ESSnet Smart Surveys

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Workpackage 2

Smart Survey Pilots

Deliverable 2.1: Living conditions - Measuring indoor environment (WP2.4)

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0. Summary

WP2 performs four diverse pilots to inform WP3 on the specifications of a smart survey platform in the European Statistical System (ESS). Important questions are to what extent design and architecture of smart surveys can be shared across ESS countries and what are country deviations. Deliverable 2.1 describes the phase 2 (functional and usability) or, if applicable, the phase 3 tests (methodology and infrastructure field tests) for each pilot. This deliverable 2.1 describes work package 2.4 and is about the measuring of indoor climate, for the substantive topic 'living conditions'. Three countries participated in pilots: DE, BE and NL. WP2.4 did not have a full phase 3 test; this deliverable describes functionality and usability of the measurement of indoor climate with a standalone sensor system. However, a pilot was performed in the LISS panel in NL as a first step towards a phase 3 test. Our main conclusion is that the topic is seen as very valuable by participants, but more work is necessary before we can use the technology in large scale population surveillance. Additional research should be aimed at measurement quality (what substances are we actually measuring and how well are they measured), how to give feedback to participants (to preclude behaviour change), ease of installation, and data analysis.

1. Introduction

Smart surveys are oriented at reduction of respondent burden and improvement of data quality by using the features of smart devices. Six such features have been identified: local storage and processing, employment of internal mobile device sensors, linkage to external sensor systems, linkage to publicly available online data, data donation through the respondent and data donation through the national statistical institute. The inclusion of smart features is promising in particular when survey topics are cognitively demanding, require detailed knowledge or recall, and/or corresponding questions are weak proxies of the concepts of interest. The promise of smart surveys only will only be real when target population response rates are relatively high and balanced and respondents understand the smart survey tasks they are invited to perform. Willingness and usability imply that respondents need to consider the tasks as legitimate and logical and need to trust the statistical institute. These requirements also hold for 'non-smart' surveys, but become more prominent in smart surveys. In these surveys respondent devices are being used and data are being collected or linked that are in part unknown to respondents themselves. Phase 2 functional and usability tests form the stepping stone to field tests and are a guarantee that technically and conceptually smart surveys deliver adequate data. Phase 3 tests inform on how to operationalize methodological and logistical choices.

WP 2.4 (Living conditions) fits the smart survey eligibility criterion, in as much as we measure elements of the living conditions with sensors, that respondents would not be able to report on, i.e., the presence of substances in their home that could have a detrimental effect on health or living satisfaction. This deliverable describes phase 2: functionality and usability of the measurement of indoor climate with a standalone sensor system. A complete phase 3 pilot has not been performed in this work package, but a questionnaire has been given to members of the Dutch LISS panel, inventorying under which conditions people would be willing to accept an indoor measurement system in their homes. This question related to the phase 3 question of effective recruitment and motivation strategies.

1.1 Measuring indoor environment

WP2.4 of the ESSnet smart surveys is about the measuring of living conditions by sensors. Living conditions are related to national health surveys, the European Health Interview Survey (EHIS) and to the Statistics on Income and Living Conditions survey (SILC). In this work package, living conditions are limited to indoor environment quality (IEQ). Air quality, and more specifically air pollution has been defined by the WHO as one of the biggest threats to human health, alongside climate change (WHO, 2021). Mostly, attention has been given to outdoor air quality, but indoor air quality likewise has been related to a wide number of diseases, like asthma, lung cancer, cardiovascular diseases, irritation of eyes and skin, obesity and diabetes, but also do decrease of productivity and learning ability. In various surveys, subjective evaluations of indoor environment are gauged, but objective measurements are quasi impossible to be provided by respondents. Respondents will not be aware of and/or unable to report on aspects of indoor environment that may impact their health. Examples are CO, CO_2 and fine dust (particulate matter), but also and noise. Such sensor data measurements have been explored already in research on indoor environment, e.g., in schools (the European project SINFONIE, 2014, see www.sinphonie.eu), in offices (the European OFFICAIR project, see Sellakaris et.al., 2020), but are still new to official statistics. However, NSI's are in a unique position to combine the subjective measurements in surveys, knowledge about respondents' illness and health and registry knowledge on buildings with the objective measurements that sensors can provide.

Very few respondents will have devices that can measure these substances, which means that devices to measure indoor environment will need to be provided to respondents. That means that these measurements introduce a significant cost-quality trade-off discussion. In addition, we have no experience with respondents' willingness to allow an NSI this kind of access to their home and willingness to let a sensor device measure their IEQ for a substantive amount of time, and what burden these kinds of measurements would pose on the participants. We also do not have experience with the kind and quality of devices that could be used for such an endeavour. For these reasons, the pilots in WP2.4 are mostly small scale, with a focus on user acceptance and usability. However, both in the inventory phase and in the data analysis phase, the quality of the measurement device and data have been given considerable attention.

The perspective of WP2.4 is less on what to measure out of the plethora of possible relevant aspects of indoor environment quality. See appendix 1 for an overview of elements of indoor environment quality that are deemed relevant by experts. More study into this aspect is necessary than the 3 months allotted for the inventory phase. Also, this might vary from country to country, relating to country specific environmental problems (e.g., problems resulting from isolation of dwellings in some countries, problems resulting from the use of polluting energy sources in others).

In the overall project plan for WP2 a number of phases is distinguished. WP2.4 participates in phases 0 (inventory), 1 (concepts), 2 (testing) and 2' (process requirements). In the inventory phase, an overview was made of potential devices for indoor environment quality and their potential utility and costs. Phase 1 was dedicated to the design of the tests, and in Phase 2 small scale usability testing took place, with about 25 participants in each of the participating countries. In Germany participants were also invited for cognitive interviews after the measurement period. In the Netherlands, a large scale questionnaire was sent to LISS panel members, to investigate willingness of the general public to receive an IEQ measurement device in their homes.

In this report, the inventory phase is described in section 2. Subsequently, the design of the pilots in the three participating countries is described in section 3. Results are described in section 4. Finally, in section 5, the link to WP3 is made with a description of statistics, process requirements and machine learning.

2. Phase 0

The first phase, the assessment phase, was concerned mainly with finding a measurement device that would be easy to install and use by respondents, without the need of substantial support. Secure data access was imperative, as was the necessity to be able to share the device and the backend between the participating countries. Early on in this first phase it was determined that it would not be possible to build (or have built) our own devices, plus a dedicated backend, and would thus have to rely on devices that were already available in the market. In this phase, we sought answers to the following questions by literature research and by extensive communications with various parties in the Netherlands and Belgium with knowledge of this subject: the University of Delft, the Dutch National Institute of Public Health and the Environment (RIVM), the Netherlands Institute of Applied Scientific Research (TNO), The Hague University of Applied Sciences, and the Belgian VITO.

- What sensors are available for the measurement of indoor environment quality?
- What is the quality of these sensors?
- How critical is the specific location of a measurement system within a room?
- How large is the expected variation between different locations in homes?
- How stable are these sensors, how often do they need to be calibrated?
- Do we aim for one measurement system with all relevant sensors, or do we aim for several systems within one room that communicate with a base station?
- How many devices will we place within one household?
- In how many rooms will we measure? If in one room: which room? Will that be the same room for all respondents, or will we choose the room where respondents spend most of their time?
- How long do we need to measure per household? Or device?
- How do we get data from the measurement device to the backend server?
- What safeguards on data security do we have from commercial sensor systems that save data in the cloud?
- How do we make data available for researchers while preserving respondent privacy?
- Is additional knowledge necessary to understand the data, e.g., age of house, isolation, heating system, ventilation?

2.1 Discussions with experts

TNO : Piet Jacobs

Dr. Jacobs is the author of TNO rapport Be Aware (2020), a description of an IEQ measurement project in the province Zuid Holland with 1000 households that were measured for one year. The report gives valuable insight in the practical operation, but also in the machine learning algorithms that were used for data analysis. As this project was highly relevant for WP2.4, an English translation was made of the summary of the (Dutch) report. See appendix 2 for this summary.

The project used sensors by Philips, measuring $PM_{2.5}$, CO_2 and temperature. These sensors worked quite well. Important was that they measured linearly: if the concentration fine dust was twice as high, the measurement was twice as high as well. Non-linear measurement does not make sense at all; correction for non-linearity is not possible.

Cheap indoor sensors generally underestimate the measurement. However, trends will still be visible. And even incorrect measurement of levels might give valuable information; e.g., a faulty level of CO_2 will still show if sufficient ventilation takes place. Many sensor systems offer 'relative humidity' as one of the measurements, but according to Dr. Jacobs, this does not make sense, as humidity does not say anything about the presence of moulds, which are the actual danger to health. NO_x (and especially NO_2) is much more important. Its value will transgress the maximal value very quickly, especially when cooking on gas. The problem is that NO_2 sensors are not specific enough. They react to anything. The same holds for measuring VOC.

TU Delft: Philomena Bluyssen

Meeting place at the TU Delft was their sense laboratory: four specially constructed rooms where all elements of IEQ (Indoor environment quality), i.e. indoor air quality, thermal environment, acoustics and illumination, can be varied independently. Prof. Bluyssen is the author of two books on indoor environment (the healthy indoor environment; 'how to assess occupants' wellbeing', from 2014, and 'the indoor environment handbook' from 2009).

Important points that were mentioned:

- All four elements of IEQ (see appendix 1) need to be measured in order to be able to make a statement about the state of IEQ.
- Cheap measurement systems are not able to measure absolute levels properly, at most change. But measuring change is not sufficient for all purposes.
- Measurements must be taken in every room and on every floor of a house if you want to be able to judge a house.
- TU Delft measures outdoor environment by default, in addition to indoor environment. Outdoors they measure among others noise, temperature, and fine dust. Prof. Bluyssen suggested to investigate whether official RIVM's measurements can be used for this purpose. This suggestion was studied in Phase 2 by a master student Data science for his thesis (Beekhuis, 2021) .
- How long you need to collect data depends on the type of sensor. Passive samplers have to measure two weeks before they are saturated; active samplers are ready after one day (they suck in air). There are also sensor buttons that people have to put on (active samplers). This will give you a more complete picture of everything respondents come into contact with, including at work.
- Fungi and moulds are important indicators, but there are no reasonably prized sensors for that.

The Hague University of Applied Sciences: John Bolte, Professor Smart Sensor Systems.

Prof. Bolte's expertise is mainly radiofrequency electromagnetic fields, but he has also published on particulate matter (PM). Prof. Bolte has experimented with all kinds of meters for all kinds of things, in all sorts of places in the house.

Important points that were mentioned:

- like mentioned in the previous conversation, biological pollutants like fungi and pollen are a new and upcoming concern, also with the Dutch ministry of housing. But measuring this is very expensive: around €50.000,-.
- There are (EU) prescribed noise models for the interpretation of noise and possible exceeding of standards: The Lden (Level day-evening-night) is a European measure to express the noise impact of environmental noise over a whole day. As of 2004, the use of the Lden became mandatory in all European countries. This was linked to the implementation of the European Environmental Noise Directive. For linkage with health, one has to look at the decibel (DBA) measurement according to Lden, but also at peaks and experienced annoyance. For noise nuisance, irregularity of rhythm is especially important. Notorious example: the blades of a windmill do not rotate symmetrically, which makes it difficult to ignore and therefore annoying. Cheap and good sensors are available for both sound and light.
- What is the reliability of meters, in isolation, but also among themselves. If the relative calibration is constant, meaningful measurements are possible, even with cheaper sensors.
- Where should the meters be in the house: in the same house there should be several sensors in one room, which will give enormously different measurements, depending on the air flows in the rooms. More than one sensor should also be placed in the bedrooms. Bedrooms give an underestimate of exposure, so measure in other places as well.
- Define better what the purpose is of the measurements. The exposure of people? The average (annual) value for a house? Your measurement systems may need to be different, according to the purpose.

RIVM: Rik Bogers and John Bolte.

- Dr. Rik Bogers is RIVM contact person for indoor environment, and board member of the international society for indoor air quality.
- Concerning substances:
  - RIVM is interested in the measurement of CO: The Ministry of the Interior and Kingdom Relations is interested in this, because of indications that health problems already occur at low exposure.
  - CO_2 is important as a measure of ventilation.
  - Moulds are important, but difficult and expensive to measure. Is also of interest to the Ministry of the Interior and Kingdom Relations
- RIVM indicates that it is necessary to measure both summer and winter in one house.
- RIVM stresses the need for a good description of the purpose of these measurements, in connection with finding a client (ministries, policy, research).
- Prof. Bolte stresses that evaluation of the data is a very important aspect, as people do strange things with the sensors.
- Characteristics of houses are very important for understanding the data.

- Sensors, if properly calibrated, can give an indication of the relative (hourly/daily) variation of concentrations over time and in specific cases the contribution of local sources
- The results of cheap sensors cannot be compared with official reference equipment in terms of quality and eloquence.
- Even after calibration, the uncertainty in results of sensors remains considerable, with a lot of variation per sensor. Detailed analyses of results from individual sensor runs are therefore not meaningful in most situations.
- The usefulness of sensor data increases when the data from multiple sensors is viewed together. This also applies to combining the sensor data with official measurement data and/or calculations.
- In specific cases, where results from sensors are calibrated and combined, the sensors can certainly provide useful results for both citizens and authorities, despite all the limitations and points for attention mentioned in this memorandum.

2.2 Inventory of OTS sensor systems

In parallel to the discussion with experts, an inventory was made of the availability of commercial sensor systems. Focus points were, apart from the substances they measured, the (security of) data access. Table 1 gives an overview of the sensor systems that would potentially be feasible.

