Influence of temperature and relative humidity on subjective and objective air quality data in shopping centers

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Abstract. Germany has 493 shopping centers mostly located in urban cities. According to STASTICA, the number of shopping centers was doubled in the last two decades .For consumers, good indoor air quality (IAQ) is a basic requirement for their shopping experience. This leads to very high air exchange rates for current operation of HVAC systems in shopping centers. Accordingly, achieving good IAQ in combination with increasing energy efficiency is a main issue for operation. Thus, previous studies were done to evaluate the intensity of shopping product emissions. Trained subject panels evaluated the emissions from retail products by using an intensity comparative scale.

In this paper, we analyze the IAQ parameters not only by trained human panel, but also by analyzing the volatile organic compounds (VOC) through objective tests. In a first step, we cluster five different product groups: books, clothing, shoes, coffee and perfume. For these groups, we measure the emissions through a multi VOC sensor system and a trained human panel, depending on two main parameters: temperature and relative humidity. The multi VOC sensor system consists of electrochemical sensors which resistivity changes according to the oxidation reactions that happens on the surface of the sensors at high temperatures. We use the results to investigate the correlation between the intensity of VOCs in respect to the two main parameters. Finally, we used the subjective data along with the objective data, to evaluate the perceived odor intensity and correlate the evaluations with the measured VOC concentrations by the multi VOC sensor system. The evaluation and visualization is done in principle of statistical data analysis methods such as Friedman test. The results show the potential for the metal oxide semiconductor sensors technology for detection of VOCs and for prediction of perceived intensity based on objective data. Moreover, a product specific regression leads to better prediction results, which shows that different limit values are required for different shop types.

Furthermore, the results show an influence of air temperature and humidity on subjective perception. Thus, for all products investigated, the perceived intensity and the percentage of dissatisfied people increases with rising temperature and relative humidity.

Keywords. Indoor air quality, shopping center, total volatile organic compounds, E-Nose, VOC
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1. Introduction

Currently, air quality control in shopping centers is largely based on the measured CO_2 concentration of the indoor air. The CO_2 sensors used in this process usually measure the CO_2 concentration in the room increased by the emissions of the human organism. The advantage of CO_2 sensors is that the measured value can be calibrated to known source strengths with proven effects on humans. The use of absolute threshold values (e.g. Pettenkofer number: 1000 ppm CO_2) simplifies the control of ventilation systems in many applications. However, in shopping centers, controlling the ventilation system based on only one parameter (CO_2) may not be sufficient from an energy and air quality perspective. For example, odors and contaminants emitted from food courts, building materials, or products from inside the stores cannot be detected by CO_2 sensors. As a result, air quality can be perceived as inadequate, even though the CO_2 parameter recorded to control the ventilation system has been set according to standards for good air quality.

Odors perceived by humans can often be traced back to so-called volatile organic compounds (VOCs). These substances occur in the air in the form of gases and vapors and are of organic origin. Even low VOC emissions are often associated with significant odor perceptions and can lead to health problems (irritation of the respiratory tract, headaches, nausea, poor concentration, sleep disturbances). In contrast to CO_2 sensors, VOC sensors are able to detect mixtures of substances in the room air with a characteristic signal [2]. However, the control of ventilation with VOC sensors is relatively rarely carried out, since no specific limit value is defined that could be used to control a ventilation system.

Due to the large number of VOC emissions in shopping centers, the goal is therefore to define acceptable objective limits for different zones of a shopping center or for different product groups. This should allow an extension of current CO_2 based regulations by VOC-based regulations according to the needs.

