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Quantification of odorous and potentially harmful substances in acrylic paint

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ABSTRACT

Within this study sixteen odour active substances (1-butanol, butyl acetate, 3-methyl-4-heptanone, butyl acrylate, styrene, ethylbenzene, propylbenzene, cumene, sec-butylbenzene, benzaldehyde, 2-ethylhexyl acrylate, naphthalene, 1-methylnaphthalene, 2-methylnaphthalene, 1,2-dimethylnaphthalene, 1,7-dimethylnaphthalene), that have previously been identified in acryl paints were quantified in ten black acrylic paint samples using GC-GC-MS (heart-cut two-dimensional gas chromatography-mass spectrometry) after prior extraction and purification via solvent assisted flavour evaporation. In this case, the preceding analysis of the most abundant odour active volatiles via GC-O (gas chromatography-olfactometry) provided indications on which smell properties might be linked with elevated and concerning levels of possibly harmful substances. Based on that work, four samples raised attention due to their mainly repelling or unpleasant odour with mainly *aromatic, solvent-like, mothball-like* or *geranium-like* smell impressions. The remaining samples either showed *fruity/fermented*, *fruity/apple juice-like, mushroom-like or cocoa-like/earthy* odour qualities. The repelling and unpleasant odour was generally linked to naphthalene or benzene derivatives that are of concern with regard to being potential carcinogens. With concentrations ranging as high as from 3.75 mg/kg to 143.41 mg/kg, *n*-butanol was found to be the odour active substance with the highest concentrations in all but one paint sample. The results showed that all paints contain different and specific patterns of the analysed odour active substances and volatiles. Whereas only two samples revealed no elevated concentration of any of the quantified substances, two samples (A9 and A10) showed elevated levels for all or nearly all substances. The concentrations for single substances were generally lower than the recommended exposure limit and therefore unlikely to cause any adverse effects with regards to toxicity and irritation as single constituents. However, as a group of substances these might exert adverse health effects due to combined or synergistic effects. Based on these observations, the occurrence of combinations of potentially carcinogenic substances in products which are occupationally used on a daily basis or are in direct skin contact should thus be regarded with care in the future.

1. Introduction

Volatile organic compounds (VOCs) are ubiquitous and can induce the perception of odour impressions if their chemical structure allows interaction with the respective odour receptors. Moreover, they might elicit trigeminal sensations when activating the nervus trigeminus leading to so-called chemesthetic sensations such as irritation, burning or cooling (Simons and Carstens, 2020; Green, 1996). However, due to their volatility, the uptake of odourless VOCs via the respiratory system might remain unnoticed and lead to acute or long-term intoxication symptoms (Norback and Edling, 1991; Wieslander et al., 1997). Exposure to certain volatile compounds of natural products, e.g. as part of the smell of the forest, has been shown to positively impact cerebral activity and salivary cortisol levels, and has therefore been related to relaxation of the human body and spirit (Park et al., 2007). In contrast, several synthetic materials have been shown to elicit unpleasant odours that can be caused by substances that have also been shown to negatively impact the wellbeing and human health (Bauer and Buettner, 2018; Denk and Buettner, 2017; Wiedmer and Buettner, 2018). Furthermore, different volatile substances and sources of indoor exposures have been tested

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regarding their correlation to the development of certain diseases. For example, physiological effects in association with specific interior surface materials and their emissions have been tested in many different countries recruiting large cohort studies. The findings show that volatile plasticizers used in PVC might lead to bronchial obstruction and asthma in children (Jaakkola et al., 1999) or a higher incidence rate of eczema (Choi et al., 2014). Furthermore, a survey study conducted in China showed that the usage of interior wall paints also might be associated with a higher incidence of asthma among children (Sun et al., 2019).

However, beyond respiratory uptake of volatile compounds, skin contact to different constituents of synthetic materials might also impact the customer. It has been shown that acrylic monomers, which can be used in acrylic nails or paints, can lead to skin irritation or contact dermatitis. Although the highest reactivity rate of allergic contact dermatitis (ACD) was caused by methacrylates, also 2-hydroxyethyl acrylate, triethyleneglycol diacrylate and ethyl acrylate showed an elevated incidence rate of ACD symptoms (Ramos et al., 2014; Rycroft, 1977; Nakamura et al., 1999; Tosti et al., 1993). Thereby, occupational ACD occurred in cases where repetitive and long skin contact of acrylate monomers was observed, e.g. while working on or wearing artificial acrylic finger nails or while spray painting (Ramos et al., 2014; Nakamura et al., 1999). Furthermore, BTEX (benzene, toluol, ethylbenzene and xylol isomers) substances, which are known for their toxic, carcinogenic or reprotoxic effects, were identified in finger paints for children (Pastor-Belda et al., 2019). Even though content levels were in a range from 0.14 ng/g to 12 ng/g, the occurrence of potentially hazardous substances in products designed for skin contact with children should be critically regarded.

In a recent study of our group six acrylic paints were analysed regarding their odour active compounds. The results showed that the paints did not only smell repulsive and were generally rated with a low hedonic score, but we also revealed that the odour was caused by a diverse mixture of constituents (Bauer and Buettner, 2018). Among the identified substances, benzene derivatives were found to affect the overall odour of the paints. Among these substances, styrene, sec-butylbenzene, ethylbenzene and propylbenzene were the most abundant and contributed to the smell of some of the paints. Furthermore, naphthalene and its derivatives 1-methylnaphthalene, 2-methylnaphthalene, 1,2-dimethylnaphthalene and 1,7-dimethylnaphthalene could be identified as important odorants. Moreover, the acrylic monomers butyl acrylate and 2-ethylhexyl acrylate contributed to the overall odour. In two of the samples butyl acrylate was even the main odorant. Benzaldehyde, 3-methyl-4-heptanone and 1-butanol were additionally identified in the paint samples. Since especially benzene and naphthalene derivatives might lead to adverse effects on human health, the question arises, how high the concentrations of these substances in the analysed paints are, and therefore exposure to these substances resulting therefrom, and if these might be high enough to show an effect on human health.