Table 1. Selection of commercial sensor systems and their features

	CO	CO2	PM10	PM2.5	PM1	VOC	Radon	NO2	O3	Geluid	Temp	Humidity	Pressure	API	Prijs
Airvisual Pro	-	x	-	x	-	-	-	-	-	-	x	x	-	+	269
Airwave Plus	-	x	-	-	-	x	x	-	-	-	x	x	x	0	269
Netatmo	-	x	-	-	-	-	-	-	-	x	x	x	-	++	99
Foobot	-	x	-	x	-	x	-	-	-	-	-	-	-	++	199
Flow 2	-	x	x	x	-	x	-	x	-	-	-	-	-	+	159
Edigreen Home	-	x	-	x	-	x	-	x	-	-	x	x	x	+	175
Uhoo Air	x	x	-	x	-	x	-	x	x	-	x	x	x	+	329

In view of the number of substances measured and other relevant features, we focussed initially on the Edigree Home and the uHoo air. After contact with the distributers on the possibility to access raw data, the security of the environment where the data are stored, and the price for data access, the choice was made to procure 25 uHoos for the ESSnet tests.

2.3 The uHoo air

Considerations for the choice of the uHoo system were:

- The uHoo stores data on a European cloud, thereby assuring adherence to European GDPA requirements.
- uHoo is used by other Dutch governmental organizations.

- The uHoo delivers the most extensive set of sensor measurements of all alternatives we considered.
- At least some of the sensors were judged by independent others, and deemed to be of adequate quality.
- The data are downloadable in raw format.

See figure 1 for an impression of the uHoo.

Figure 1. the Uhoo Air

In a recent (independent) publication by Baldelli (2021), the uHoo was evaluated in a research project aiming to generate a user-friendly, low-cost, reproducible, and stable platform to validate low-cost monitors. In this research, the correlation and cross-sensitivity of each sensor in the uHoo were compared to reference methods in stable conditions and in a real indoor environment. Table 2 shows the detectable range, resolution and estimated accuracy of the uHoo sensors from this analysis. These data were provided by the manufacturers of the single sensors included in uHoo monitors.

Table 2. Detectable range, resolution, and estimated accuracy of the uHoo sensors

Sensor	Type	Model	Detectable range	Resolution	Estimated accuracy
$PM_{2.5}$	Optical scattering	Shinyei Kaisha PPD42-60	0-200µg/m3	0.1µg/m3	±20µg/m3 or 10% of reading
CO_2	NDIR	ELT Sensor T-110-3V	400 to 10.000 ppm*	1 ppm	±50 ppm or 3% reading
CO	Electrochemical	Figaro Engeneering TGS5342	0-1000 ppb**	0.1 ppb	±10 ppm
TVOC	Metal oxide	Cambridge CMOS CC881B	0-1000 ppb	1 ppb	±10 ppb or 5% of reading, based on the types of VOC
O_3	Metal oxide	SGX Sensortech MICS-2714	0-1000 ppb	1 ppb	±10 ppb or 5% of reading
NO_2	Metal oxide	SGX Sensortech MICS-2714	0-1000 ppb	1 ppb	±10 ppb or 5% of reading

note: table from Baldelli, 2021.

* ppm = parts per million, or 10^{-6} **ppb = parts per billion, or 10^{-9}

RH = relative humidity, PM2.5 = Particulate Matter (fine dust) smaller than 2,5 µm, CO_2 = Carbon dioxide, TVOC = Total Volatile Organic Compounds, CO = Carbon Monoxide, NO_2 = Nitrogen dioxide.

A series of algorithms has been developed by uHoo to transform the raw data from each sensor into user-friendly data showing measurements of each indoor pollutant, via an app on the user's smartphone. The device generates readings each minute and auto-calibrates the CO_2 sensor every 168 h (7 days) and the TVOC, O_3 and NO_2 sensors every 24 h. This auto-calibration estimates exposure levels that the sensor is subject to during operation; then the software updates and becomes more accurate to the specific operating conditions. Due to this auto-calibration, a 48-h warm up period is needed (Baldelli, 2021). Auto-calibration is important because chemical sensors age faster in polluted environments and their baselines need to be recalibrated frequently (Hagan et al., 2018, in Baldelli, 2021).

In the ‘real life’ setup, three uHoos were placed in a residential building located in central Vancouver, Canada. The uHoos and the reference instruments were located at an approximate height of 1 m over the top of a drawer and at the centre of a room. The recording period was two times seven days.

It was found that the uHoo $PM_{2.5}$ sensors and the reference method showed strong correlation. However, $PM_{2.5}$ is underestimated by uHoo during peak activities like cooking, floor cleaning, and frying. These activities generated peak PM levels that varied between 15 and 45 µg/m3 as measured by reference methods. However, when analysed with uHoo $PM_{2.5}$ sensors the range was 12–35 µg/m3. It appeared that for low PM levels, uHoo $PM_{2.5}$ sensors are overestimating $PM_{2.5}$ since they cannot detect levels below 4.5 µg/m3 . For high levels, on the other hand, the uHoo underestimates $PM_{2.5}$. This is possibly a result of the different methods of particle collection: passive by the uHoo versus active (drawing air into the device) by the reference method. As only 1.3% of the data exceeded the upper or the lower limits, correlation was still strong between uHoo sensors and the reference method.

A fairly good correlation was also identified between uHoo sensors and the reference method for CO_2 readings. Moreover, the difference between the three uHoo monitors was about 3.7%. When no occupants were present the uHoo CO_2 sensors showed higher levels compared with the reference instrument (about 35% of difference). However, the uHoo CO_2 sensors and the reference meter were strongly correlated in the presence of occupants and during activities (such as heating and cooking).

UHoo O_3 sensors do not show strong correlation with respect to a calibrated O_3 sensor, but they do agree with each other: no more than 2.6% difference between the devices.

Baldelli (2021) concludes that, in general, the field tests showed that uHoo sensors could identify the trend and sudden rises in indoor levels of $PM_{2.5}$, CO_2, and O_3, with a small margin of error. High correlation with reference methods, low-cost efforts, and ease of use make uHoo monitors an appealing alternative to measure indoor levels of pollutants (p.9). Despite the large agreement between the three uHoos, Baldelli suggest using more than one unit in one space, since this generates more robust results.

The other sensors in the uHoo were not (yet) considered. However, Baldelli warns that MOx gas sensors like the uHoo TVOC sensor respond to a large variety of gases, and show a response to practically all relevant targets and interfering gases, with the exception of CO_2. NO_2 and CO are known to interfere with TVOC sensors. It will be shown in section 4 that this lack of specificity caused a large amount of unrest among the participants in the Phase 2 tests.

2.3.1 Using the uHoo

In order to use the uHoo, an app must be downloaded on the smartphone. The App is available on both IOS and Android platforms. In order to link the uHoo to the smartphone and to the uHoo cloud environment, an email account and password are needed. Email accounts and passwords were generated for each uHoo in the project.

Once the account is set up, the participant is able to see an overview of their measurements (by hour, day or month), see figure 3 for an example. The measurements are colour coded to indicate healthy (green), worrisome (orange) and unhealthy (red) levels for each of the sensors.

The working of all the uHoos is monitored in a password protected 'admin' environment, where an overview is given of the working and measures of all devices. Per device a summary can be generated for any given period, and raw data can be generated and downloaded. See figure 2 for an example of the summary the uHoo generates for CO_2 and $PM_{2.5}$.

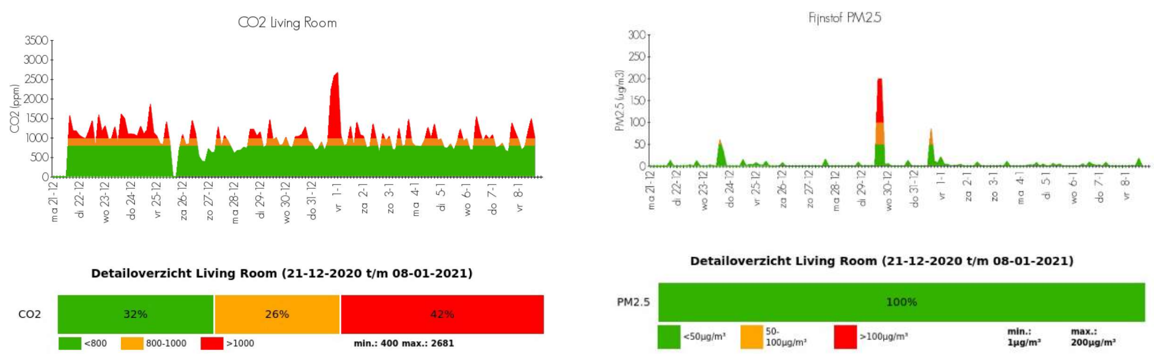


Figure 2. Example of respondent overview for CO_2 and $PM_{2.5}$

From the minute the respondent connects the uHoo to their WiFi, the administrator can see the data. This insight facilitates the detection of set up, and also if the data collection is uninterrupted. If data collection is disconnected, it is in principle possible to warn the respondent to remedy the cause. The fact that we see the data right away and monitor regularly may be something that respondents need to be made aware of, however.

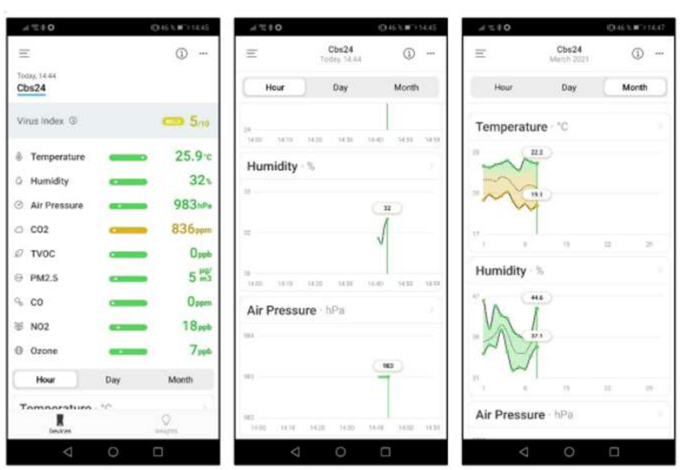


Figure 3. App screenshots showing all nine air quality indicators with their current measures and limit exceedances in colour (left), as well as fluctuation of specific values within either one hour (middle) or one month (right).

All these thresholds can be adjusted by the user for every indicator and can also easily be reset to the default values.

Other than showing real-time measurements, the app also allows setup of push-notifications, changing settings, and provides additional information about the sensors. The app comes in various languages, among which Dutch, English, German, French, and Spanish.

The inventory in Phase 0 gave answers to most of the questions we posed on page 5. However, due to practical considerations, it was not always possible to adopt the optimal solution. For the pilots in the three countries, we opted to use one device per household (for the question how many devices to put in one household), we chose one measurement system with many relevant sensors, instead of several systems within one room, we chose to measure in two rooms, and not all rooms, and we chose to measure for a limited amount of time (two consecutive months), instead of measuring in different seasons. These choices were made with an eye on respondent burden, but definitely also with an eye on researcher and funds burden.

3. Phase 1: Design and preparation of Phase 2 tests.

3.1 The Dutch pilots

The Netherlands performed two pilots. The first one was a small scale pilot (n=25) with a convenience sample of friends, family and colleagues. The goal of this test was to get a general idea about the feasibility of doing sensor measurements in people's homes, both from the respondents' point of view, and the NSI's point of view. Goal was to study burden, quality, accessibility and privacy. An additional goal was to develop a feeling for the machine learning that would be necessary to analyse the data. The ESSnet project partners in Germany and Belgium were among the participants in the

Dutch pilot, to give them an early experience with the sensor systems, but also to secure that the systems would function in other countries.

Participants were sent or given the uHoo with a short introduction where to find the app in the app store, where to place the uHoo in the home. See Appendix 3 for the instruction. It was found that generally, the instruction in the app itself was sufficient for most participants. In addition, variations between smartphones also implied variations in the look and feel of the app, that would be very hard to incorporate in an extensive instruction. Participants also received a two-way jack, to make sure that the uHoo would always be connected to electricity; a lesson learnt from the TNO Be Aware project.

The uHoo was to be placed in the home for two months, one month in either the living room (if the house had a closed kitchen) or between the kitchen and the living room (if the house had an open kitchen). The uHoo was to be placed at a height of 1.5 meter. Participants received an email when to change the uHoo from one room to another. At that moment, they also received an overview of their measurements of the first month. See Appendix 4 for an example of the kinds of overviews sent. After the second month, participants again received an overview and a pre-paid return label.

Shortly before the end of the measurement period, participants received a short questionnaire with some background information on their house: location, year of construction, heating system, kind of glass (single, double, triple), what kind of stove, what kind of extractor hood, the presence and use of a woodstove, number of times food was fried per week, burning of candles, etc. Subsequently, questions on family health, air quality in the home and the environment, and satisfaction with the house were asked. Finally evaluation questions were posed on the use of the uHoo: where it stood, if it stood at the required height, if it always measured, and if not, why not, if the participant looked at the measurements, if they changed their behaviour as a result of the measurements, and if yes, how, and finally, if they found the measurements by the uHoo privacy sensitive. See Appendix 5 for the questionnaire. The questionnaire was adapted from the one used in the TNO Be Aware project (Jacobs et al, 2020); some questions from the Dutch Housing Survey were added.