2. Methodology

2.1 E-Nose: Sensor Methodology

Different sensor types can be used to detect gas concentrations. Possible sensor types are metal oxide semiconductor sensors, and infrared optical gas sensors. In this study, metal oxide semiconductor sensors are selected for the detection of volatile organic compounds. Their operating principle is based on the dependence of the electrical conductivity of metal oxides on the gas concentrations and gas types present. Metal oxide semiconductor sensors can be divided into thin-film and thick-film sensors and exhibit, among other things, high sensitivity to low gas concentrations, a long service life and a low price, making them potentially suitable for use in the demand-based control of ventilation systems. On the other hand, there are non-linear sensor characteristics depending on the gas concentration, which make calibration difficult, as well as drift and aging behavior that cannot be neglected. Furthermore, there is a cross-sensitivity of additional parameters such as relative humidity and air temperature. Due to the high operating temperatures of 300 °C - 900 °C, these sensors can also have a comparatively high energy consumption of more than 1 watt, which can, however, be reduced to almost 90% by an optimized design [3].

2.2 E-Nose: Sensor system development

For the setup of the VOC sensor system, different metal oxide semiconductor sensors of the MQ sensor series are used to enable the detection of several gases.

Tab. 1 – Overview of the detectable chemical components of the sensors used.

E-Nose Sensor	Description
BME680	Industrial sensor (TVOC)
MQ-2	Hydrogen, methane, propane, i-butane, LPG , alcohol, smoke
MQ-3	Alcohol, ethanol, smoke
MQ-7	Carbon monoxide
MQ-9	Carbon monoxide, flammable gasses
MQ-135	NH_3,NO_x, alcohol, benzene, smoke, CO_2
HCHO	Benzene, toluene, alcohol, formaldehyde gas, hydrogen
DHT22	Temperature and humidity sensor

The MQ sensors are connected to a single board Arduino Mega microcontroller for power supply as well as data transfer. In addition, a temperature sensor and a humidity sensor are integrated to compensate for cross-sensitivities to these parameters. With the help of a TVOC sensor, the sum of volatile organic compounds can be recorded and thus a total air pollution can additionally be estimated [4]. **Tab. 1** gives an overview of the used sensors. **Fig. 1** shows the schematic for the developed E-Nose.

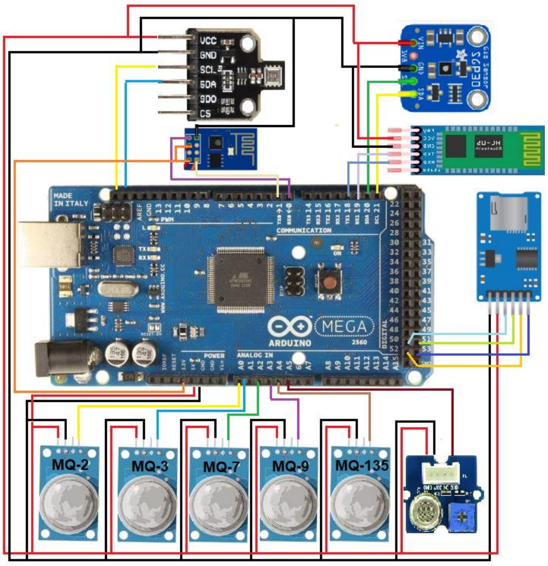

Fig. 1 – Schematic of the developed E-Nose.

Fig. 2 – Developed E-Nose.

An SD card is connected to the microcontroller for local data storage. In addition, the sensor system has a Bluetooth module to establish a wireless connection to other devices. **Fig. 2** shows the final VOC sensor system including an optimized housing as well as the circuit diagram of the system.

2.3 Subjective and objective tests

According to previous studies, Fangers Group, conducted a series of subjective tests. These studies confirm the significant decrement of the acceptability with increasing temperature and humidity [5–8].

The aim of the study is to collect both subjective and objective data for the evaluation of odors or air quality for selected product groups and to derive possible limit values. In particular, the influences of air temperature and relative humidity are to be analyzed. The objective evaluation is carried out with the developed VOC sensor system. The subjective evaluation is carried out with a group of test persons trained according to DIN ISO 16000-28 with regard to acceptance and perceived intensity by using a acetone comparative scale [9].

2.3.1 Emission chambers

The study is conducted in the air quality laboratory of the Institute for Energy Efficient Buildings and Indoor Climate (EBC). The product groups are divided into 5 categories: clothing, books, shoes, perfume and coffee.

Fig. 3 – Positioning of the E-Nose and the product inside the emission chamber.

