	7	3
styrene (100–42-5)	chemical – plastic – plastic	1 / 2	3	19	3
styrene (100–42-5)	chemical – solvent pungent, acrid	1 / 2	3	7	-
styrene (100–42-5)	chemical – sweet – sweet	1 / 2	3	18	3
toluene (108–88-3)	chemical – sweet – sweet	- / 2	2	18	2
toluene (108–88-3)	chemical – solvent – pungent, acrid	- / 2	2	7	-
trichloromono-fluoro- methane (75–69-4)	chemical – cleaning products – other cleaning products	- / -	-	12	-
trimethylamine (75–50-3)	organic – animal – fish	- / -	-	2	-
valeraldehyde (pentanal) (110–62-3)	organic – fruity – fruity	17 / 1	17	14	10
valeraldehyde (pentanal) (110–62-3)	musty – musty – musty	17 / 1	17	21	17
3-methylbutanal (590–86-3)	burnt – smoky, roasted – smoky, roasted	13 / 4	13	7	4
2-methylpropanal (78–84-2)	burnt – smoky, roasted – smoky, roasted	14 / 1	14	7	3

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Table 4 (continued)

Substance (CAS No.)	Category L ^a 1 – Descriptor L ^a 2 – Odour note L ^a 3	Number of rooms with findings in GC-MS, HPLC / GC-MS-sniffing	Overall number of rooms with analytical findings	Number of rooms with mentions of the odour note by panellists	Number of agreements between sensory and chemical assessment
2-ethylhexyl acetate (103–09-03)	burnt – smoky, roasted – smoky, roasted	1 / 1	2	7	-
1-pentanol (71–41-0)	chemical – plastic – plastic	1 / 4	5	19	5
caprolactam (105–60-2) ^b	chemical – cleaning products – chlorine	b	b	b	b
4-phenylcyclohexene (4994–16-5) ^b	chemical – plastic – carpet, textile	b	b	b	b

^a L1 to L3 represent levels 1–3 of the odour wheel

^b No data available, substance or odour note was added to the odour wheel retrospectively

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