The second pilot was performed in the LISS panel (n=3500). The LISS panel is a longstanding representative probability panel. Surveys given to participants can be enriched with relevant background information from prior questionnaires. The goal of this second pilot was to gauge willingness among the general public of allowing sensor systems in the home. A questionnaire was delivered to the panel members that first asked some information about characteristics of the house and the health of the household. Subsequently, an explanation on measurement of indoor air quality was given, and a recruitment question was asked if participants would be willing to receive a measurement system in their homes. The recruitment question varied on five dimensions: where the device would stand, what the device measures, the kind of feedback that would be given, if a picture of the feedback was shown, and whether respondents would be given the opportunity to edit their data. The text of the introduction read:

> *It is well known that air quality has a great impact on our health. This applies to the air quality outside, but also inside the house. There are small devices that can measure the air quality in your home, such as the amount of CO_2, nitrogen and particulate matter. We would like to install such a device in your home to do research on the relationship between indoor climate and health.*

To get a good picture of the air quality in your home, the device must measure the air quality #location for two months. The results will show you [#why]. [#Feedback]. [#Picture]. [#Edit].

May we place such a device in your home? Yes / No

The [#location] variation was:

1. measure in the living room.
2. measure one month in the living room and one month in your bedroom.

The [#why] variation was:

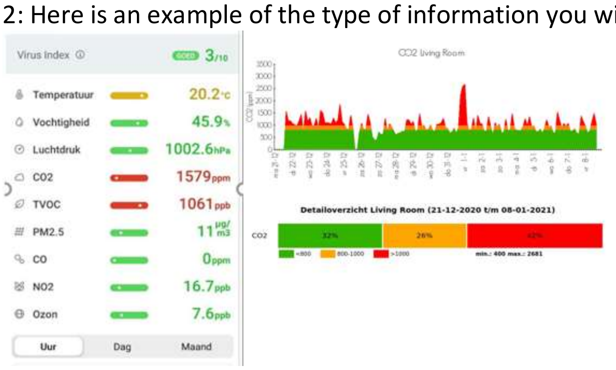
1. whether the air quality in your home is healthy.
2. whether the air quality in your home is healthy, what, if anything, is wrong, and what you can do about it.

The [#feedback] variation was:

1: Via a smartphone app, you can check the air quality at any time.
2: At the end of the two months you will receive an extensive overview of the air quality during the measuring period.

The [#picture] variation was:

1: [empty]
2: Here is an example of the type of information you will receive:



The [#edit] variation was:

1. [blank]
2. You can decide after two months if we can use your indoor climate data for research.

After this first recruitment question, people were given four additional vignettes of this question, with the request to read them carefully, and see what their answer to the recruitment question would be if they would have received that version of the question.

The LISS panel pilot was a questionnaire only. There was neither time nor budget to add a field period with the uHoos. The results of this questionnaire in terms of willingness to place a sensor system at home are described in section 4.2.3

3.2 The German pilot

In Germany, one pilot was performed, among a convenience sample of 20 participants, colleagues of the researchers. The setup was similar to the first pilot in the Netherlands, but the measurement period was one week shorter: four weeks in the living room / kitchen and three weeks in the bedroom. The German participants filled in the same questionnaire as the Dutch and Belgian ones, adapted slightly to the German circumstances and translated by the research team.

At the end of the measurement period, the participants were invited to participate in one of several small focus groups with two to four test persons. The participants varied both in demographics (sex, age, household size) as well as their interest in the topic of air quality and how tech-savvy they were.

Being colleagues, no incentives were paid for either the measuring period or the focus group.

3.3 The Belgian pilot

In Belgium, one pilot was performed, among a convenience sample of 24 colleagues of the researchers, of whom 21 delivered the requested sensor data . The setup was similar to the first pilot in the Netherlands. The Belgian participants first filled in a questionnaire on the process of installation and their evaluation of the sensor measurement that was developed by the Belgian research team. This questionnaire was answered by the participants, and in 7 cases also by a partner or other household member. Some weeks later, participants also filled in the questionnaire on their living conditions that was also used in NL and DE, adapted slightly to the Belgian circumstances.

4. Phase 2: results

The topics for which we sought an answer in WP2.4 are the following:

- Logistics: are people able to install the device and the app? How much support is needed? Do they adhere to instructions?
- What is the perceived respondent acceptance and burden?
- What, if any, are privacy issues, both in terms of objective criteria (who has access to the data, how do the data reach the NSI's back end) and subjectively. The objective aspect of privacy is described in detail in deliverable 2.8. The subjective aspect is discussed in the focus groups and questionnaires and is described in the present deliverable.
- What is the quality of the data quality in terms of stability, calibration, repeatability, reproducibility, and limit of detection
- Do participants change their behaviour as a result of the feedback they receive? From the point of view of monitoring, that would be undesirable as measurement would no longer show what the default values in the household are (the ones that influenced the household's health prior to measurement).

In the following sections, these research questions are addressed: section 4.1 describes logistics and support, section 4.2 describes respondent acceptance and burden, section 4.3 is on privacy, and 4.4 on data quality.

4.1 Logistics and support

Before the uHoos could be used, they had to be individually registered at the uHoo platform. For this, 25 email accounts were created (IEQtestCBS01@gmail.com to IEQtestCBS25@gmail.com) and 25 different passwords. Participants received the uHoo and the appropriate email account and password. In the Dutch pilot, all participants but one were able to install the uHoo app. It turned out that this participant possessed a 5G WiFi network, which, we found out later, did not support the uHoo. In the later pilots, potential test persons were warned that they could not participate if they had a 5G network. The installation did not always go smoothly with the other participants though, for reasons that were not always clear. Most participants eventually succeeded in connecting the device to WiFi after trial and error, where it was not always clear what the problem was. One respondent mentioned that she struggled with the installation, but that her son had it fixed in a couple of minutes. As most of the participants were not very young, part of the problems could be generational. We eventually found out that resetting the device too often (necessary for trying again to connect to wifi) would result in the necessity to reconnecting the device to the platform by the 'owner' of the device. One participant erroneously used his own email account, and was thus not able to see data on his smartphone, although the data did come in in the administrator cloud environment. One respondent was blacklisted by their provider because an unknown device (but probably the uHoo) was sending an inordinate amount of signals. This respondent discontinued participation. A new respondent who used the same device did not have this problem, though. This particular problem was never before encountered by the distributer. A lot of contact was necessary with the uHoo distributer's service desk, who were very helpful, but also not always able to understand the problem. In addition, there were initially problems with the data access for some of the uHoos (through a fault during the connection of the uHoos with the platform). The uHoos had eventually to be sent back to the distributer who made the connection for us. After this, this part of the logistics worked fine for the remainder of the project.

In the Belgian pilot, the issue of installing the uHoo was addressed in the questionnaire. 22 of 26 respondents indicated that installation transpired well. Those who reported problems mentioned that the connection to WiFi failed initially and that multiple trials had to be undertaken. One respondent mentioned that the instruction was unclear. Also the installation of the app itself was problematic for 5 of the respondents. Once installed, the app worked well according to 21 respondents. 18 of them mentioned good to exceptional app features.

In the German pilot similar problems were encountered. A solution that was given to the German participants was to restart the app several times, until it finally prompted for the (automatic) WiFi setup. Two participants could not see their data in the app, although the device itself worked and generated data in the cloud environment (it is probable that they too used their own email account instead of the provided one). These participants were kind enough to keep measuring even though they could not see their data.

It is important that participants follow the instruction on the placement of the device, both for the location and the height. This element was addressed in the questionnaire. There were differences between the countries, with 75% of Belgians complying to this request, 64% of Dutch, but only 33% of Germans. As the placement of the device can have large influence on the measurements, it is important that this is uniform among participants. Apparently, additional attention needs to be given to this topic in the instruction.

Also a topic in the questionnaire, albeit one that can also be ascertained via data analysis, is the question if the device measured all the time. 72% of Dutch participants indicated that it did, 68% of Belgians, and 38% of the Germans. Despite the offered two way jack, disconnecting the uHoo from electricity was often mentioned, but also WiFi problems.

Summarizing: for most participants the download of the app, the subsequent installation of the uHoo and connecting it to WIFI was quickly and easily done. However, a substantial minority of participants struggled and had to try several times, either by resetting the device or by restarting the app. This is a level of devotion that is probably not to be expected in the general public. Especially elderly participants would struggle. A alternative approach to the installation, or the creation of an instruction video, or finding a device where the installation is easier needs to be embraced for future large scale measurements.

4.1.1 Moving the uHoo to another room

After one month, the participants received an instruction to move the uHoo from the living room / kitchen to the sleeping room. For data analysis, it is imperative to know if and when the relocation actually took place. One of the master students working with the (Dutch) data tried to develop an algorithm for this problem, based on trends in temperature, $PM_{2.5,}$ CO_2 and NO_2 , as these show a clear change of trend over time, e.g., a sudden change of fluctuation / standard deviation and a small period of missing values around the time the device should have been moved to the bedroom. Five devices had missing data around the time the device should have moved. It is assumed that this missing data is a result of temporarily no power or internet connection. Eleven devices had a notable difference in temperature change around the breakpoint date. For four devices, no change in trend of indoor air quality measurements was found, which is why it is assumed that these devices did not change rooms. At the end, however, an algorithm could not successfully be trained, and the data split was done by hand. It was clear however, that most of the households had a different moment when the change took place. Results for the other countries will be analysed and described in deliverable 2.5 on sharability.

The important lesson here was that even our extremely dedicated participants did not always adhere to the instructions to the last letter. Monitoring and intervention could be considered, but that would be a large infringement on participant privacy. The analysis into adherence to instruction to move the device has not yet been done for the two other pilots.

4.1.2 How long should we measure?

In the pilots we chose more or less randomly the measurement period of one month. The period of one year that was used in the Be Aware project (Jacobs, 2021) was of course not feasible, and very short periods were neither, as the device needs time to calibrate. One month was deemed an acceptable compromise between respondent burden and data quality. However, if we could measure shorter, or should measure longer, that would be valuable information for future endeavours.

Schaminée (2021) writes: *"Are four weeks enough to find a trend in air quality in the living room areas?" and "Are four weeks enough to find a trend in air quality in the bedroom area?", we first must answer if there are any trends in the data. The answer to this question is yes. Trends with peaks and dips were found and are in line with the literature that was reviewed.*

After it was clear that trends were found in the data, the effect of the length of measuring days was tested. Multiple models tested the RMSE for each amount of training days. It was found that the RMSE stabilizes after 10 training days for the CO_2 models and the $PM_{2.5}$ model for the bedroom. The $PM_{2.5}$ model for the living rooms is less stable in comparison to the other models, but still shows somewhat stable trend after 15 days. Especially the sharp decrease in error for the first three days of training shows the importance of multiple training days. However, it is important to note that all measurements are made in the winter. The answer to the second data science question, "Are four weeks enough to find a trend in air quality in the bedroom area?", is yes. The results suggests that a period of more than two or three days has the same effect".

It appears then, that shorter periods than one month per room could be sufficient. Shorter periods could be welcome as it allows for faster circulation of devices. However, the measurement period of all three pilots was during the Covid pandemic. It is well possible that trends are less predictable if people are out of the house more. In addition, we need to remember that ideally, we should measure in two different seasons in each household, as heating during winter periods, or keeping the windows closed when it is cold, can result in significantly different measurements.

4.1.3 Should we measure in more than one room?

As was described in section 2, ideally we should measure throughout the dwelling. This does not seem feasible. This would mean either giving the household 10 different sensor boxes, or measuring during long periods, where the device needs to be moved after a specific period. As was shown in section 4.2.1, one move was already difficult for our dedicated participants. For the general public, this would seem to be impossible. The measurements in two rooms showed markedly different findings, as will be described in section 4.4. As people spend substantial amounts of time in their bedroom, measuring in the two rooms seems necessary and feasible. Ideally, machine learning algorithms learn to determine if and when the devices are moved.

4.1.4 Costs

Even measurement devices that are described in the literature as 'cheap', cost about €300, see table 1. However, the systems are robust and usable multiple times. The uHoo air has a guarantee period of five years. That means that the costs per household, depending on the measurement period, will be around €5 (for measurement periods of one months) or €10 (for measurement periods of two months). To this costs must be added the costs of sending the device to the participant, and have them sent back again.

Probably, costs savings can be attained by developing our own sensor systems. In Phase 0 we experimented with building our own sensor systems. The system thus attained was indeed much cheaper than the commercial system, but obviously lacked the well-developed API, app and customer feedback that were so appreciated by the participants. Developing a slick device with all the trimmings and back-end is obviously costly as well.

4.2 Respondent acceptance and burden

Remarkably, in hind sight, the subject of respondent acceptance and burden was not explicitly addressed in either of the questionnaires, or the focus groups. Nevertheless, some information can be gleamed from other topics. Some burden was introduced by the not always flawless installation of the app and the sensors. However, once the sensor was installed, participants did not have to do anything else, apart from moving it after one month, and sending the device back after two months. Acceptance was perfect in all three pilots. No participant withdrew participation once the device was installed. However, some psychological burden was definitely introduced by two factors: the push notifications that the app sends when thresholds are passed. This notification can be silenced, but not all participants were aware of that. This is an element that should be added to the instruction. A second burden was introduced by warnings for high levels, where people did not understand where the levels originated and what could be done to alleviate the situation. This was especially the case for the TVOC levels that often showed high levels. This is illustrated by figure 4, from Schaminée (2021). The figures show extreme spikes in the trends. These trends appear in all rooms, but are consistently high in the bedrooms.