These are filled into so-called emission chambers. These chambers are made of stainless steel in order to minimize the influence of oxidation reactions on the air. In addition, these chambers have both a connection for the introduction of conditioned supply air via a central ventilation unit and an outlet fitted with a glass cylinder at which the group of test subjects can evaluate the air quality. A control of the supply air volume flow with a measurement of the actual condition via an orifice plate allows a precise adjustment of the air exchange in the emission chambers. In order to achieve good mixing even at low air changes, an additional fan, which circulates the air in the chamber, is installed in each case. **Fig. 3** shows an example of the positioning of the clothing and the sensor system in one of the emission chambers. The sensor system is positioned directly in front of the fan.

A total of three emission chambers can be used in parallel in the EBC air quality laboratory, shown in **Fig. 4**. An exhaust hose is positioned above each cylinder of the emission chambers to prevent contamination of the room air by the outflowing air from the chambers. In addition, each chamber is equipped with a laptop computer on which subjects can enter their subjective ratings regarding acceptance and perceived intensity. In addition, one of the three VOC sensor systems is positioned in each of the chambers.

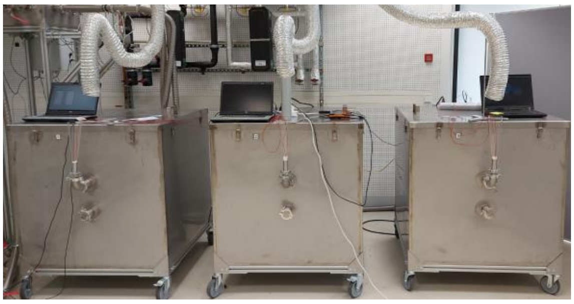

Fig. 4 – Emission chambers in the EBC air quality laboratory.

2.3.2 Acetone comparative scale and subject panel

In order to be able to evaluate the intensity of the air, an acetone comparative scale is used according to DIN ISO 16000-28, see also **Fig. 5**. The concentration of the acetone-air mixture at the different cylinders can be reproducibly adjusted with this test rig. According to DIN ISO 16000-28, the acetone concentration in mg/m^3 can be converted into PI. Here, 0 PI corresponds to the odor threshold concentration or an acetone concentration of 20 mg/m^3. The increase by 1 PI corresponds to a linear increase of the acetone concentration of 20 mg/m^3 (e.g. 15 PI = 320 mg/m^3).

Fig. 5 – Acetone comparative scale in the EBC air quality laboratory.

In previous investigations Hegemann et. al used a maximum intensity of 14 PI for a shopping center product (shoes) [10]. Since the current study also tests other products such as perfume, for which significantly higher ratings are expected, the upper end of the comparative acetone scale is extended to 28 PI (580 mg/m^3). In choosing this value, the stated National Institute for Occupational Safety and Health (NIOSH) limits of 590 mg/m^3 (250 ppm) and Emergency Exposure Guidance Levels (EEGLs) of 2400 mg/m^3 (1000 ppm) for exposure over 24 hours are met [11].

According to DIN ISO 16000-28, the minimum size of a group of testers (hereinafter referred to as the subject group), for the evaluation of acceptance is 15 persons (untrained) and for the evaluation of perceived intensity is 8 persons (trained). In order to increase the statistical significance of the results, the training of a larger group of subjects is aimed at. Out of a total of 26 participants, 17 persons successfully completed the 5-day training.

2.3.3 VOC classes for shopping center products and method of detection

Tab. 2 shows a classification of product groups from shopping centers or their emissions with respect to different VOC classes. As relevant and suitable product groups for the main study, shoes, clothing, books, perfume and, representing the food courts, coffee are identified. In **Tab. 2**, sensors with correspondingly high sensitivity are also assigned to the VOC classes. For example, formaldehyde can be emitted from new clothing, new shoes, or new books. The HCHO sensor is suitable for detecting formaldehyde [12]. Sanaeifar et al. use the MQ-135 sensor for the detection of aromatic compounds emitted from food [13]. Perfumes and detergents contain alcohols, which can be detected with the MQ-3 sensor. Cosmetics containing alkanes can be detected with the MQ-2 sensor [14].