To the best of our knowledge, no prior study focused on the quantification of the odorous volatile substances in acrylic hobby paint. Therefore, we quantified the odour active compounds in a set of ten different black acrylic paints within this study to estimate possible adverse health effects.

2. Material and methods

2.1. Chemicals

Dichloromethane (DCM) and anhydrous sodium sulfate were purchased from VWR (Darmstadt, Germany). Prior to use, DCM was distilled freshly to improve its purity and separate potential odorous substances from the solvent. Benzaldehyde, [$^{13}C_1$, $^{2}H_1$]-benzaldehyde, butanol, [$^{2}H_{10}$]-butanol, butyl acrylate, butyl acetate, 1,2-dimethylnaphthalene, 1,4-dimethylnaphthalene, isobutylbenzene, 1-methylnaphthalene, [$^{2}H_{10}$]− 1-methylnaphthalene-d, 2-methylnaphthalene, [$^{2}H_8$]-naphthalene-, propylbenzene and styrene were supplied by Sigma-Aldrich (Steinheim, Germany). The substances [$^{2}H_{12}$]-cumene, 1,7-dimethylnaphthalene, [$^{2}H_8$]-ethylbenzene, 3-methyl-4-heptanone and [$^{2}H_8$]-styrene were purchased from abcr (Karlsruhe, Germany). Cumene, ethylbenzene and 3-methyl-4-heptanone were obtained from TCI (Zwijndrecht, Belgium). We obtained *sec*-butylbenzene from Th. Geyer (Renningen, Germany). All substances were at least of analytical grade. The standards [$^{2}H_9$]-butyl acrylate, [$^{2}H_9$]-butyl acetate and 2-ethylhexyl propionate were synthesized since no standards were commercially.

2.2. Samples

We quantified the odour active substances in ten acrylic paints from different suppliers (P1–10). The samples were purchased via online suppliers in Germany and covered different types of paint regarding quality, price and declared drying properties, therefore representing a wide range of the market. All analysed paints contained black colouring pigments that are further specified as follows: Seven paints contained carbon black, two paints mars black and one paint lamp black as their colouring pigment. The closed paints were stored for a maximum of four weeks at room temperature before they were worked up for analysis.

2.3. Samples preparation

The paint samples were prepared by mixing an aliquot of 0.5–2.5 g paint with 15–45 ml dist. water and stirred at room temperature until a homogenous suspension was obtained. The thinned paint was then mixed with the internal standards (see Table 2). Standard solutions were prepared by diluting each standard with DCM. Isotopic labelled standards were used where available or were synthesised accordingly. Any type of recovery of odorous substances underlies loss of substance, comprising extraction and distillation, as well as concentration steps. To compensate for the losses, the addition of isotopic labelled substances is accordingly recruited as quantification strategy. The amount of internal standard that was added to the mixture was determined for each sample by semi-quantitative evaluations using GC-MS screenings. Depending on the used amount of paint, 40–70 ml of DCM were added, and the mixture was stirred for 60 min at ambient temperature. The phases were separated and the aqueous phase was washed twice with 25 ml of DCM each time. The organic phases were combined, resulting in a total volume of 90–120 ml. The non-volatile compounds were separated from the extract via a high vacuum distillation system using the solvent assisted flavour evaporation (SAFE) technique at 50 °C (Engel et al., 1999). The obtained distillates were then dried over anhydrous sodium sulfate and concentrated to a volume of 100 μl by means of Vigreux distillation and

Table 1
Used pigments and most abundant odour qualities detected in GC-O analysis.

Paint no.	Used Pigment	Strongest odour according to GC-O
A1	Mars Black	fruity/apple juice-like, aromatic, earthy/cocoa-like
A2	Mars Black	fruity, aromatic, earthy/cocoa-like
A3	Carbon Black	fruity, earthy/cocoa-like
A4	Carbon Black	aromatic/solvent-like, fruity, mushroom-like
A5	Carbon Black	aromatic/solvent-like, mushroom-like, fruity
A6	Carbon Black	fruity/apple juice-like, aromatic/solvent-like
A7	Lamp Black	fruity, earthy/cocoa-like
A8	Carbon Black	fruity/fermented, earthy/cocoa-like, mothball-/naphthalene-like
A9	Carbon Black	aromatic/solvent-like, fruity, mothball-/naphthalene-like
A10	Carbon Black	aromatic/solvent-like, mushroom-like/geranium-like, fruity

Table 2
m/z-ratios and retention indices that were used for the identification and quantification of the listed substances.

		Retention index[a] of the target substance	
Target substance /internal standard	*m/z*-ratio used for SIM	FFAP	DB-5
1-butanol / 1-butanol-d_{10}	56 / 64	1143	n.d.[b]
butyl acetate/ butyl-d_9 acetate	73 / 75	1067	825
3-methylheptan-4-one /2-methylheptan-4-one	128 / 128	1142	931
butyl acrylate/ butyl-d_9 acrylate	73 / 75	1175	903
styrene / styrene-d_{12}	104 / 112	1249	892
ethylbenzene / ethylbenzene-d_8	91 / 98	1120	858
propylbenzene / propylbenzene-d_8	91 / 93	1196	957
cumene / cumene-d_{12}	120 / 132	1166	929
sec-Butylbenzene /iso-butylbenzene	105 / 92	1237	1008
benzaldehyde /benzaldehyde-$d_1^{13}C_1$	106 / 108	1511	957
2-ethylhexyl acrylate /2-ethylhexyl propionate	112 / 112	1469	1232
naphthalene / naphthalene-d_{10}	128 / 136	1728	1178
1-methylnaphthalene /1-methylnaphthalene-d_{10}	142 / 152	1857	1316
2-methylnaphthalene /1-methylnaphthalene-d_{10}	142 / 152	1835	1292
1,2-dimethylnaphthalene /1,4-dimethylnaphthalene	141 / 141	2055	1452
1,7-dimethylnaphthalene /1,4-dimethylnaphthalene	141 / 141	1978	1411

[a] Retention index as described by van den Dool and Kratz (van Den Dool and Dec. Kratz, 1963)
[b] n.d.: not detectable due to coeluation with the solvent peak

micro distillation (Bemelmans JMH, 1979). The distillates were stored at − 80 °C and analysed within two weeks after workup. Each paint sample was prepared as two replicates.