Figure 4. Plot of TVOCs in the living room/kitchen and bedrooms.

The German focus groups showed that participants did not know how to influence these indicators. Some participants did some research and tried to ventilate when the reported TVOC value was outside the thresholds. But they could not understand how and why the value is rising. Some state it seemed to change randomly, others speculated it is related to having a dog around, freshly washed laundry, new furniture or the television. Participants with high TVOC values were uncertain and wanted to do more research on this topic (e.g.: Where does it come from? What can I do?) because they wanted to avoid any negative consequences for their health. One participant reported that she was ventilating twice a day for a long time (more than 30 minutes) because of high TVOC values. But other participants simply ignored the indicator as they got the impression of it being rather random values. The awareness and uncertainty with this indicator depended on the reported values: unsurprisingly, persons were more concerned when the TVOC values were outside the thresholds repeatedly. So, without knowing the indicator and how it can be influenced, participants reacted differently. In the end, most of them did not change their behaviour, even if some would have liked to do so.

Other participants called - really worried - for advice, or changed the position of the device in order to not to be burdened by the findings.

As TVOC was also shown in Baldelli (2021) to be unspecifically measured and to be influenced by the levels of other substances, we should warn participants not to heed those measures if we would continue using the uHoo, or, alternatively chose another measurement device that does not measure TVOC. The literature indicates that reliable measuring of VOC is improbable with cheap sensors.

But in general, the participants appreciated learning about their IEQ and even appreciated being shocked by some of the findings, leading to sometimes lasting behaviour change. Some were very sorry to see it go, and inquired about purchasing one themselves. Others asked to be able to use it longer, or use it in additional rooms (like the bedroom of the children).

4.2.3 Respondent willingness in the LISS panel

In the LISS panel, a probability panel in the Netherlands, 3254 panel members (15 years and older) received a short questionnaire on their living conditions, reminiscent of the common questionnaire in the three Phase 2 pilots, and subsequently the question if they would be willing to put a measurement device in their home. 2569 persons filled in the questionnaire (response rate 78.9%). The consent question varied the location where would be measured (only living room vs living room and bedroom), the kind of feedback promised (continuous on app or afterwards), whether a picture of the feedback was shown (yes or no), and whether people would be given the opportunity to edit their contribution. See section 3.1 for more detail. People received five versions of this question (five vignettes) with random allocation of the various elements. The first willingness question had a 'yes/no' format resembling the yes/no decision that people need to make in real life when asked for their participation, while the subsequent four had a 6 point scale, allowing more insight into subtleties within that decision. The various combinations of the relevant elements led to 32 different variants of each question that were randomly distributed amongst the respondents.

It was made clear in the questionnaire that no actual measurement would follow.

Overall, 54% of LISS panel members were willing to put a measurement device in their homes according to the first vignette (unweighted results)[1]. That willingness depended on the one hand on characteristics of the respondents, and on the other hand on the specific vignette they received. In the most popular version, 61% of respondents would be willing, while in the least popular version only 40.5% was willing. The independent elements of the vignettes hardly led to significant differences though. The only exception was (remarkably) that just mentioning 'the results show if the indoor quality if your house is healthy' led to higher participation than the added remark that the results also show the cause and remedy. This pattern was visible in all five vignettes, although only significant in the first vignette. The most popular vignette mentioned that measurements would take place in the living room and the bedroom, that results showed air quality, that the feedback would be immediate and continuous, that respondents could decide if their measurements would be shared, and a picture was shown. The least popular vignette mentioned measurement in the living room, that the results showed air quality and would give information on how to improve it, no picture was shown and respondents were not given the opportunity to choose if their results could be used.

[1] These are unweighted results. The distribution of the response is however very skewed, with 36% of the respondents being 65+ of age, against 23% in the population. The eldest age group were the relatively little inclined to participate. The time lacked to develop a weighting model.

The results of the second to fifth vignette were made binary by classifying scores 0 (absolutely not) to 2 as ‘no’ and scores 3 to 5 (Yes, certainly) as ‘yes’. Classified as such, the percentage potential participation increased substantially, with 77% assent for the most popular vignette, while the least popular was rated with 49% consent. This indicates that a substantial number of people is slightly hesitant in their consent or refusal: of those binary reclassified as refusers, 63% were at the scale end of absolutely not, while of those reclassified as participants, 58% is unequivocally positive. The explanation that is given during the request is hence very important in determining the success of the request.

If people indicated in the first vignette that they would participate, almost every one of them indicated the same in the second vignette, no matter the contents of the second vignette (96% said ‘yes’ in both questions). On the other hand, people who indicated that they would *not* be willing in the first question could to some extend be persuaded to reconsider in the second vignette: 20% of initial refusers switched to the positive side of the scale, albeit mostly not at the most positive end of the scale.

Apart from the contents of the invitation, the characteristics of the respondents played an important role: consent (to the first vignette) was significantly related to education, age, ownership of dwelling, smartphone use, embracing of new technology and worries about air quality. See table 3 for an overview. Consent was not related to gender and urbanicity.

The low percentage of willingness in the youngest age group is noteworthy. Preliminary analysis of the reasons they gave for not participating indicated that refusals did not necessarily have anything to do with the devices as such but more with their situation: a substantial part still live at home and indicated that it was not their decision to take. Others indicated that they lived in a student home and did not have a living room. Subsequent analysis should not include this group.

Table 3. Willingness to participate by respondent characteristics.

	% consent	n	p[1]
Have a smartphone			***
Yes	56.7	2345	
No	33.2	226	
Embrace new technology			**
As a forerunner	57.3	75	
2	64.3	272	
3	56.3	893	
4	52.0	561	
As a follower	51.2	768	
Education			***
Primary	34.4	180	
Lower vocational	45.4	496	
HAVO/VWO	55.0	258	
MBO	57.0	630	
University of applied sciences	61.0	671	
University	61.6	341	
Dwelling			*
Owner	56.5	1859	
Rent	50.1	709	
Age			***
15-24	35.7	207	
25-34	57.1	282	
35-44	65.3	297	
45-54	61.9	386	
55-64	57.3	482	
65+	50.3	926	
Worry about air quality			***
Never	50.4	909	
Seldom	54.0	1025	
Sometimes	60.5	526	
Regularly	69.1	94	
Always	57.7	26	

note *** p<.001 ** p <.01 * p < .05 according to Chi2 test of distribution

4.2.2. Respondent behaviour change

Behaviour change was a topic in the common questionnaire in the three pilots, and was also addressed in the second questionnaire in Belgium, and the focus groups in Germany. The common questionnaire showed that in the three pilots, about half of the participants changed their behaviour as a result of the measurements: 58% in Belgium, 48% in the Netherlands, and 45% in Germany. A follow-up question ascertained the kind of behaviour change, see table 4. Most participants indicated that they aired more often or longer. Some changed the temperature. But some went so far to purchase extra plants, a dehumidifier and even an air purifier.

Table 4. Behaviour change by participants

	n
Air more often	18
Air longer	2
Lower temperature	2
Increase temperature	3
Close windows when outside EQ is bad	3
Placed dehumidifier	2
Bought air purifier	1
Put plants in sleeping room	1

Read about air quality	1
Light woodstove more often (as IEQ did not decrease, as we thought)	1

The focus groups ascertained that for some participants the influence on their behaviour is enduring and they developed new routines, e.g. they started to ventilate the bedroom before going to sleep. Others changed their behaviour only for the time the uHoo was in the specific room and fell back to their normal behaviour as soon as the uHoo was in another room. For some participants the influence on their behaviour was stronger in the beginning of the test and declined by time. Not all participants changed their behaviour though, even when the values were bad. They either did not trust the thresholds in the app or knew the reasons for their poor values and decided to accept it. Participants had e.g. the uHoo in their bedroom and the app was telling them that it is too cold in the room[2]. But they did not change their behaviour because they simply like to sleep in a cooler room or do not see the necessity to heat the sleeping room more. Others were well informed about humidity and said that their humidity value is absolutely fine according to other sources while it was outside the threshold in the uHoo app.

To sum it up: Participants changed their behaviour when they were informed about bad IAQ values for a well-known indicator and were convinced that the suggested values would be better. If participants were not convinced of the suggested values, they did not change their behaviour. If the indicator was unknown, like the TVOC, there was uncertainty about how to react to bad values, but most of those participants did not change their behaviour either because they ignored the values or they did not know what to do.

During the focus group, we also talked about the possibility to participate, without being able to see the results on the smartphone. By accident we found out how this could be accomplished (e.g., by using participants' own email address for the login procedure). Some of the test persons would indeed do that under the condition that a personal report would be sent afterwards

4.3 Privacy

The data on indoor environment quality are potentially quite sensitive. For example, it can easily be ascertained how many people are present in the house or in the bedroom, how late people generally leave the house and at what time they return again. In the 'context' questionnaire, one question addressed the respondent's evaluation of the privacy of the measurements. There was a remarkable difference between the countries, with 48 % of respondents in the Netherlands finding these data sensitive, 42% of Germans[3], but only 10% of Belgians. Nevertheless, as a question in the dedicated Belgian questionnaire ascertained, the participants were aware of the device's measuring. They just didn't find this bothersome. The Belgian questionnaire also asked whether respondents found the

[2] As viruses thrive in colder circumstances, the uHoo sets the temperature threshold for 'healthy' values quite high.

[3] Regretfully, the question as translated in German contained a double negative. It is unclear if all respondents picked up on the precise direction of the answering categories.

measurements in the bedroom bothersome. None of the participants did, indicating perhaps that they were not aware of the possibly sensitive nature of some of the measurements.

In the focus groups, this issue was discussed as well. It was recognized that a key element in determining data privacy and security concerns of future survey participants is whether the sensor data obtained is actually considered sensitive, i.e. in need of protection, and if so, to what degree. Results of the focus groups reveal that views on this subject differ. The majority does not consider air measurement data to be sensitive per se (without context), some respondents however do rate such data as personal, and thus consider it sensitive and in need of protection. Reasons brought up as to why such data could be considered sensitive are:

- It is data about one's personal space, it therefore belongs per definition to one's private data.
- Sensor data reflect on the participants' behaviour
- Data without context are not meaningful (e.g. an increased level of carbon dioxide can have a multitude of reasons). This only holds true though, as long as it does not include any personal data or context information.
- If context information (even WiFi could potentially allow identification of someone's residence) is supplemented, it could allow inferences about someone's indoor behaviour: If an address is included or traceable, one might indirectly infer when someone is at home, how many household members live in a specific apartment, or when someone wakes up or goes to bed. This would then be quite sensitive data.
- Similarly, if data gets into the 'wrong hands', it bears risk of misuse: a landlord or an insurance could theoretically deny payment of mould removal, citing a lack of ventilation by the residents.

Overall, indoor air sensor data is considered uncritical by most when it comes to data sensitivity, while few rate it as personal data in need of protection. However, even among the latter, the level of data privacy is judged as rather low. This includes one important prerequisite however: It only applies as long as no context data or otherwise related data is also being collected (on the same device). If this is the case, most participants feel that indoor air sensor data becomes sensitive private data in need of protection, as it allows inferences about one's personal living space, behaviour, or household specifics.

The Germans concluded that, in summary, we have learned that data sensitivity is rather low when it comes to indoor air sensor data per se. We can therefore conclude that this mostly will not be an impediment to participating in future studies or even national surveys. It is important however that the assessment varies depending on whether and how much context data has to be supplied. Context data that is needed should therefore ideally be collected independently of the sensor device. It is also important to create trust in the device (that it only tracks what is absolutely needed and should ideally not represent similar commercially available devices which include additional sensors, such as Amazon Alexa) and into the handling of data, e.g. aspects such as secure data transmission and storage, or anonymous publishing. To further reduce or even eliminate concerns and increase willingness to participate, data should ideally be stored offline on the device and not be sent via WiFi to a cloud, and third-party suppliers should be avoided or at least chosen according to their publicly perceived trustworthiness

4.4 Data quality

Rai et al., 2017, contend that the most importance hindrance to deploying low-cost sensors at a large scale lies in the quality of the data. Sensor response is impacted by environmental conditions, particle characteristics and cross-sensibilities (e.g., when CO_2 increases, the VOC indicator also increases) . In addition, inadequate sensor calibration seems to be another issue plaguing data quality. In order to be reliably usable, sensor manufacturers needs to provide calibration equations and identify major factors that affect their sensor's response. For the uHoo, we have not been able to receive this vital information, making it doubtful that the uHoo will be the measurement instrument of choice if and when indoor quality measurement will be incorporated in population surveillance. Nevertheless, some information on the theoretical data quality of the uHoo is discussed in section 2.3. How the uHoos performed in our pilots is not (yet) extensively studied. Some information can be gleamed from the data analysis that was performed by three master students Data Science from the University of Utrecht, who have written tree separate theses on three different topics on the Dutch data (Beekhuis, 2011; Ghaffarinejad, 2021; Schaminée, 2021). Regretfully these theses are not published on the UU website[4]. A short overview of a selection of relevant results is shown here. They show that the uHoos show meaningful and interpretable measurements for some, but not for all sensors. They also show how the measurements relate to characteristics of the homes and to participants' behaviour, like cooking or going to bed.

Ghaffarinejad (2021) started by defining the recommended safe levels of the substances by the WHO or other authorized institutions. Then he analysed if the measured levels of gases in the households pass the high-risk levels defined. Table 5 gives an overview of the values mentioned by the WHO and in literature.