Since only three emission chambers are available, the study is divided into two sub-studies. In the first sub-study, clothing, shoes and perfume (variant 1) are evaluated. In the second sub-study, books, coffee and perfume (variant 2) are evaluated. Perfume is rated in two variants, as the highest ratings were recorded here. The second variant corresponds to a 60 % reduction in source strength compared to the first variant. In each sub-study, the group of test subjects is also divided into two sub-groups due to hygiene protection with regard to the Corona pandemic, so that the first sub-group participated in the study in the morning and the second sub-group in the afternoon.

Tab. 2 – VOC classes and assignment to product groups of shopping centers and suitable sensors for detection.

Product group	VOC class	Detecting sensor
Clothes	Formaldehyde	HCHO
Shoes		
Books		
Food	Aromatics	MQ-135
Furniture Polishes		
Perfumes	Alcohols	MQ-3
Cleaning Agent		
Cosmetics	Alkanes	MQ-2

2.3.4 Test procedure

The test procedure is shown schematically in **Fig. 6**. One setting is selected per day for the air temperature and the relative humidity of the supply air, which is not varied during the day. Two hours before the arrival of the group of test subjects, the test stand is switched on to create stationary boundary conditions. After a welcome and brief acclimation of the subject group, the evaluation begins. Once an evaluation is completed for all three emission chambers, the volumetric flow rate or air exchange rate is varied. During the test run, the subject group is almost exclusively in the air quality laboratory. After all assessments are completed, the subject group is dismissed.

The parameter variations carried out are included in **Tab. 3**. This corresponds to a total of 36 evaluations per subject and product. The temperature and humidity were chosen to be inside the acceptable thermal comfort range boundaries [15].

In addition to evaluating the perceived intensity, an additional question is used to determine the percentage of dissatisfied subjects. For this purpose, the 17 trained subjects are asked the question: "Imagine you were exposed to the air from the emission test chamber for several hours a day. Would you rate the odor as acceptable?" "Yes" and "No" are

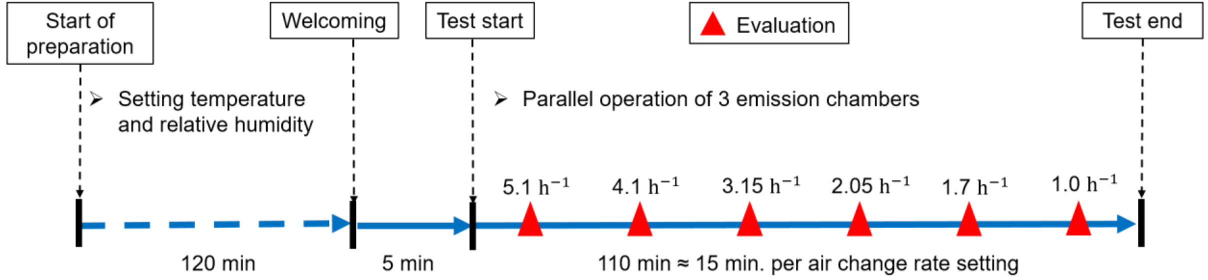

Fig. 6 – Test procedure.

available as response options. The proportion of no ratings is defined as the proportion of dissatisfied. The evaluation is carried out for each parameter variation, so that a total of 36 evaluations per product and test person are recorded here as well.

Tab. 3 – Overview of parameter variation.