2.4. Gas chromatography-mass spectrometry (GC-MS) for semi-quantitative evaluations

A 7890 A GC-System (Agilent, Waldbronn Germany) equipped with either a DB-5 or DB-FFAP capillary column (30 m, 0.32 mm i.d., 0.25 µm film thickness) was used for gas chromatography-mass spectrometry analysis. A sample volume of 1 µl was automatically applied on a pre-column (deactivated fused silica capillary, 2–3 m, 0.32 mm) using the cold on-column technique. The injection in the Cooled Injection System CIS4 (Gerstel, Duisburg, Germany) was performed using a multi-purpose sampler (MPS, Gerstel, Duisburg, Germany). The temperature program was as follows: The initial temperature of 40 °C was held for 5 min and was raised with a rate of 8 °C/min thereafter. When using a DB-5 column, the final temperature of 300 °C was held for 5 min, whereas the oven temperature in case of the DB-FFAP column was held at 240 °C for 5 min. Helium was used as carrier gas at a constant flow of 1 ml/min. Mass spectra were generated using an Agilent 5975 C MSD quadrupole mass spectrometer (Agilent, Waldbronn, Germany) in full scan mode ($m/z = 30–350$) in the electron ionization (EI) mode at an ionization energy of 70 eV. For identification, the mass spectra and retention indices of the unknown odorants were compared to those of reference substances analyzed under identical conditions. Analytes were classified as identified, if they showed a match that was greater than 92% and a maximum RI difference of five. If no standards were available, the NIST 14 database was used for identification.

2.5. Heart-cut two-dimensional gas chromatography-mass spectrometry/olfactometry (GC-GC-MS/O)

The quantification was carried out using a two-dimensional gas chromatography system that consisted of two Agilent 7890B gas chromatographs (Agilent Technologies, Santa Clara, USA) that were connected via a cryogenic trap system (CTS, Gerstel GmbH & Co. KG, Mühlheim an der Ruhr, Germany). Helium was used as carrier gas for both GCs at a constant flow of 2.5 ml/min for the first and 1.2 ml/min for the second system. An aliquot of 2 µl was applied via a multi-purpose sampler (MPS, Gerstel) directly onto a precolumn (deactivated fused silica capillary, 3 m 0.32 mm i.d.) using the cold-on-column injection. The first GC system was equipped with a DB-FFAP column (30 m, 0.32 mm i.d., 0.25 µm film thickness, Agilent Technologies). The initial temperature of 40 °C was held for 2 min and raised with a rate of 8 °C/min to the final temperature of 240 °C, that was held for 5 min. The effluent was transferred to a multi-column switching system (MCS, Gerstel), and further either to the cryo trap system (CTS) or to a Y-splitter that directed the gas flow to both, a flame ionization detector (FID) and an olfactory detection port (ODP). The FID and ODPs were held at a temperature of 250 °C and 270 °C, respectively. The CTS was used to transfer the analytes of interest from the first to the second system. To separate the analytes in the second system, a DB-5 column was used (30 m, 0.25 mm i.d., 0.25 µm film thickness, Agilent Technologies) starting with a temperature of 40 °C for 1 min. The temperature was then raised at a rate of 8 °C to the final temperature of 300 °C, which was held for 5 min. Thereafter, the effluent was split using a Y-splitter and led to an ODP and an Agilent 5977B mass spectrometer. The mass spectrometer was operated with an ionization energy of 70 eV (EI mode). For identification and semi-quantitative analyses the MSD was operated at full scan mode recording spectra at *m/z* values from 35 to 350. Analytical standards were used for identification by comparing the retention indices on two columns of different polarity as well as the mass spectra of the standards with the substances found in the samples. Prior to the quantification, all samples were tested in TIC (total ion current) mode to scan the analysed samples regarding potential overlaps in the mass spectra so that an artificial increase of specific *m/z* values, deemed as being used as quantifier, by coeluting non-target substances could be avoided. For quantification, the mass spectrometer was operated in single ion monitoring (SIM) mode recording the most abundant *m/z* value for each target substance during their corresponding retention time ± 0.5 min. As the concentrations of the target substances varied widely between the analysed samples, and were rather low in some cases, SIM mode was used where appropriate to increase sensitivity. The *m/z* values used for quantification are given in Table 2. Exemplary chromatograms for both dimensions are given in Fig. 1.

Each sample was prepared in duplicates and each of these extracts was measured once with blank runs in between. The calibration solutions of the target substances and standards were prepared in DCM with standard/analyte ratios of approximately 5:1, 2:1, 1:1, 1:2 and 1:5 based on the concentrations that were estimated in semi-quantitative evaluations. The calibration standards were measured once. All calibration curves showed a linear regression with a coefficient of determination above 0.999.

All samples with a detectable amount of the analytes showed a signal-to-noise ratio of at least 18, so that the LOQ was not determined separately.

2.6. Gas-Chromatography Olfactometry (GC-O)

For gas chromatography-olfactometry a Trace Ultra GC (Thermo Finnigan, Dreieich, Germany) equipped with a DB-5 capillary column (30 m, 0.32 mm i.d., 0.25 µm film thickness, J&W Scientific, Fisons Instruments, Mainz-Kastel, Germany) was used. Samples were applied using the cold on-column technique (40 °C). An aliquot of 2 µl of the samples was manually injected on a pre-column (deactivated fused silica capillary, 3 m, 0.32 mm). The initial temperature of 40 °C was held for 5 min and was then raised with a rate of 8 °C/min to 200 °C. Thereafter, the temperature was raised by 15 °C/min until the oven reached the final temperature of 300 °C. This temperature was held for 5 min. Helium was used as carrier gas at a constant flow of 2.5 ml/min. To detect