Table 5: recommended safe levels for indoor airborne agents[5].

	recommended safe mean concentration over averaging time						alert threshold / exposer duration
Pollutant (unit)	**15 min**	**30 min**	**1 hour**	**8 hours**	**24 hours**	**1 year**	
PM2.5 (µg/m3) [1]	*	*	*	*	25	10	25 / per year
CO (ppm) [1]	100	*	35	10	7	*	10 / average 8 hours daily
NO2 (ppb) [1]	*	*	200		*	40	200 / one hour
CO2 (ppm) [1] [2]	*	*	2000-4000 (2h)	1000-2700 (1-6h)	*	3000-5000 (13d-6m) 700-3000 (13d-15d)	No value suggested

[4] Interested readers can obtain a copy of the theses from the first author.

[5] NB the levels reported by Ghaffarinejad have not been checked for accuracy.

TVOC(ppb) [30]	314 (short term and long term)	940 / temporarily exposure
Ozone (ppb) [43]	maximum average of 60 ppb at 8 hours daily	120 / one hour

* means no value exists for that time span

This translates to the following ranges for safe levels and medium and high risk levels, see table 6.

Table 6. Levels for medium and high risk values for air pollutants

averaging period of pollutant x over a month

Pollutant (unit)	safe levels	medium risk	high risk
PM2.5 (µg/m3)	x <10	10<x <25	25<x
CO (ppm)	x <7	7<x <10	10<x
NO2 (ppb)	x <40	40<x <200	200<x
CO2 (ppm)	x <900	900<x <3000	3000<x
TVOC(ppb)	x <314	314<x <940	940<x
Ozone (ppb)	x <60	60<x <120	120<x

Finally, table 7 gives an overview of the values thus measured in the NL pilot. It appears that most households, in spite of certain alarming warnings by the uHoo app, are mostly well within the save regions, with some exceptions where medium risk values are measured, and one exception where a high risk value is measured for fine dust. The table also indicated that the medium risk levels are mostly measured in the sleeping room, and that the gas mostly reaching medium risk levels is CO_2.

Table 7. median and mean values of measured pollutants in all households per each months of the study.

household	NO2 (ppb)* median/mean	CO2 (ppm)** median/mean	PM2.5 (µg/m3)* median/mean	OZONE (ppb) median/mean	TVOC (ppb) median/mean
	1st M 2nd M	1st M 2nd M	1st M 2nd M	1st M 2nd M	1st M 2nd M
1	14/16 | 0.6/13	818/856 | 807/816	6.1/7 | 6.8/7.4	6.9/6.7 | 5.3/6.5	187/265 | 120/190
2	31/26 | 44/54	580/660 | 602/655	3/4.9 | 4/5.1	8/7.2 | 9.10/9.3	46/89 | 65/118
5	0.5/16 | 0.5/12	667/735 | 681/741	3.5/3.9|4.3/5.9	5.3/6.4 | 5.1/5.9	41/72 | 99/248
6	1.4/8.3-0.6/12	543/596|528/588	2/3.4|3.3/3.9	6.5/6.1|6.8/6.3	54/144|114/255
7	0.5/5.7|0.5/0.8	629/644|772/803	1.9/2.3|1.6/1.9	4.6/5.3|3.8/3.8	57/109|103/157
8	10/11 | 7.4/14	621/633 | 748/793	2/3 | 4.3/5.4	7.3/7.4 | 7.5/7.4	25/32 | 250/362

9	0.5/1.6 | 7.8/22	477/569 | 646/730	4.2/27 | 10.30/16	4.6/4.6 | 6.3/7	28/92 | 64/98
11	0.5/2.9 |0 .5/1.9	437/487 | 517/541	2/2.1 | 3.2/4.3	7/6.8 | 4.8/4.6	2.9/20 | 28/138
12	22.5/23.5|13.5/17	722/698|852/1043	5.7/6.6|6.5/7.9	7.4/7.4|7.1/7.1	76/137|156/369
14	0.5/0.5|.5/.68	843/875|730/735	2/3.14|2.1/2.6	4.5/4.2|4.8/4.9	99.1/174|40/146
15	42/33 | 76/76	944/981 | 841/858	3.8/7 | 4/5.6	8.5/7.9 | 11.10/10.9	79/112 | 78/205
16	17/26 | 12/27	813/826 | 834/928	3/4 | 3.4/4.2	7.4/7.8 | 7.20/7.8	57/83 | 71.5/141
17	4.1/7.3|1.5/16.4	641/685|678/789	2.6/3.8|3.4/3.9	6.8/6.8|6.9/7.2	49.7/106|126/278
18	.5/11.7|.5/19	781/810|809/846	1.6/2.3|2.5/3.7	5.4/6.13|5.5/6.7	47/87|54/125
19	.55/16.2|.5/7.6	650/719|1167/1458	2.5/3.2|3/3.4	5.4/6.5|5.2/5.6	42/100|226/460
20	4.5/8.2 | 0.5/3.8	591/638 | 734/918	2.1/2.3 | 3.8/4.7	6.9/6.0 | 4.3/5.1	13.1/30 | 100/287
21	4.8/8.3|0.8/3.5	596/642|736/913	2.5/2.8|4/6.5	4.5/6.3|4.3/5.1	13.3/35|140/187
22	12.2/18.9|68/86	766/811|540/596	2.5/4.2|3.4/4.6	7.3/7.3|10.7/11.6	102/140|135/242
24	0.6/6.3 | 0.5/7.3	714/712 | 698/720	5.5/6.14 | 6.3/8	4.7/5.7 | 4.7 | 5.6	47/67 | 96/142
25	3.6/23 | 81.9/70	816/857 | 666/691	5.4/6.8 | 6.8/9	7.7/8.5 | 12.4/11.7	58/68 | 66/106

Green color indicates safe levels, orange colors indicate low risk levels and red color indicates high risk levels.

Ghaffarinjad (2021) found that NO_2 and CO_2 levels are higher in newer buildings. This could be a result of higher degrees of isolation; see also the results by Schaminée (2021) who shows that CO_2 levels are higher in bedrooms, but not living rooms, with triple glass, compared to single or double glass[6]. On the other hand, levels of $PM_{2.5}$ and TVOC are lower in newer buildings. This effect could likewise be due to isolation (keeping $PM_{2.5}$ from outside sources out of the house), but also to the fact that newer houses are built with higher quality and less harmful materials.

Schaminée (2021) shows trends over time for a number of substances. Figures 5 and 6 show CO_2 levels over time and the mean trend as a line. A boxplot with the average trend over the day and the extreme values is placed right beside the monthly trend plot.

[6] This could of course also indicate that people who invest in triple glass in the bedroom are loath to chuck the isolation value out the window by opening it. Or that people who need triple class in the bedroom live in areas with large amounts of traffic.

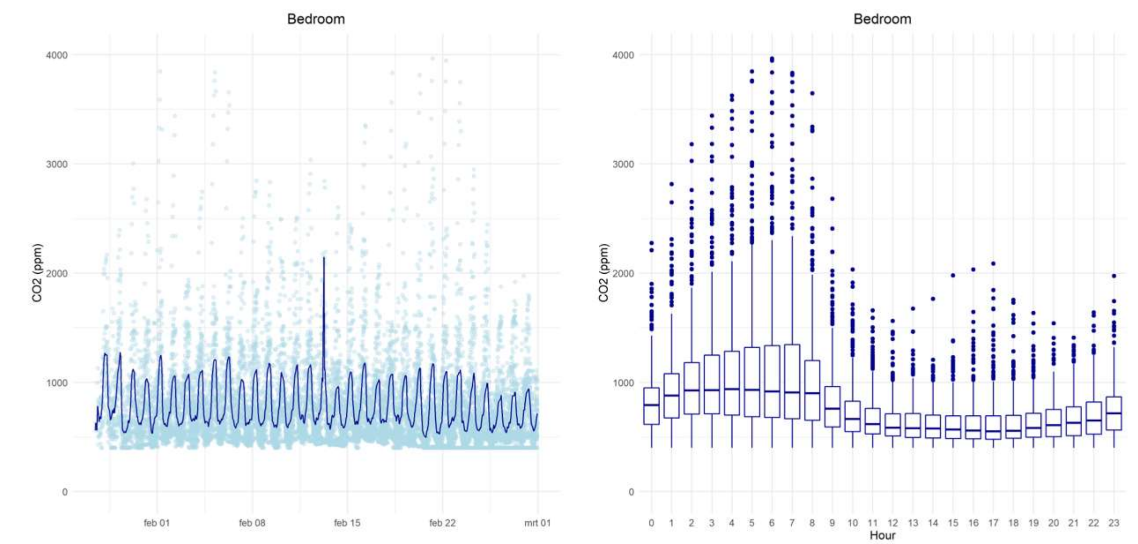


Figure 5. Monthly and daily trend of CO_2 levels in the bedroom

The mean line shows a clear trend with peaks and dips over time. The boxplot confirms this trend and shows that the trend has its peak during the night and its dip during noon. This trend indicates that CO_2 levels rise during the night, when people sleep in the bedroom, and falls during the day, when people are in the living room or away from home. There is a high peak at 6 am on the 13th of February. This can be explained by a possible malfunction in the uHoo server, because from the 19 devices only one device measured at this hour. At 5 am there are no measurements. The dispersion increases during the night, which could indicate that some people leave their bedroom window closed whilst others open their window to let fresh air in. Note that the interquartile range is much smaller during the day in comparison to the nightly hours. This means that there is a higher spread in CO_2 levels during the night. The next plot shows the monthly and daily trend of the CO_2 levels in the living room.

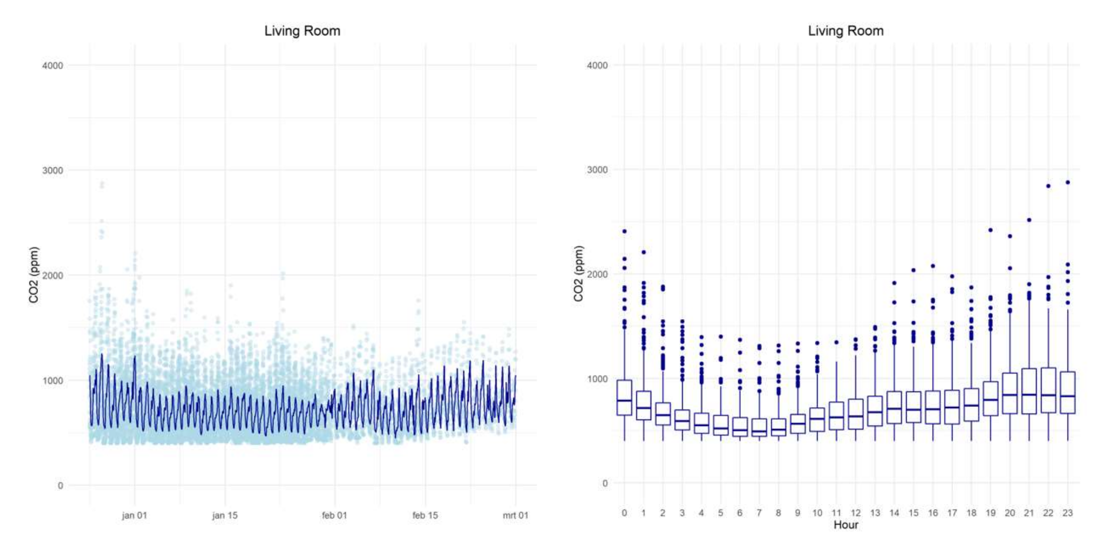


Figure 6. Monthly and daily trend of CO_2 levels in the living room

The mean line of CO_2 levels in the living room indicates a trend with peaks and dips too. There is however a less stable trend in comparison to the bedroom CO_2 trend; the fluctuation of the mean line is less stable. The boxplot of the living room shows an opposing trend to the trend of the bedroom. The CO_2 levels start to rise during noon, peak during the end of the evening and start to dip during the night. The extreme values are less extreme in comparison to the bedroom extreme values and the dispersion of the extreme values is more stable over the hours. This trend could indicate that the CO_2 levels rise when people are in the living room, namely during the day, and fall during the night, when people are in the bedroom.

Schaminée then goes on to study the relations between some of the substances, and characteristics of the dwelling, see table 8 for the prediction model for CO_2 levels and table 9 for the prediction model for $PM_{2.5}$.

Table 8. Regression coefficients of the prediction model for CO_2 levels.

	Model 1a		Model 1b		Model 2a		Model 2b	
	b	s.e.	**b**	s.e.	**b**	s.e.	**b**	s.e.
(Intercept)	785.729***	3.397	-232.021***	26.729	718.023***	1.854	-1515.029***	31.219
Hour1	-13857.743***	349.298	-8817.283***	297.852	8917.873***	223.249	4851.791***	178.801
Hour2	3219.482***	349.298	-1449.536***	296.585	7505.411***	223.249	3606.222***	179.434
Hour3	10003.394***	349.298	5464.399***	295.027	-5653.293***	223.249	-2880.235***	173.669
TVOC [l]			729.597***	14.613			292.508***	7.549
Relative Humidity [l]			407.434***	19.075			1052.514***	16.028
Temperature [l]			373.959***	30.147			1869.087***	30.135
Double glass [r]			-	-				
HR glass			-60.759***	6.379				
Triple glass			348.655***	9.542				
Mechanic ventilation system [r]							-	-
No ventilation system							-27.960***	3.258
Most of time window open while cooking [r]							-	-
Sometimes window open while cooking							3.540***	8.262
Rarely window open while cooking							4.408***	7.966
R-squared	*0.190*		*0.468*		*0.189*		*0.531*	
RMSE	*349.275*		*281.833*		*217.306*		*177.577*	

AIC	*153825.7*	*149391.1*	*198022.9*	*191503.9*
BIC	*153862*	*149763.8*	*198060.8*	*191579.7*

Note: *significance levels need to be interpreted with caution because of the high number of data points.*
**** p<.001; **p<.010; *p<.05. [l] = logarithmic transformed and normalised. [r] = Reference category, training set = 75%.*
Random seed = 123, N = 14.097

Table 9. Regression coefficients of the prediction model for $PM_{2.5}$ levels.