Parameter	Value
Air temperature in °C	20; 23; 27
Relative humidity	30 %; 50 %
Air change rate in 1/h	1; 1.7; 2.05; 3.15; 4.1; 5.1

3. Results

3.1 Influence of temperature and humidity on the perceived intensity

In **Fig. 7**, the ratings per air exchange setting averaged over all test subjects are plotted against temperature. These mean values are shown as colored circles per product group. The relative humidity is 50 % for the evaluation. Based on the results, a slightly proportional relationship between air temperature and perceived intensity can be seen. Thus, the perceived intensity increases with increasing air temperature. The slope of the regression lines varies slightly between the individual product groups. Furthermore, it can be seen that the difference in perceived intensity due to the product groups is significantly higher than the influence of temperature. Perfume (variant 1) has by far the highest ratings between about 19 and 27 PI. The reduced source strength for perfume (variant 2) leads to a reduction to values between approx. 12 and 16 PI. The ratings for coffee are at a similar level to perfume (variant 2). Shoes and books are significantly lower, at about 10 to 12 PI and about 6 to 10 PI, respectively. The lowest ratings, between about 5 and 7 PI are observed for clothing.

Fig. 8 shows, as an example for the perfume product group (variant 1), the ratings averaged over all test subjects per air change rate setting plotted against temperature. The data for the relative humidity of 30 % are shown as red circles and for 50 % as black crosses. In addition, the regression lines are drawn. Both regression lines run almost parallel with the same slope. However, the ratings at 50 % humidity are shifted upward by about 2 PI compared to 30 % humidity. The results for the other product groups show a similar behaviour.

Overall, it can be concluded that as temperature and humidity increase, the perceived intensity also increases. The influence of temperature differs slightly for the different product groups, but is of the same order of magnitude as the influence of relative humidity for the value ranges considered.

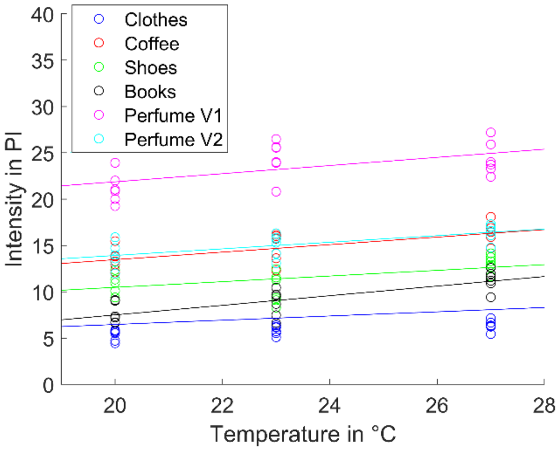

Fig. 7 – Influence of temperature on the perceived intensity at 50 % relative humidity.

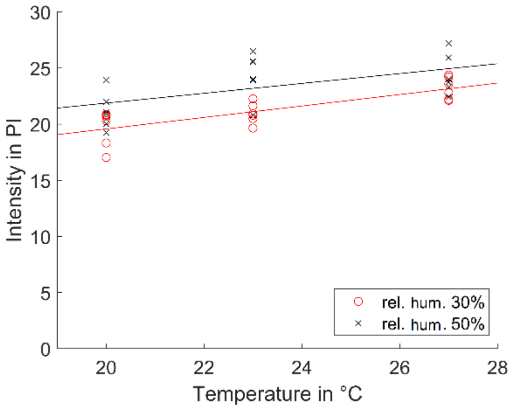

Fig. 8 – Influence of relative humidity on the perceived intensity for perfume (variant 1).

In order to evaluate whether the variation of temperature and humidity leads to a statistically significant difference with respect to the subjects' evaluation, the Friedman test is used. The Friedman test is a statistical test suitable for the evaluation of non-parametric data, so it does not assume a normal distribution of the data [16]. As a result of the test statistic, the "p-value" is output, which is compared with the previously determined significance level α. The significance level indicates the probability with which the null hypothesis is falsely rejected, even if it is actually true. This is called a first kind error or α-error. In this paper, a significance level $\alpha = 0.05$ is chosen for this purpose. If $p>\alpha$, the null hypothesis cannot be rejected and a difference between the sample distributions cannot be detected. However, if $p<\alpha$ holds, the null hypothesis is rejected and the alternative hypothesis is accepted, i.e., a significant difference exists.

The results of the p-value are included for the analysis of temperature differences in **Tab. 3**. All values are smaller than the defined significance level, so that statistically significant differences due to the variation in temperature can be assumed. An analysis for the influence of relative humidity leads also to p-values < 0.05.