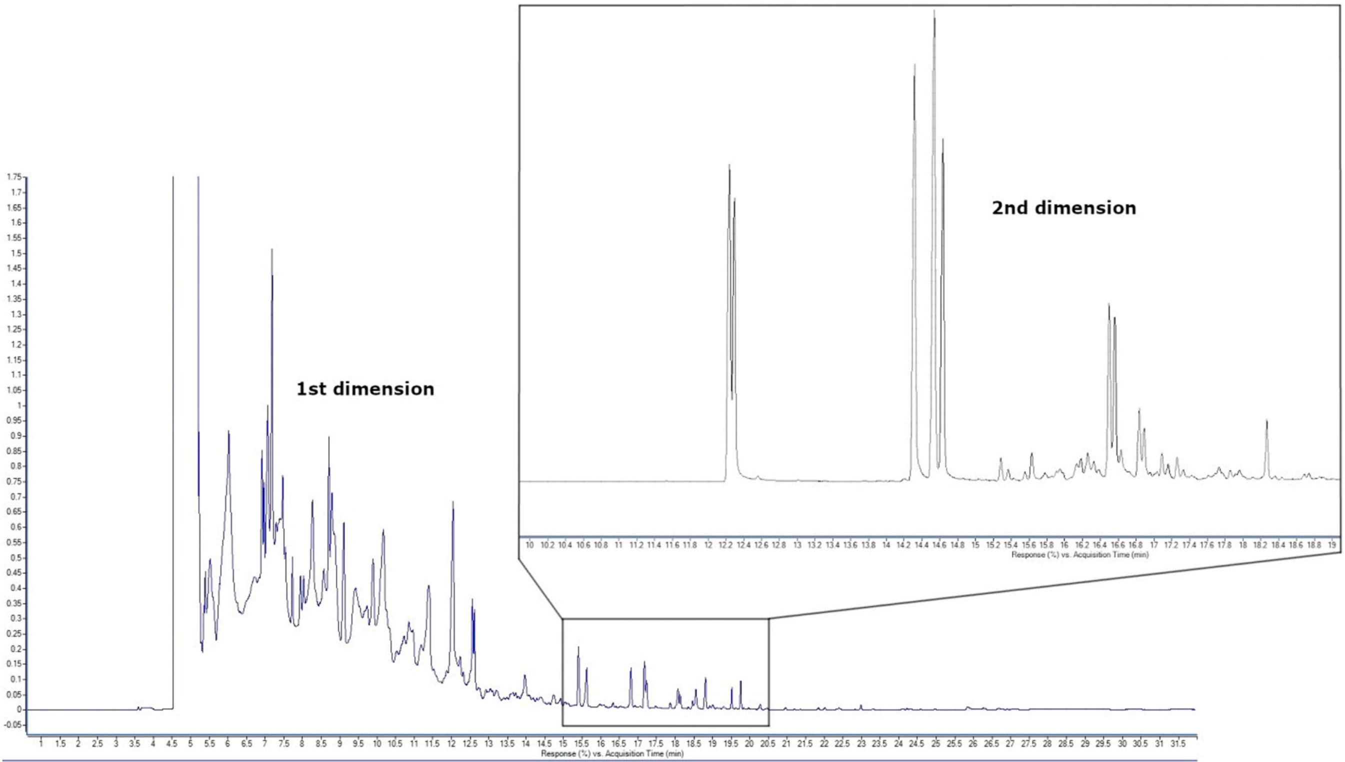

Fig. 1. Exemplifying chromatograms of one paint sample. Since extracted substances are co-eluting in the first dimension (left), the target substances are transferred to a second dimension using a cryo trap. Using a column with a different polarity allows target substances to separate in the second dimension.

the odorous substances in the samples, the effluent was split after the analytical column by a glass Y-splitter and led to a flame ionization detector (FID) and a sniffing port using two deactivated fused silica capillaries (0.7 m, 0.32 mm). Both detectors were held at a temperature of 250 °C.

2.7. *Synthesis of analytical standards*

To compensate for the losses during the workup process, isotopic labelled substances were used to obtain reliable results. Since there were no isotopic labelled standards available for butyl acrylate, butyl acetate and 2-ethylhexyl acrylate, the isotopic labelled analogues were synthesized for butyl acrylate and butyl acetate. Due to their similar structure and properties, we synthesized and used 2-ethylhexyl propionate as the internal standard for 2-ethylhexyl acrylate. The purity of all standards was controlled via ^{1}H NMR and GC-MS. The isotopic purity was further confirmed by GC-MS analyses.

2.7.1. *Synthesis of [$^2H_9$]-butyl acrylate*

We synthesized the standard following the synthesis route described by Xiao et al (Xiao et al., 2015). Triethylamine (4.5 mmol, 0.455 g) and 1-butanol-d_{10} (2.7 mmol, 0.223 g,) were dissolved in dichloromethane (DCM, 10 ml), and cooled in an ice-water bath to 0 °C. Acryloyl chloride (3.6 mmol, 0.33 g) was added dropwise and the mixture was stirred for five minutes before the ice bath was removed. The mixture was then allowed to warm to room temperature and was stirred overnight. The reaction was terminated by the addition of 2 ml of water. The phases were separated and the organic phase was dried with anhydrous sodium sulfate. The organic solvent was removed under reduced pressure and the crude product was purified by column chromatography (silica gel; petroleum ether / ethyl acetate = 30:1). We obtained 1.46 mmol (200 mg, yield: 54%) of the isotopic labelled standard butyl-d_9 acrylate as a clear liquid.

2.7.2. *Synthesis of [$^2H_9$]-butyl acetate*

Dichloromethane (10 ml) was cooled down to 0 °C in an ice-water bath. Then, trimethylamine (4.5 mmol, 0.455 g) and 1-butanol-d_{10} (3.0 mmol, 0.252 g) were added to the DCM and completely dissolved. Acetyl chloride (3.6 mmol, 0.283 g) was then added dropwise and the mixture was stirred for five minutes before the ice bath was removed. The mixture was allowed to warm to ambient temperature and was stirred overnight. The excess acetyl chloride was deactivated by the addition of 2 ml of water. The phases were separated and the aqueous phase was washed twice with 2.5 ml of DCM each time. The combined organic phases were then dried with anhydrous sodium sulfate, and the organic solvent was removed under reduced pressure. The crude product was purified by column chromatography (silica gel; petroleum ether / ethyl acetate = 30:1). We obtained 2.26 mmol (172.3 mg, yield: 45.9%) of the isotopic labelled standard butyl-d_9 acetate as a clear liquid.