	Model 3a		Model 3b		Model 4a		Model 4b	
	b	s.e.	**b**	s.e.	**b**	s.e.	**b**	s.e.
(Intercept)	5.329***	0.059	-0.815***	0.5579	5.494***	0.097	23.066***	1.799
Hour1	22.271***	6.081	34.937***	6.2402	160.842***	11.725	146.494***	11.855
Hour2	75.031***	6.081	60.774***	6.2105	161.106***	11.725	77.463***	11.926
Hour3	-17.618**	6.081	-28.746***	6.181	-120.355***	11.725	-111.232***	11.530
TVOC^{l}			1.9927***	0.307			13.542***	0.504
Temperature^{l}			7.310***	.0624			-17.858***	1.926
Relative Humidity^{l}			2.248***	0.405			-10.168***	1.017
Floor isolated			-1.152***	0.119				
Wall isolated			-1.852***	0.130			-4.701***	0.271
Extractor regularity: never^{r}							-	-
Extractor regularity: sometimes							-0.048***	0.342
Extractor regularity: half of time							-3.796***	0.343
Extractor regularity: most of time							-1.020***	0.234
R-Squared		0.016		0.065		0.032		0.087
RMSE		6.199		6.107		12.069		11.721
AIC		68175.33		67642.51		112560.30		111479.80
BIC		68211.66		67715.17		112598.20		111570.80

***Note:** significance levels need to be interpreted with caution because of the high number of data points.*
**** p<.001; **p<.010; *p<.05. ^{l} = logarithmic transformed and normalised, ^{r} = Reference category, training set = 75%.*
Random seed = 123, N = 19.336

The data in this section were shown to illustrate that the measurements are plausible and interpretable; we found the trends that we expected and found them to correlate with factors that we expected. Further analysis of these data is foreseen. If the analysis is further advanced by the end of the ESSnet, we will include further findings in the final documents.

5. Phase 2'

Phase 2' is about deriving and summarizing statistics from the sensor data and the machine learning necessary to calculate these. Our thinking on how to use this kind of data is not yet strongly developed. The analyses so far have used regular linear analysis techniques. Machine learning algorithms have been developed by the manufacturer, that form the basis of the participant feedback on the app and in the monthly overviews. The first step, thus, would be to develop these algorithms ourselves. The developed algorithms should be used for automatic peak detection, determination of source strength, automatic room detection and source detection for cooking on gas and candles. In addition, an algorithm needs to be developed that detects server breakdown, as happened during the NL data collection period.

Before the end of the ESSnet, we envisage doing more data analysis, including the German and Belgian data that are so far not analysed at all. These analyses will be reported in deliverable 2.5.

6. Summary and conclusions

Quoting from the review of Scherpenzeel (2022, p1): '*The measures of indoor environmental quality which are tested in this deliverable constitute an enrichment of survey data, as such environmental parameters cannot directly be observed and hence not measured by questionnaires. Moreover, they are 'passive' forms of measurement, for which respondents do not have to fill out lists of questions, wear devices on their body, or perform tests or other activities. […] In other words, this report is not only about new methods of data collection, but actually about new data'.*

With the topic of measuring indoor climate we have touched upon a subject that is near to participants' hearts. In addition, no more incentive than the feedback on the indoor environment of the home appears to be necessary. To be sure, the participants in the three pilots were not representative of the general population, being colleagues, friends and families, probably highly motivated and highly educated. The results of the pilot in the Dutch LISS panel indicated that in some, but not all, groups in the population the potential acceptance of a measurement system in the home is very high, depending on the framing of the consent question and the characteristics of the respondent. To be sure, also these panel members are not entirely representative of the population, in terms of willingness to participate in surveys and additional tasks.

However, we are not yet ready to fully embrace the technology in the state that we have tested in this work package. There are still important considerations and questions to be addressed before we could think about large scale population surveillance. We summarise the most important ones here.

The first concerns the quality of the data that are measured. We have been unable to receive satisfying information from the distributer on measurement precision and reliability, nor on the calibration algorithms that are used for the sensors. Even though one study (Baldelli, 2021) showed satisfying measurement quality for some of the sensors (the other ones were not studied yet), this lack of openness is disturbing. We have found on the other hand, that the data analysis shows interpretable results with at least face validity. The consensus among the experts is that sensors can give an impression of the relative variation over time. The question is, of course, if that is good enough for our purposes. Precise definition of those purposes will help answering this question.

One of the substances measured was TVOC: the Total of Volatile Organic Compounds. Baldelli (2021) already showed that the measurement of VOC's cannot be accomplished precisely enough, something that was also mentioned by Piet Jacobs, one of the experts we consulted. In our pilots, this feature led to considerable unrest with some of the participants. The level of TVOC would often show very large 'unhealthy' peaks, and participants who googled the possible impact of high levels of TVOC on health became very frightened. In addition, it was often unclear where the high peaks originated from, and what could be done to alleviate the situation. We need to be absolutely certain that we do not frighten participants without due course, and should rather refrain from measuring substances that cannot be measured with relatively cheap sensors.

If we implement this kind of measurement for population surveillance we need to be sure of what we are measuring. Ideally, this entails having potential sensors checked against professional benchmarks, e.g., those of the National Institute of Public Health and the Environment or the Institute of Applied Scientific Research.

On the other hand, the large advantage of the commercial device chosen, is the attractive Application Programming Interface (API) between the uHoo and the participant's smartphone and the professional backend that allowed easy generation of worthwhile and professional overviews on various levels of abstraction. This is why we were able to send monthly feedback overviews to participants without much trouble; see appendix 4 for an example. The API showed the participant the state of their indoor environment on their smartphone at any moment. The drawback of this, however, is that a large part of participants changed their behaviour as a result of what they learned. Mostly, this entailed airing more often and for longer periods of time, although more radical reactions were also witnessed. The feedback that participants receive is probably the main reason why they participate, but we need to find a way to deliver that feedback without influencing participants' behaviour, e.g., only at the end of the measurement period. With a device that needs the participant to download an app, this is however not so easily accomplished. Perhaps we stumbled on the solution thanks to the two German participants who connected the uHoo to WIFI with their own email address and password, with the result that they could not see the data on the app, while the administrator still received the data in the cloud environment.

Another issue for concern, is that for a substantial minority of participants the installation of the app and the device was far from smooth. Several struggled and had to try several times, either by resetting the device or by restarting the app. This is a level of devotion that is probably not to be expected in the general public, and this issue could potentially cost many respondents in large scale surveillance. The solution chosen in the large scale and long running 'Be Aware' project, see appendix 2, was to have the devices installed by a firm, but that would take a heavy toll on any project's budget. Another option is to choose a device that doesn't need to connect to the internet, but that stores the data on the device. This solution would also solve some of the privacy and security issues concerned with the use of a commercial cloud environments, like the one used in this project. See deliverable 2.8 – Living conditions for an in-depth discussion of this issue.

For comparable and good quality measurement, it is important that participants follow instructions on the positioning of the device, both in terms of location, and in terms of the position within the location. A substantial part of our very dedicated participants did, however, not follow these instructions. We need to better stress in the instruction how important it is that they are followed.

There was a remarkable difference between the countries in the degree that they found the data to be sensitive, with 48 % of respondents in the Netherlands finding these data sensitive, 42% of Germans[7], but only 10% of Belgians. Overall, indoor air sensor data is considered uncritical by most

[7] Regretfully, the question as translated in German contained a double negative. It is unclear if all respondents picked up on the precise direction of the answering categories.

when it comes to data sensitivity. However, this only applies as long as no context data or otherwise related data is also being collected (on the same device). Nevertheless, these data are potentially very sensitive, as they allow inferences about the number of household members and their absence and presence patterns. It is crucial that participants understand that the data will be analysed only for their intended purpose of learning about indoor environment.

Deriving statistics from these data may be relatively straightforward (what is the mean level of exposure, what is the maximum, what is the duration of maximum exposure, etc.), but the more interesting and relevant information comes from understanding the measurements and understanding their relation with health indicators. Bluyssen (2014) indicates that if we want to make a step forward in assessing the health and comfort of a building, all types of indicators at different levels are potentially important to consider: dose-, occupant- and building-related indicators. So far, there is not yet enough data to make the ultimate analysis of all factors and indicators per scenario possible. NSI's are in the unique position to produce large scale data with uniform methodology. In addition, in order to understand the multitude of mutual dependencies, the analyses need to step away from linear-based analysis techniques towards more advanced data science techniques.

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Appendix 1. Elements of indoor environment quality

4 elements of indoor environment quality are distinguished, each with subcategories:

1. Air Quality
    a. Chemical pollutants
        i. Inorganic gasses: carbon monoxide (CO) and dioxide (CO_2), Nitrogen oxides (No_x)
        ii. Volatile Organic Compounds (VOCs)
    b. Physical pollutants
        i. Fine dust: coarse < 10µm (PM_{10}), fine ($PM_{2,5}$), ultra fine < 0.1µm
    c. Biological pollutants
        i. Molds, mites, fungi.
2. Thermal quality
    a. Temperature
    b. Humidity
    c. Air velocity
3. Lighting quality
    a. View, luminance ratio's
4. Acoustic quality
    a. Indoor and outdoor noise
    b. Vibrations

Appendix 2. TNO Be Aware project

This appendix shows the translation of the summary in the report written by Jacobs, P., Hoes, E., Vijlbrief, O, & Komaat, W. (2020). Public final report TKI Be Aware. Awareness of indoor air quality in homes: sources and effective energy-efficient intervention (in Dutch: Openbaar eindrapport TKI Be Aware. Bewustwording van binnenluchtkwaliteit in woningen: bronnen en effectieve energie-efficiënte interventie strategieën. TNO rapport R10627. Accessible at https://repository.tno.nl//islandora/object/uuid:2b40ecf6-f819-4fbb-93a9-514799c27568

The sensor system used in this project was the Philips AirVibe sensor, see the figure below. Like the uHoo system used in this deliverable, participants were able to see their values during participation.

Summary

The indoor air quality in homes often leaves much to be desired. The more energy-efficient homes are, the greater the risk of poor air quality. As a result, support for the transition to energy-efficient homes is declining. Insights into sources of pollution and appropriate energy-saving interventions are lacking. The aim of the Be Aware project is to gain insight into the fundamental aspects that determine indoor air quality, to automatically identify sources of indoor air pollution based on monitoring data and to provide appropriate energy-efficient interventions.

Measurements in 1000 dwellings.

The TKI Be Aware project builds on a measurement campaign of indoor air quality (temperature, particulate matter, CO_2, and RH) in 1000 dwellings launched by the Inhome Air Quality Consortium in September 2018. A full year has been analysed. Within this measurement period, Blaauw Research carried out several surveys of the occupants in order to map out their experiences with indoor air quality and to obtain a picture of the housing characteristics and the behaviour of the occupants. At the start of the measurement, sensors were installed in 859 homes. After the sensor data has been checked for reliability, 285, 137 and 101 dwellings remain for the winter period, the summer period and the full year, respectively. Despite the decrease in the number of dwellings in the dataset, based on 16 dwelling and occupant characteristics, the resulting dataset still appears to be representative for the initial dataset except for 2 characteristics.

Exceedance of recommended values $PM_{2.5}$ particulate matter

Literature research shows that $PM_{2.5}$ particulate matter is dominant in the disease burden caused by indoor environmental factors. The World Health Organization (WHO) has indicated that the advisory value for $PM_{2.5}$ of 10µg/m3 annual mean also applies to indoor areas. The annual average $PM_{2.5}$ concentrations in the living room/kitchen of the measured dwellings is 8.2 µg/m3 . In 15% of these dwellings the annual mean concentration is higher than the WHO annual mean recommended value. The concentration based on presence in the living room/kitchen is higher, see table 1-1. As this only concerns exposure in presence, these values are not comparable with the WHO annual mean recommended values.

Particulate matter intervention strategies

For measures for the reduction of particulate matter, the occupational hygiene priority should preferably be applied: as a first step, sources are removed, if this is not possible, compartmentalisation and source extraction are applied in the second step, and only then, as a third step, the pollution is diluted with ventilation or filtration. The source approach ensures 100% effectiveness. For example, stop smoking, stop cooking on gas and stop burning candles in the house. Compartmentalisation and source extraction can also ensure 100% effectiveness if carried out properly. However, this is much more sensitive to residents' behaviour. Dilution with ventilation is not very effective with fine dust and often results in discomfort and extra energy consumption. Filtering has fewer of these disadvantages. The literature indicates that the installation or improvement of air filters in the ventilation system or the installation of stand-alone air cleaners has a cost effectiveness of more than a factor 104. This means that the health benefit expressed in euros is a factor of 10 as high as the cost of the measure.