Tab. 4 – p-value results of the Friedman test for a comparison of subjective ratings as a function of temperature.

50 % relative humidity 20 – 23 – 27 °C		30 % relative humidity 20 – 23 – 27 °C	
SC product	p-value	SC product	p-value
Perfume (Variant 1)	$1.39e^{-41}$	Perfume (Variant 1)	$7.24e^{-46}$
Perfume (Variant 2)	$1.05e^{-53}$	Perfume (Variant 2)	$1.40e^{-40}$
Books	$4.30e^{-47}$	Books	$3.79e^{-35}$
Coffee	$6.95e^{-55}$	Coffee	$8.79e^{-17}$
Shoes	$4.30e^{-47}$	Shoes	$3.30e^{-13}$
Clothes	$7.79e^{-41}$	Clothes	$4.42e^{-36}$

3.2 Influence of temperature and humidity on acceptance

Fig. 9 shows an example of the percentage of dissatisfied people for the perfume product (variant 1) across the different scenarios. The values in each case represent an average value over all test subjects and set air change rates. It can be seen that the percentage of dissatisfied people increases with rising air temperature and rising relative humidity. The influence of the temperature is higher at a relative humidity of 50 % than at 30 %.

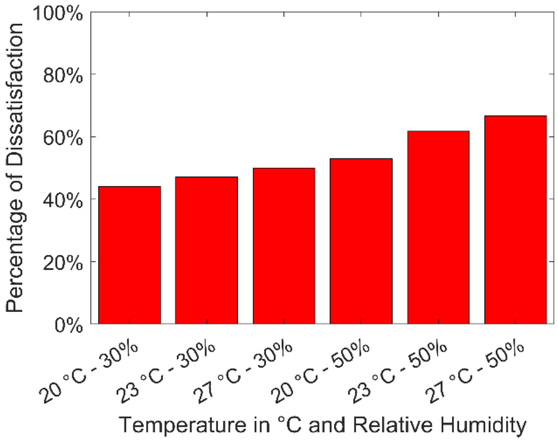

Fig. 9 – Influence of temperature and humidity on percentage of dissatisfied for perfume (variant 1).

In **Fig. 10**, the percentage of dissatisfied people is plotted against the Perceived Intensity. The colored symbols are mean values of the 17 evaluations by the test persons for each combination of product, temperature, relative humidity and air change rate. It can be seen that the range of ratings for the products studied varies. The highest ratings for perceived intensity and the proportion of dissatisfied persons exist for the product perfume (variant 1). The lowest ratings occur for clothing and books, with an intensity of approximately 5 PI resulting in a proportion of dissatisfied of approximately 20 %. It can be seen from the data that the proportion of dissatisfied people increases in principle with perceived intensity. In addition, a linear regression function is plotted in red through the data cloud. It should be noted, however, that the data show a high degree of scatter, especially in the middle range between about 10 and 17 PI, so that the proportion of dissatisfied people varies by about 30 % for the same intensity.

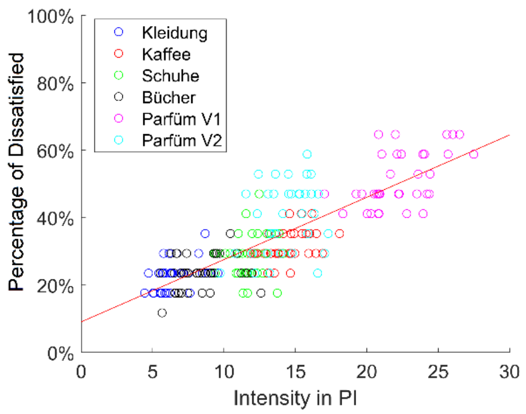

Fig. 10 – Correlation between perceived intensity and percentage of dissatisfied.

3.3 Influence of temperature and humidity on the sensor signal

In the following, the results for the MQ-3 sensor are presented exemplarily, since it has the highest sensitivity to the products investigated. **Fig. 11** shows the sensor signal as a function of temperature for various products at a relative humidity of 50 % for the MQ-3 sensor. For all products except clothing, the sensor signal increases with increasing air temperature.