2.7.3. *Synthesis of 2-ethylhexyl propionate*

A mixture of 10 ml DCM, trimethylamine (4.5 mmol, 0.455 g) and 2-ethylhexanol (3.0 mmol, 0.391 g) was cooled down to 0 °C in an ice-water bath. Propionyl chloride (3.6 mmol, 0.333 g) was added dropwise and the mixture was stirred for 5 min before it was allowed to warm up to room temperature and stir overnight. The reaction was terminated by the addition of 2 ml of water. The phases were separated and the organic phase was dried with anhydrous sodium sulfate. The crude product was purified by column chromatography (silica gel; petroleum ether / ethyl acetate = 30:1). We obtained 1.38 mmol (421.0 mg, yield: 75.3%) of the standard 2-ethylhexyl propionate as a clear liquid.

3. Results

3.1. *GC-O analyses*

For the GC-O analyses the three most abundant odour qualities were considered. Four samples (A4, A5, A9 and A10) showed *aromatic,* *solvent-like, mothball-like* or *geranium-like* and therefore a mainly repelling and unpleasant odour in the GC-O experiments. The remaining samples were described with either *fruity/fermented*, *fruity/apple juice-like, mushroom-like or cocoa-like/earthy* odour qualities.

3.2. Quantification

The relative standard deviation of the duplicates was generally below 5%. For samples with higher relative standard deviations, the standard deviation is given in Table 3. Among all analysed substances, 1-butanol was found with the highest concentrations in nine of the ten analysed paints. Hereby, the concentrations ranged from 3.75 mg/kg to 326.74 mg/kg between all samples. Butyl acetate as well as 3-methyl-4-heptanone could be detected in all analysed paint samples. Whereas butyl acetate was found in concentrations ranging from 0.55 mg/kg to 18.13 mg/kg, 3-methyl-3-heptanone showed lower concentrations in a range of 0.01 mg/kg to 0.45 mg/kg. Butyl acrylate was detected in nine out of ten paint samples and was present in concentrations between 0.01 mg/kg and 26.5 mg/kg, whereas 2-ethylhexyl acrylate was only detected in five samples ranging between concentrations from 0.03 mg/kg and 98.9 mg/kg. However, 2-ethylhexyl acrylate revealed the highest concentration in paint sample 10. Four benzene derivatives, namely styrene, ethylbenzene, propylbenzene and cumene, were determined in nearly all analysed samples with concentrations within the range from 0.01 mg/kg to 10.93 mg/kg. Benzaldehyde showed concentrations in a range of 0.06 mg/kg up to 18.64 mg/kg, and could be detected in all samples. Naphthalene and its methylated derivatives 1-methylnaphthalene and 2-methylnaphthalene could be detected in eight, three and five paint samples, respectively. The concentrations of naphthalene were generally higher than those of its methylated derivatives in all but one sample. Overall, their concentrations ranged from 0.012 mg/kg to 12.5 mg/kg. The derivatives 1,2-dimethylnaphthalene and 1,7-dimethylnaphthalene were detected in two and three samples respectively, showing concentrations between 0.13 mg/kg and 1.16 mg/kg.

4. Discussion

4.1. GC-O analysis

Prior to quantification, all investigated paints were analysed regarding odour active substances via GC-O. Overall, four paints (A4, A5, A9 and A10) showed mainly odour qualities that were characterized as repelling or unpleasant during the GC-O experiments. The samples were described as *aromatic* and *solvent-like* as one of their most prominent odour qualities. This odour can be traced back to styrene, ethylbenzene, propylbenzene, cumene and sec-butylbenzene, which were described to elicit corresponding odour impressions, and were detected in elevated concentrations within these samples. Furthermore, *mothball-like* odours were detected in A8, A9 and A10. These samples were found to contain the highest concentrations of naphthalene and its methylated derivatives within this study. As naphthalene and its derivatives are known to elicit such odour qualities, the elevated concentration could be linked to the *mothball-like* odour of the samples. Sample A1, on the other hand, also showed elevated naphthalene concentrations but was not described as smelling *mothball-like.* This was due to the fact that the odour quality was less prominent as in case of samples A8–10, and was rather dominated by other smell impressions so that the *mothball-like* quality was not specifically listed. The *mushroom-like* odour was predominantly observed in A4, A5 and A10 and accordingly in samples that contained the highest concentrations of butyl acrylate. The *mushroom-like* odour was complemented by *geranium-like* nuances caused by elevated levels of 2-ethylhexyl acrylate. The remaining paint samples were predominantly described as *fruity/fermented* or *fruity/apple juice-like* and corresponded with odour qualities that were elicited by *n*-butanol, 3-methyl-4-heptanone and butyl acetate. Since *n*-butanol showed the highest concentrations of all analysed substances, it occurred as the main odorous substance in most samples as long as no elevated concentrations of alkylated benzene derivatives or naphthalene derivatives were detected. In samples that contained elevated concentrations of 3-methyl-4-heptanone and butyl acetate (A6), the odour

Table 3
Concentration of all analyzed substances in the investigated samples.