In order to determine the effectiveness of possible measures, emission profiles have been drawn up on the basis of the data from this project. The emission profiles are based on the measurement data of dwellings that do not have adequate cooking extraction, because the calculated cooking emissions for these dwellings are the most representative. In houses with an extractor hood, cooking emissions are (partly) removed. The surveys show that 48 out of 285 dwellings do not have an adequate extraction hood. For these dwellings, 50th and 90th percentile emission profiles have been derived based on the emission strength and frequency in the winter period, see Table 1. The ratio between the number of emissions at breakfast, lunch and dinner is approximately 1:3:10. It should be noted that, in particular during the preparation of dinner, concentrations may occur that are much higher than the annual mean outdoor concentration, which is currently about 11.5 µg/m3 in the Netherlands.

Particulate emissions in dwellings where residents have indicated that candles are burned are significantly different between 21 and 24 hours compared to dwellings where this is not the case. These emissions due to candles are not included in the emission pattern below in order to simplify the drafting of the emission pattern.

Table 1. PM2.5 concentration in the living room / kitchen based on 24 hour average and presence.

Indoor air concentration [μg/m^3]	winter n=268	summer n=131	entire year n=101
24 hours	9.0	8.1	8.2
Presence based on CO_2	10.0	8.6	8.9
Presence based on timing*	12.7	9.4	10.4

* weekdays betwenen 18 and 23h, weekend between 10 and 14h and between 18 and 24h.

Previous excess percentages refers to the average concentration as measured with the AirVibe sensor. From various studies it is known that fine dust meters based on optical measurement principles underestimate the concentration in case of cooking as a source of fine dust. This has been corrected in a simulation. This leads to the situation that in almost 50% of dwellings the annual average WHO advisory value for $PM_{2.5}$ is exceeded.

The WHO daily mean advisory value for $PM_{2.5}$ of 25 μg/m3 is exceeded on more than 10 days a year (uncorrected). However, the variance is large, there are dwellings where this value is not exceeded on any day and dwellings where it occurs more often than 35 days a year.

Sources of particulate matter

Based on both the number of emissions and the source strength, cooking appears to be the largest indoor source of $PM_{2.5}$ particulate matter. Most emissions take place between 18 and 20 hours. On average during the heating season the contribution from indoor sources is 41%, with a spread between 0 and almost 100%. The infiltration factor, the effect of the outdoor concentration on the indoor concentration, is 0.52 on average. This means that in the absence of indoor sources, an outdoor concentration of 11.5 μg/m3 (mean value for the Netherlands) leads to an indoor concentration of 6 μg/m3. The mean infiltration factor is comparable to other studies reported in the literature.

Exceedance of recommended values for carbon dioxide

Carbon dioxide (CO_2) is used as a marker for indoor air quality in dwellings. The Health Council of the Netherlands uses a recommended value of 1200 ppm for CO_2. On average, the concentration in the living room in winter rises above 1200 ppm for 4 hours a week. The National Monitoring Survey3 shows that in approximately 60% of the more than 1200 living rooms in the 2004/2005 heating season the CO_2 concentration was higher than 1200 ppm for a shorter or longer period of time. In the dwellings where this was the case, this was on average 14 hours per week. In the TKI Monicair project, measurements were taken in 62 dwellings during the 2012/2013 heating season and the number of overrun hours in the living room was on average 11 hours per week. In BeAware, therefore, the number of CO_2 overrun hours is significantly less. A possible explanation for this is that the installation of the AirVibe has led to awareness and improved ventilation behaviour.

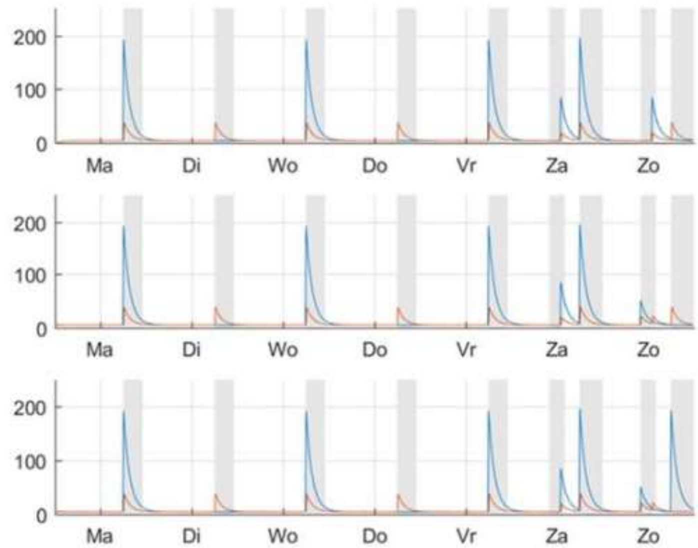


Figure 1-1 Resulting $PM_{2.5}$ concentration at the 50th (red) and 90th (blue) percentile emission pattern in the living room/kitchen during three weeks; the time periods assumed for presence in the living room/kitchen are shaded grey.

Simulations effect intervention strategies

Subsequently, COMIS simulations were carried out with these emission profiles for different outdoor air concentrations, type of ventilation system and domestic air densities in order to quantify the effect of the measures. Particularly at low outdoor concentrations, the effect of cooker extraction on the fine dust concentration in the living room is high. This is more pronounced at the 90th percentile emission pattern. This is due to the fact that in the simulations the majority of indoor sources are caused by cooking emissions. At higher outdoor concentrations, air cleaners become more effective because they also filter out particulate matter from outside air infiltration. For a dwelling with ventilation system D (balanced ventilation with heat recovery), cooking extraction and the combination of cooking extraction with an F7 (ISO $ePM^{2.5}$ - 70%) filter in the ventilation unit at a 50th percentile emission profile results in a 45% and 73% reduction during the period of presence in the living room / kitchen, respectively, see figure 1-2.

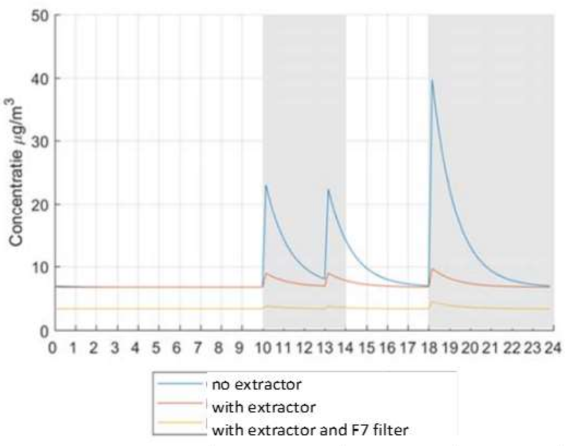


Figure 1-2. System D, 50th percentile emission pattern, course of concentration over time, the grey blocks indicate the period that is assumed that people are present in the living room / kitchen (Sunday, week 3).

Thereafter, the simulation results for the concentration of particulate matter in the living room during presence of people were combined with typical scenarios for presence to arrive at a typical weekly mean exposure. A fixed residence scenario was used for the period that people stay in the living room, in the bedroom, in the open air or at work. Table 2 shows the results for the weekly mean exposure to particulate matter for the 50th percentile emission pattern at different outdoor air concentrations. Simulations show that the combination of cooking extraction with decentralised air cleaners in the indoor environment gives the largest exposure reduction of 65% at an outdoor air concentration of 11.5 µg/m3 (the average outdoor air concentration in the Netherlands). This is because this combination tackles both cooking emissions and diffuse outdoor air infiltration through seams and cracks. The air cleaner also captures the part of fine dust that escapes the extractor hood.

The air cleaner also captures the part of fine dust that escapes during cooking. Another advantage of this intervention strategy is that it can be used with all ventilation systems, even in homes without a ventilation system (system A). The disadvantage of this combination is that it is a relatively expensive solution, consisting of at least two air cleaners, one in the living room / kitchen, and the other in the bedroom(s). The electrical energy consumption of this scenario is also relatively high, at over 2 kWh per day. This can be reduced to approximately 1 kWh by using demand-driven sensors integrated in the air cleaners.

Table 2. Weekly average exposure at three outdoor air concentrations in a dwelling with ventilation system C and D, a qv.10 of 80 dm3/s and 50th percentile emission pattern.

Oudoor concentration [µg/m3]	1		11,5		22	
exposure according to scenario:	[µg/m^3]	reduction	[µg/m^3]	reduction	[µg/m^3]	reduction
C, no cooking extraction (reference)	**3**		**7,4**		**11,8**	
C, with cooking extraction	0,7	76%	5,3	29%	9,8	17%
C, with air cleaner in living rooms	0,9	70%	3,2	57%	4,7	60%
C, with cooking extraction and air cleaners	0,4	86%	2,6	65%	4,7	60%
D, no cooking extraction (reference)	**2,5**		**8,2**		**13,8**	
D, with cooking extraction	0,8	67%	6,6	20%	12,3	11%
idem + F7 filter	0,6	75%	4,3	48%	8	43%
D, with air cleaners in living rooms	1	58%	3,8	54%	6,5	53%
D, with cooking extraction and air cleaners	0,5	80%	3,3	60%	6	56%
idem + F7 filter	0,4	83%	2,5	62%	4,6	67%

The combination cooker extractor and an F7 filter in the air supply can only be used in dwellings with balanced ventilation (system D). It is a relatively inexpensive, energy-efficient concept. In average houses the total exposure reduction is 48%, in very airtight houses even 58%. The heat loss as a result of ventilation and infiltration is a factor 7 lower when applying this concept than in a comparable very airtight dwelling equipped with ventilation system C. The energy consumption is low because of heat recovery from the ventilation air and because cooking heat is also recovered. The NeroZero demo house was developed with this concept in the TKI project VentKook. Considering the potential, energy savings and improvement of air quality, the recommendation is to further develop the combination of integrated cooking extraction in balanced ventilation with WTW with F7 particulate filtering into a widely applicable concept for new houses and renovation.

Algorithms

Compared to previous studies, BeAware is much larger in terms of both scale and duration. This makes it necessary to develop automatically working algorithms for data analysis. The developed algorithms can be used for automatic peak detection, determination of source strength, automatic room detection and source detection for cooking on gas and candles. In time, this will enable companies to develop new products and services that respond to consumer awareness, enabling them to make targeted interventions to improve the indoor climate.

Recommendations

Simulations based on large-scale monitoring data indicate that adequate boil extraction can reduce total $PM^{2.5}$ particulate exposure by 20-29%. It is recommended to combine such cooking extractors with decentralized air cleaners in existing homes. With this combination the total $PM^{2.5}$ particulate exposure can even be reduced by 65%,

In order to enable the wide application of this cooking extractor in energy efficient homes, it is necessary to revise building regulations and impose additional requirements, thus providing

300m3/hour supply and extraction capacity in the kitchen. When combined with an F7 filter in the air supply of houses equipped with balanced ventilation, this cooker extractor can reduce $PM_{2.5}$ fine dust exposure by 48% and in very airtight houses even by 58% (without the use of air cleaners). Energy saving and a healthy living environment go hand in hand.

In order to test the effect of the various interventions, it would be desirable to carry out an intervention study in which the air quality in several households is measured over a long period of time both before and after the intervention.

Appendix 3. Instruction uHoo

The instruction was given in Dutch to Belgian participants and in German for German participants.

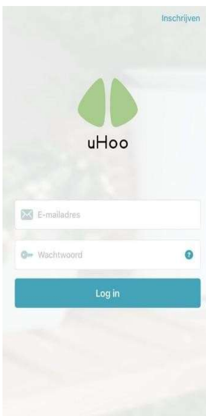
Thank you for participating in the first test with the uHoo's to measure indoor environment. The uHoo will stay with you for two months, one month in the living room and one month in the bedroom.

What should you do?

1. Install the **uHoo app** via app store or play store. Take the 'regular', free version.

2. Once the app is on your phone, it will ask you for an email address and password. For you that is

IEQtestCBS25@gmail.com and **testCBS25**



3. Follow the instructions within the app. You will need to pair the uHoo with your WiFi once. It will notify you that the WiFi is unsecured. You can ignore that message. It will also ask for permission to trace your location. Allow that as well. After installation you can undo that in the settings if you want.

4. After a few minutes the first measurements will be shown on the screen. Don't be alarmed if some values are very bad: the uHoo will need a few days to calibrate.

5. Ideally, set the uHoo at a height of about one and a half meters. If you have an open kitchen, put it between kitchen and living room. If you have a closed kitchen, put it in the living room.

6. Always keep the uHoo powered. In order to facilitate that, we included a two way jack in the package.

6. After one month I will send you an email with the request to move the uHoo to the bedroom.

7. After two months you can send the uHoo back to me. I will send you a return label by that time. Please keep the boxes in which the uHoo was packed.

I hope it all works out, but if not please send me an email (a.luiten@cbs.nl).

Appendix 4. Indoor climate overview

AirTeq.eu
Online monitoring

Periodic
Indoor climate
Report

Period: 12-04-2021 till 12-05-2021

Why:
You receive this periodic report through the AirTeq platform.

Set automatic period:
You can adjust the frequency of this report in the 'Reporting' tab in the portal. This can be per day, per week or per month.

App:
There is also a handy app available for your phone or tablet. How to install this can be found under the support tab.

Explanation portal/app:
Instructional videos are available under the support tab.

Limits:
The desired limit values for CO2 and temperature can be found under the tab 'documents'.

Sensor failure:
Under the support tab you will find a step-by-step plan in case a sensor has failed, so you can reinstall it yourself.

Questions:
Answers to most questions can be found under the support tab. It includes manuals and video instructions.