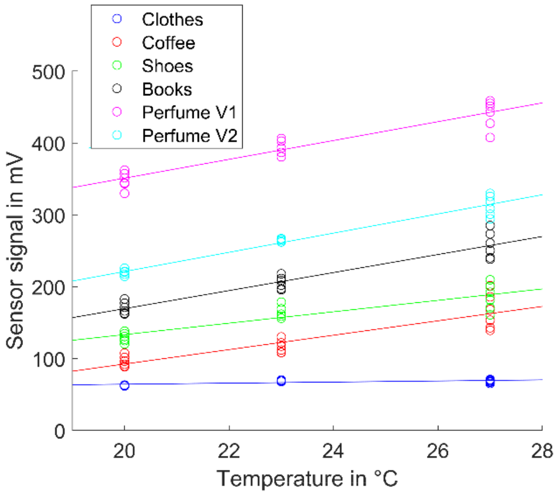

Fig. 11 – Influence of temperature on the sensor signal at 50 % relative humidity for MQ-3 sensor.

Comparing this with the subjective data from **Fig. 7**, a similar behaviour can be seen for the sensor signal as a function of temperature. When looking at the order of the perceived intensities with the measured sensor signals, it can also be seen that these are the same except for position 3 and 5, see also **Tab. 5**. The subjects rate coffee as more intense than shoes, books and clothing, whereas the sensor signal is only weaker for clothing than for coffee.

Fig. 12 shows an example of the sensor signal as a function of temperature for perfume (variant 1) at a relative humidity of 30 % and 50 % for the MQ-3 sensor. It can be seen that the sensor signal increases with increasing relative humidity. This behavior is similar to the observation for the evaluation of perceived intensity in **Fig. 8**.

Tab. 5 – Ranking of the SC-Product according to perceived intensity and to the sensor signal of MQ-3.

SC-Product	Perfume V1	Perfume V2	Books	Shoes	Coffee	Clothes
Subjective Test	1	2	3	4	5	6
Objective Test	1	2	5	4	3	6

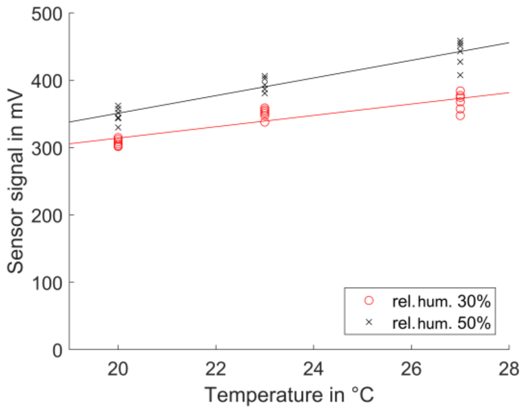

Fig. 12 – Influence of relative humidity on the sensor signal for perfume (variant 1) for MQ-3 sensor.

3.4 Correlations between objective and subjective evaluation

In order to use VOC sensors for advanced demand-controlled ventilation in shopping centers, limit values are needed that can be used as set points for the controlled variables. In **Fig. 13**, the perceived intensity is plotted against the sensor signal for the MQ-3 sensor. In addition, the investigated product groups are shown with different coloured markers.

It can be seen that for the different product groups the point clouds in the diagram have different positions. From this, it can be seen that the correlation of the perceived intensity and the objective sensor signal should be done depending on the product groups. For example, the evaluation of the intensity of coffee is significantly stronger than that of shoes or books for the same sensor signal. In addition, linear regression lines are shown on the basis of the five product groups investigated, whose functions, the coefficients of determination R^2 and the root mean square error (RMSE) are contained in **Tab. 6**. In each case, a linear regression approach is used to derive a correlation between the sensor signal in mV and the perceived intensity in PI. It can be seen that the coefficient of determination for the separate analysis of the product groups books, coffee, clothing and shoes is smaller compared to a regression over all data, but the RMSE can be reduced from 3.2 PI to as low as 0.9 PI. It is noticeable that for books, coffee and shoes the slope of the regression function is the same and only the Y-axis intercept differs.