	Concentration in mg/kg									
Substance	A1	A2	A3	A4	A5	A6	A7	A8	A9	A10
1-Butanol	125.24	136.21	79.70	80.34	87.23	326.74	3.75	12.55	143.41	59.42
Butyl acetate	0.40	0.45	1.34	0.44 ± 0.03	6.24	18.13	0.14	1.23	0.55	8.34
3-Methyl-4-heptanone	0.22	0.36	0.06	0.03 ± 0.003	0.06	2.67	0.01	0.03 ± 0.001	0.45 ± 0.04	0.32
Butyl acrylate	n.d.	0.20	0.01 ± 0.001	1.11	26.5	0.03 ± 0.002	0.12	0.17 ± 0.009	0.04	7.19
Styrene	0.08	0.09 ± 0.01	0.14 ± 0.01	0.03 ± 0.001	11.61	4.32	n.d.	0.04	10.66	0.59
Ethylbenzene	0.04	0.10	n.d.	0.92 ± 0.01	5.31	0.22	0.02	0.02	10.93	10.89
Propylbenzene	0.02	0.02	n.d.	0.65	0.06	0.06	n.d.	0.01 ± 0.0005	6.89	4.3
Cumene	0.07 ± 0.004	0.18	0.01	0.99 ± 0.07	0.06	0.08	0.01	0.01	4.33 ± 0.22	5.87
sec-Butylbenzene	n.d.	n.d.	n.d.	0.090	n.d.	0.011 ± 0.002	n.d.	n.d.	2.91 ± 0.44	0.85
Benzaldehyde	0.34	1.08	0.29	1.54	3.79	10.47	0.06	0.31	18.64	16.23
2-Ethylhexyl acrylate	0.03 ± 0.002	n.d.	n.d.	n.d.	0.57	n.d.	n.d.	1.80	0.44	98.9 ± 9.0
Naphthalene	0.38	0.023	0.017	n.d.	n.d.	0.12	0.012 ± 0.001	0.31 ± 0.02	7.02	0.18
1-Methylnaphthalene	0.022	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.	0.039 ± 0.003	7.46	n.d.
2-Methylnaphthalene	0.020	0.014 ± 0.0007	n.d.	n.d.	n.d.	0.026	n.d.	0.035 ± 0.003	12.5	0.027
1,2-Dimethylnaphthalene	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.	0.63 ± 0.01	0.05
1,7-Dimethylnaphthalene	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.	0.02 ± 0.001	0.13	0.14

n.d.; target substance was not detectable in the sample quality shifted towards apple juice-like tonalities instead of fermented notes. Benzaldehyde revealed no relevance to the overall odour as higher concentrations could only be detected in samples that also contained elevated concentrations of substances with other distinct smell impressions. In addition to the analysed substances, a *cocoa-like* and *earthy* smelling substance could be perceived during the olfactory analysis in five samples. Since the substance was not detectable in GC-MS and GC-GC-MS scans it was concluded that it had a very low odour threshold. The odour exerted a smell reminiscence of methylated pyrazine derivatives, but could not be identified within this study.

4.2. Quantification and potential relevance in view of adverse health effects

Within this study, the absolute concentrations of target substances were quantified in the respective samples. Depending on the applied painting technique the overall amount of paint used ranges from a few grams up to hundreds of grams, when using a pouring technique on a large surface canvas. The amount of used paint as well as the substances volatility and release from the paint are essential parameters when evaluating the respiratory exposure. Furthermore, the size and the ventilation of the working space need to be taken into account when evaluating the exposure in a specific facility. Since these parameters are not further investigated within this study, the absolute concentration can be used to in a worst case scenario and compared against toxicological thresholds, assuming a full release of the target substances from e.g. 100 g paint into a room of 50 m^3 .

With concentrations of up to 326.74 mg/kg *n*-butanol showed the highest concentrations among all analysed substances and was the most prominent compound in nine out of ten test samples. The alcohol is used as a reactant together with acrylic acid to from butyl acrylate, one of the major ingredients for water based acrylic paints. Thus, n-butanol is a potential residual constituent in the paints as impurity of butyl acrylate or might be formed by ester cleavage of butyl acrylate. However, since the analysed amounts of *n*-butanol exceeded the amount of butyl acrylate by far in all samples, it was concluded that butanol was also added as a solvent for other ingredients or as an additive. Due to its comparatively high odour threshold n-butanol, however, contributes only to a smaller extent to the overall odour of the paint samples. With the determined concentrations in the paint samples, a dermal or respiratory uptake needs to be considered in the frame of common usage of the paints. Butanol is known for its defatting and drying properties that can lead to skin irritations and severe eye irritations. In view of potential irritation effects, a permissible exposure level of 100 ppm (300 mg/m^3) has been determined by the Occupational Safety and Health Administration (Occupational Safety and Health Administration, 2021). However, the detected concentrations are potentially not high enough to reach the levels mentioned before.

The determination of the amounts of naphthalene and its derivatives in paints were of high interest for us since naphthalene was not only one of the most distinctive odour active substances in our previous study (Bauer and Buettner, 2018), but is also known to have adverse health effects. Besides causing irritations and dermatitis, naphthalene can damage red blood cells, thus causing methemoglobinemia (Volney et al., 2018). Furthermore, naphthalene is classified as a category 2 carcinogen as e.g. increases in the incidence of neuroblastoma and adenoma in rats after inhalation exposure to naphthalene could be observed (National Toxicology Program, 2000; ECHA, 2018; National Toxicology Program, 1992; ECHA, 2003). However, data about causative concentrations are not available yet. Within this study, naphthalene was detected in nearly all samples (8 out of 10) in concentrations between 0.012 mg/kg and 7.02 mg/kg. While most samples showed either very low concentrations (<0.1 mg/kg) or low concentrations between 0.12 mg/kg and 0.38 mg/kg, only sample A9 showed an elevated concentration of 7.02 mg/kg. However, the concentrations in the paints are potentially not high enough to exceed the DNEL (Derived No-Effect Level) of 0.053 mg/m^3 under which no adverse effects on the human health are expected (ECHA, 2018; Dodd et al., 2012). Regarding dermal exposure there is no information available to date (ECHA, 2003). In view of that it is important to note that there are painting techniques that do not only require brushes and spatulas but also hands or fingers, leading to direct skin contact of the paint, so that higher concentrations of naphthalene in paints might have an effect on their health. A potential effect depends on concentration level, exposure time and exposure frequency, and would need to be assessed by further studies.

Methylated naphthalene derivatives were found in three (1-methylnaphthalene) and six (2-methylnaphthalene) samples in concentrations between 0.014 mg/kg and 12.5 mg/kg. Concentrations were generally low (<0.1 mg/kg) for all samples except for A9 that also showed the highest concentration for naphthalene. With concentrations as high as 7.46 mg/kg for 1-methylnaphthalene and 12.5 mg/kg for 2-methylnaphthalene, the samples contained at least 191-times (1-methylnaphthalene) and 357-times (2-methylnaphthalene) higher concentrations than the other nine samples. Unlike in the case of naphthalene, there is no report on mutagenic or carcinogenic effects of its methylated derivatives to date. Both substances have been tested regarding their acute and chronic effects in digestion studies in mice, and a significant increase in damage of lung tissue (pulmonary alveolar proteinosis) was observed at concentrations of 50 mg/kg (Murata et al., 1993, 1997). However, no clear conclusions from ingestion studies can be drawn.

The naphthalene derivatives 1,2-dimethylnaphthalene (1,2DMN) and 1,7-dimethylnaphthalene (1,7DMN) were detected in 2 and 3 samples, respectively, and therefore in less samples than naphthalene and other naphthalene derivatives. With concentration between 0.05 mg/kg and 0.63 mg/kg for 1,2DMN and 0.13 mg/kg and 1.16 mg/kg, both substances were detected in low to medium concentrations. Likewise, both substances were only found in samples that also contained naphthalene and other naphthalene derivatives in medium to high concentrations. Especially sample A9, with highest amounts of naphthalene and methylated naphthalenes, contained also elevated amounts of 1,2DMN and 1,7DMN. Both substances have to date not been recognized as hazardous.

Commonly, black pigments like carbon black are manufactured via combustion of natural gas or oil. Depending on the manufacturing process, it is possible that by-products such as naphthalene and its derivatives are formed during the combustion. Thus, the quality of the used pigment plays an important role regarding naphthalene concentration in paints. The manufacturing process also serves as explanation for the occurrence of the methylated derivatives in such paint samples that also contained higher concentrations of naphthalene. However, no correlation between a certain type of pigment (see Table 1) and the naphthalene concentration could be found.

Styrene was detected in nine out of ten samples in a range between 0.03 mg/kg and 11.61 mg/kg. Thereof four samples showed very low concentrations (<0.1 mg/kg), and two samples showed medium values of 0.14 mg/kg and 0.56 mg/kg. The three samples A6, A9 and A5 however contained elevated values as high as 4.32 mg/kg, 10.66 mg/kg and 11.61 mg/kg. Styrene is commonly used as a copolymer in acrylic dispersions and can thus be found as a monomer therein. Depending on the type and quality of dispersion, styrene can be found in variable concentrations. In its latest report about the carcinogenic risks, the IARC classified styrene as a 2 A carcinogen (Cancer IAfRo, 2019; Cruzan et al., 2017; Huff and Infante, 2011; Nissen et al., 2018). The National Institute for Occupational Safety and Health established a recommended exposure limit of 50 ppm (215 mg/m^3). Concentrations found in the paint samples do not exceed these limits. However, presence of a potentially carcinogenic compound should raise awareness. Since styrene's primary metabolite styrene-7,8-oxide reacts directly with DNA, the frequent and direct contact with styrene should be avoided (Cancer IAfRo, 2019; Rappaport et al., 1996). Consequently, skin contact with paints is not recommendable, and appropriate ventilation should be ensured during the use of acrylic paints.

Within this study further four benzene derivatives were analysed namely ethylbenzene, propylbenzene, cumene and sec-butylbenzene. These derivatives could be detected in nearly all samples except sec-butylbenzene, which was present in only four samples. Although the concentration levels were generally low (<0.1 mg/kg) or medium (<1 mg/kg) some samples revealed elevated levels. For ethylbenzene, concentrations as high as 5.31 mg/kg, 10.89 mg/kg and 10.93 mg/kg were found in sample 5, 10 and 9, respectively, corresponding with the elevated concentrations of styrene in samples 5 and 9. Accordingly, a similar pathway into the paints is conceivable, especially if one considers that ethylbenzene is used as a precursor in the synthesis of styrene. Another possible source might be an impurity in used solvents, since the hazardous BTEX (benzene, toluene, ethylbenzene, xylene) substances can be impurities or constituents of hydrocarbon-based petroleum spirits that can either be used as paint thinners or solvents. Acute respiratory effects, such as throat irritation, irritation of the eyes, and neurological effects such as dizziness as well as chronic effects like kidney damage in animals were observed for ethylbenzene (ATSDR, 2010). However, the determined concentrations did not exceed the recommended exposure limit of 435 mg/m^3. A carcinogenic potential, as observed in animal studies, has not been proven in humans yet (Hard, 2002; Program, 1999).

Propylbenzene was generally detected in concentrations < 0.1 mg/kg, while elevated levels could be found in sample A9 (6.89 mg/kg) and A10 (4.3 mg/kg). However, there is only little toxicological information available for propylbenzene, so that potential effects cannot be ruled out (Agency USEP, 2009).

Cumene revealed levels as high as 4.33 mg/kg an A9 and 5.87 mg/kg A10, whereas concentrations in the other samples were generally < 0.1 mg/kg. Irritation and chronic as well as acute toxic effects are usually observed in higher concentrations for this substance (Centre ECJR et al., 2001). However, cumene has been shown to be related to the development of cancer in mice and rats (NTP, 2009). Although concentrations in the mentioned studies were higher than the amounts found in our paint samples, the occurrence of a possible carcinogen in products that come in close contact with humans should raise attention.

Likewise, with 2.91 mg/kg in A9, sec-butylbenzene showed an elevated concentration in only one of the samples.

Comparing the concentrations and paint samples containing the benzene derivatives, it became apparent that those substances occurred together. Thus, we assume that solvents had been added to the paint samples A9 and A10 as benzene derivatives can occur in solvents.

Butyl acrylate was found in nine of the analysed samples, and was determined with concentrations between 0.01 and 26.5 mg/kg. The highest concentration could be detected in samples P5 (26.5 mg/kg), P10 (7.19 mg/kg) and A4 (1.1 mg/kg), which had also been found to contain mushroom-like VOCs in GC-O analyses. Although these samples showed elevated levels of butyl acrylate, the concentrations are unlikely to be of physiological relevance as the recommended airborne exposure limit over a 10 h work shift was set to 10 ppm (National Institute for Occupational Safety & Health), and concentrations were potentially too low to have acute irritating effects. Furthermore, butyl acrylate has not been reported to have carcinogenic effects (Substance Evaluation Conclusion, 2019). In seven samples, butyl acrylate showed even lower concentrations and was thus considered as being an impurity in these samples. In P1, 2-ethylhexyl acrylate was found instead of butyl acrylate. Accordingly, it was concluded that P1 contained a different acrylic dispersion than the other paint samples.