Tab. 6 – Derived correlations between sensor signal in mV (x) and perceived intensity in PI (y).

Data	Correlation	R^2	RMSE
All data	$y = 0.05 \cdot x + 4.75$	0.65	3.2 PI
Books	$y = 0.026 \cdot x + 3.72$	0.40	1.4 PI
Coffee	$y = 0.026 \cdot x + 11.48$	0.30	1.5 PI
Clothes	$y = 0.053 \cdot x + 3.39$	0.40	0.9 PI
Perfume	$y = 0.05 \cdot x + 5.20$	0.65	2.5 PI
Shoes	$y = 0.026 \cdot x + 7.09$	0.20	1.5 PI

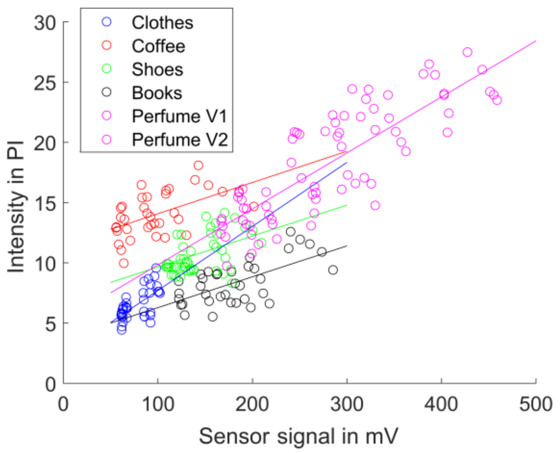

Fig. 13 – Correlation between the sensor signal of MQ-3 and the perceived intensity

In **Fig. 14**, the percentage of dissatisfied persons is plotted against the sensor signal of the MQ-3 sensor for the product groups investigated. The strong scattering of the data along the regression line drawn in red can be seen. This makes it difficult to derive an exact objective limit value.

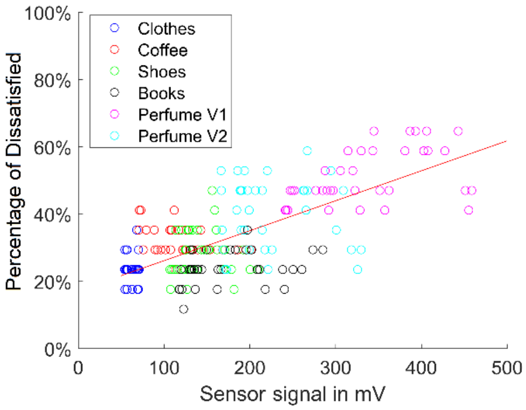

Fig. 14 – Correlation between the sensor signal of MQ-3 and the percentage of dissatisfied.

4. Conclusion

Currently, CO_2 sensors are mainly used in shopping centers for demand-based volume flow control of HVAC systems. In order to additionally detect emissions from building materials and products, VOC sensors are suitable in principle. Depending on their design and measuring principle, these sensors exhibit cross-sensitivities to air temperature and humidity as well as low selectivity, so that interpretation of the sensor signals is not trivial. However, based on the results of the study carried out with the metal oxide semiconductor sensors used, it is in principle possible to correlate the objective sensor signals with subjective evaluations for individual product groups. However, the definition of exact limit values is not possible due to the scattering of the data. Nevertheless, the results show in principle the potential of such sensor technology. With a larger amount of data, which would require further studies, it would also be possible to use machine-learning methods to analyze the data. With these, it might be possible to derive correlations between the sensor signals and the subjective evaluations much more easily and robustly. Important findings were also obtained in connection with the influence of air temperature and humidity on subjective perception. Thus, for all products investigated, the perceived intensity and the proportion of dissatisfied persons increases with rising temperature and relative humidity. This should be taken into account when selecting set points for the control of temperature and humidity, especially if there are complaints from the people present.

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Data Statement

The datasets generated during and/or analysed during the current study are not available because the authors are still processing the data, but the authors will make every reasonable effort to publish them in near future.