2-Ethylhexyl acrylate (2EHA) was detected in five samples. Whereas four samples showed low concentrations between 0.03 mg/kg and 1.80 mg/kg, we could determine concentrations as high as 98.9 mg/kg in P10. 2EHA has been reported with high LD_{50} values (4000–6000 mg/kg), while irritation of the skin or eyes is a risk in working with 2EHA (Centre ECJR et al., 2005). In skin tests its irritating effects were revealed which led to erythema, oedema or skin lesions. However, concentrations used in these tests were significantly higher (e.g. 0.5 ml), so that such pronounced irritating effects are not expected to be caused by concentrations found in the paints. Associated cytotoxic effects that were observed in gene mutation assays are therefore not to be expected in temporarily limited exposure scenarios (Amoruso et al., 2008; Murphy et al., 2018).

With concentrations between 0.01 and 2.67 mg/kg 3-methyl-4-heptanone (3M4H) showed medium to high concentrations among the analysed substances, and yielded the highest concentration in A6. Although the concentrations were much lower than the concentrations of n-butanol, its influence on the overall odour of the paints cannot be neglected. Since its odour threshold was determined as low as 0.032 ng/l_{air} the influence can be underestimated when just taking the absolute concentration in the material into consideration (Bauer and Buettner, 2018).

Butyl acetate was detected in all analysed samples in concentrations of 0.14–18.13 mg/kg. This substance is known as solvent in different kinds of paints, and might therefore have been also added to the investigated samples of this study as solvent for other ingredients. However, since half of the paint samples showed concentrations below 1.0 mg/kg, butyl acetate might have also been formed in the paints from n-butanol and acetic acid, or might have ended up in the samples as an impurity originating from process of butyl acrylate formation. Although butyl acetate was found in lower concentrations than n-butanol, butyl acetate shows an odour threshold between 0.037 and 20 ppm and therefore influences the overall fruity odour (Cometto-Muñiz and Cain, 1991; Documentation of the Threshold Limit Values and Biological Exposure Indices, 1991). This substance has previously been shown to have influence on the health of mice that were exposed to butyl acetate vapours in time intervals that represent a general working week (6 h a day, 5 days a week). Effects were observed in vapour concentrations as high as 1500 ppm and 3000 ppm (David et al., 2001). However, concentrations of 500 ppm (approximately 2600 mg/m^3) were considered as the no-observed-effect-level (NOAEL). Since concentrations in the analysed paints were not high enough to obtain such high vapour concentrations, butyl acetate concentrations may be considered as safe in the here investigated test samples.

Lastly, benzaldehyde showed concentrations of 0.06–18.64 mg/kg in all of the analysed samples. Although the concentrations were comparatively high in samples 6, 9 and 10, the substance does not appear to have an explicitly high impact on the overall odour of the paints. Despite its odour threshold of 0.06 ppm the almond-like odour could not be determined during the evaluations, and might therefore be perceptually comprised within the fruity odours or the sweet nuances of the gasoline-like odorants. The concentrations found in the samples were most likely not high enough to cause any adverse health effect (Andersen, 2006).

5. Conclusion

Within this study 10 black acrylic paint samples were analysed regarding their concentration of sixteen odour active and partly harmful substances that have been identified in a previous study (Bauer and Buettner, 2018). Evaluating the patterns and concentrations of the analysed substances, the likely sources of several compounds could be elucidated. Naphthalene, and in some cases its derivatives, could be found in nine out of ten samples, and these are considered being unwanted by-products of the pigments. Therefore, the reduction of their concentration might only be achieved via the optimization of the manufacturing process. Since alkyl benzene derivatives are known constituents of solvents, the replacement of solvents by less harmful substances is advised. The results suggest that solvents containing alkyl benzene derivatives have mostly been replaced by 1-butanol.

All paints showed a different and specific pattern of the analysed odour active substances and volatiles. Whereas only two samples (A2 and A7) yielded no elevated concentrations for any of the analysed substances, all other samples showed at least one substance that was well above average. The pattern of elevated concentrations was, nevertheless, specific for all paints. Thus, it could be concluded that the repulsive odour was not caused by a specific substance in general, but by an individual mix of odorous substances. Only one sample A9 showed elevated concentrations in nearly all analysed substances.

The concentrations for single substances were generally below the recommended exposure limit and therefore most likely too low to cause any adverse effect with regards to toxicity and irritation. As several substances were found to potentially cause cancer, adverse health effects could not be excluded especially with regards to combined or enhancing effects by group effects of these substances. The occurrence of carcinogenic and potentially carcinogenic substances in products, which are occupationally used on a daily basis and can be used in direct skin contact, should thus raise awareness. Since A9 elicited the strongest *gasoline-like* and *mothball-like* odour and the highest concentrations of potentially harmful substances, the human sense of smell might be indicative for consumers with respect to which products should be avoided or at least regarded with caution. Quality control entities should thus consider unusual or intense smells with more care in future products.

Ethics approval

The study was conducted in agreement with the Declaration of Helsinki. The study (registration number 180_16B) was approved by the Ethical Committee of the Medical Faculty, Friedrich-Alexander-Universität Erlangen-Nürnberg. Informed consent was obtained from all subjects participating in the study.

Authors contribution

PB and AB conceived and designed the experiments. PB performed the experiments and analysed the data. PB and AB conceived the publication. All authors have read and approved the final manuscript and are accountable for the content of the work.

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CRediT authorship contribution statement

Patrick Bauer: Conceptualization, Methodology, Validation, Investigation, Writing – original draft. **Andrea Buettner:** Conceptualization, Resources, Funding acquisition, Supervision, Writing – original draft.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data Availability

Data will be made available on request.

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