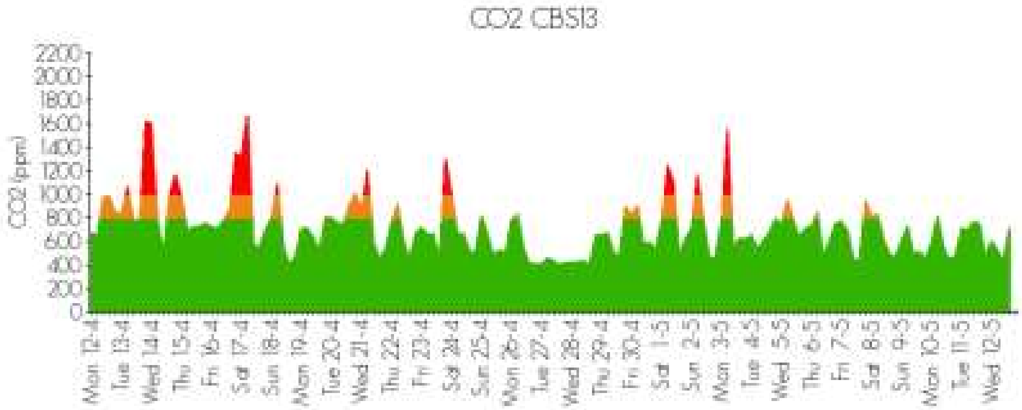
possibly Additional questions or additional research can be reported in the support tab.

Overview CBS-13
Period: 12-04-2021 t/m 12-05-2021:

	CBS13
Temperature Minimum in °C	20.4
Temperature Maximum in °C	25.3
Relative humidity Minimum in %	20.3
Relative humidity Maximum in %	47.0
CO2 Maximum in ppm	1671.0
CO2 Percentage time over 1000ppm	1.9
Particulate matter/PM2.5 Maximum in µg/m³	200.0
Volatile organic compounds/VOC Maximum in ppb	1200.0
Volatile organic compounds/VOC Average in ppb	220.6
Nitrogen dioxide/NO2 Maximum in ppb	103.2
Carbon monoxide/CO Maximum in ppm	0.0
Ozone/O3 Maximum in ppb	11.2

Continued on next page

CBS13 (CO2)



Detail report CBS13 (12-04-2021 - 12-05-2021)

Average CO2-value during office hours	624.6 ppm	
Highest daily average during office hours	841.2 ppm	20-04-2021
Highest measured value	1671 ppm	17-04-2021 09:11

Measurements optimal: 0 - 800ppm

This is the safe level of CO2 concentrations for extended periods of time.

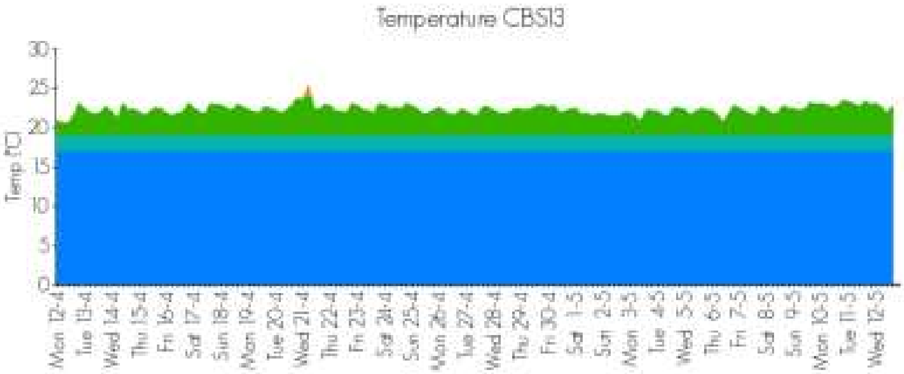
Measurements acceptable: 800 - 1200ppm

This CO2 level causes a decrease in mental performance and can lead to aggravation of complaints such as allergies for sensitive groups.

Measurements increased: > 1200ppm

At this level, steps should be taken to reduce exposure to CO2 in the air. More than 1200ppm can cause headaches, fatigue and drowsiness.

CBS13 (Temperature)



Detail report CBS13 (12-04-2021 - 12-05-2021)

Average temperatuurvalue during office hours	22.0 °C	
Highest daily average during office hours	22.8 °C	11-05-2021
Highest measured value	25.3 °C	21-04-2021 09:03

Measurements optimal: 21 - 26°C

This is the optimal range for humans that is considered comfortable, although specific occupations or people prefer slightly higher or lower temperature.

Measurements decreased: 10 - 21°C

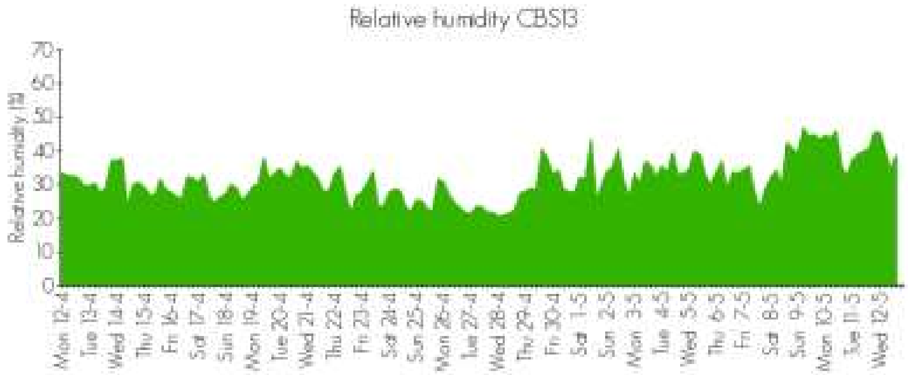
At this temperature, the body begins to feel uncomfortable with the cold and can cause chills and drowsiness. Some people may also become short of breath and have difficulty walking. Below 12°C, some people may have difficulty breathing and the cold can affect motor skills and reflexes, as well as the ability to respond to stimuli. It is also possible to become unconscious because your internal body temperature drops.

Measurements increased: 26 - 40°C

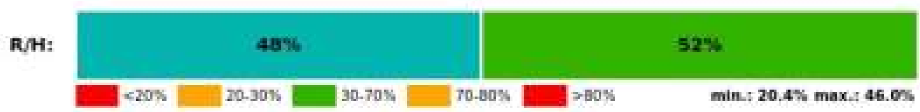
This temperature is uncomfortable and can cause problems with concentration. When it's this hot, heat cramps and exhaustion are likely, and most people should limit their activities to keep their body temperature down. Extremely high temperatures above 50°C are dangerous and can result in heat stroke, a serious condition defined by an elevated internal body temperature that can result in unconsciousness and the shutdown of internal organs.

AirTeq

CBS13 (Relative humidity)



Detail report CBS13 (12-04-2021 - 12-05-2021)



Average LV-value during office hours	30.4 %
Highest daily average during office hours	41.2 % 10-05-2021
Highest measured value	47.0 % 09-05-2021 09:46

Measurements optimal: 30 - 50%

This optimal moisture level prevents fungal infections, mold and mildew and helps to prevent the spread of bacteria. This range also reduces emissions of volatile organic compounds.

Measurements reduced: 10 - 30%

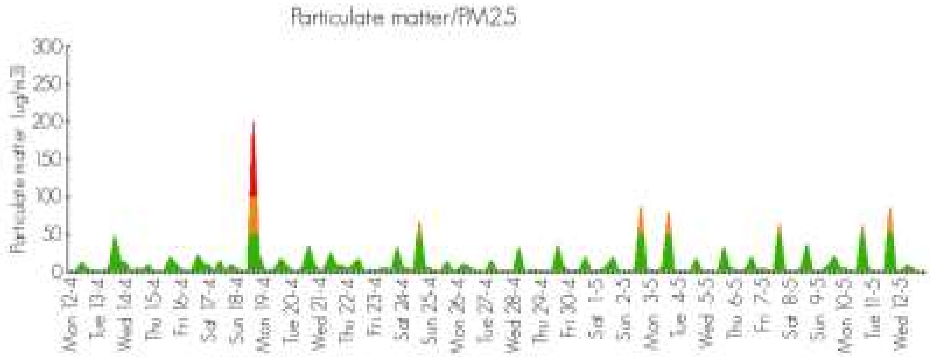
This reduced humidity, which can occur during the winter months, can cause dry skin, sore throat and itchy eyes. Because the skin is dry and flaky, conditions such as eczema can develop or worsen. Viruses such as the flu virus can survive in a room for extended periods with very low humidity.

Measurements increased: 50 - 100%

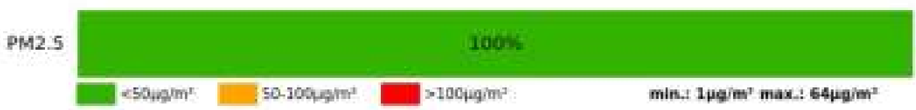
Too much humidity causes condensation in a room, which can stain walls, ceilings and furniture. It is also a risk factor for mold, which can cause odors and respiratory problems. Extended periods of high humidity can also cause rot and structural damage. High humidity can also cause allergic reactions and is a problem for people with respiratory problems. High humidity, which is above 70%, increases the level of moisture in a building. Bacteria and dust mites thrive in moist and humid environments. It also breeds harmful fungi that can exacerbate allergies and asthma attacks.

AirTeq

CBS13 (Particulate matter/PM2.5)



Detail report CBS13 (12-04-2021 - 12-05-2021)



Average PM25-value during office hours	4.0 µg/m³
Highest daily average during office hours	8.5 µg/m³ 21-04-2021
Highest measured value	200 µg/m³ 18-04-2021 20:10

Measurements optimal: 0 - 50ug/m3

This is the safe level of concentrations for PM2.5 in the air for short periods of time. There is little to no risk associated with these levels. Over a period of 24 hours, it is advised to keep the average measured value lower than 35 mg/m3.

Measurements acceptable: 50 - 100ug/m3

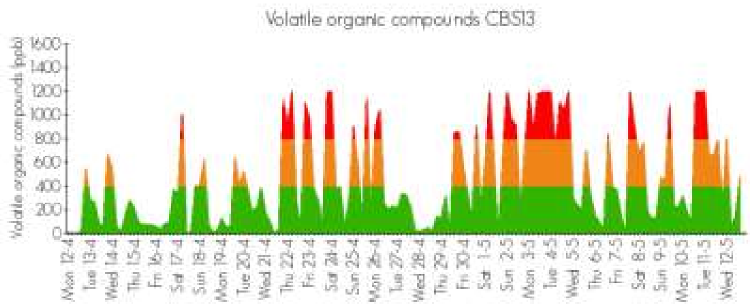
This level of particulate matter may be considered unhealthy for sensitive groups, such as those with respiratory problems, for an extended period of time. Over a 24-hour period, an average of 36 to 55 mg/m3 is considered unhealthy. People who are sensitive to particulate matter can develop breathing problems at these levels, with the most vulnerable risks being an aggravation of heart and lung disease. Exposure to amount of particles over a prolonged period of time is considered unhealthy and can cause respiratory problems for all people in all age groups.

Measurements increased: 100 - 200ug/m3

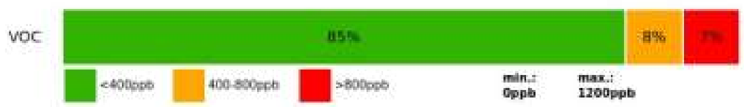
At this level, immediate steps should be taken to reduce exposure to airborne PM2.5. More than 150 mg/m3 causes significant deterioration of heart and lung function and can cause premature death in people with cardiopulmonary disease or in the elderly

AirTeq

CBS13 (Volatile organic compounds/VOC)



Detail report CBS13 (12-04-2021 - 12-05-2021)



Average VOC-value during office hours	220.6 ppb	
Highest daily average during office hours	1022.8 ppb	03-05-2021
Highest measured value	1200 ppb	22-04-2021 07:18

Measurements optimal: 0 – 400ppb

This is the acceptable level of TVOC in a room and no adverse health effects should be expected.

Measurements acceptable: 400 – 800ppb

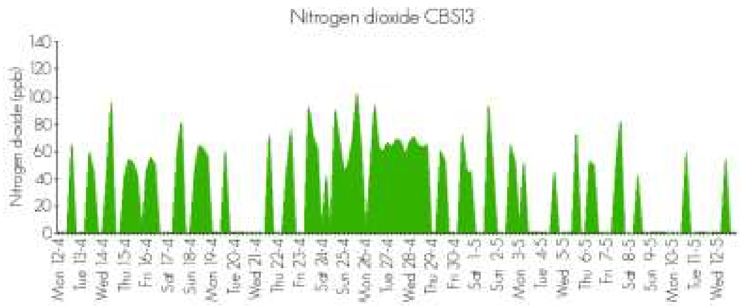
Short exposure (hours to days) can cause headaches, nausea, dizziness and irritation of the respiratory tract and eyes. It is important to identify and eliminate the sources of volatile organic compounds.

Measurements increased: 800 – 1100ppb

Prolonged exposure (months to years) to high TVOC levels can cause liver damage, kidney damage and cancer. Usually, this level of damage will only occur with long-term chronic exposure. Eliminating the source of VOC must be done.

AirTeq

CBS13 (Nitrogen dioxide/NO2)



Detail report CBS13 (12-04-2021 - 12-05-2021)

Average NO2-value during office hours	28.4 ppb	
Highest daily average during office hours	66.3 ppb	26-04-2021
Highest measured value	103.2 ppb	25-04-2021 19:21

Optimum readings: 0 - 100ppb

In general, no symptoms will be found in people exposed to this amount of nitrogen dioxide.

Measurements acceptable: 100 - 250ppb

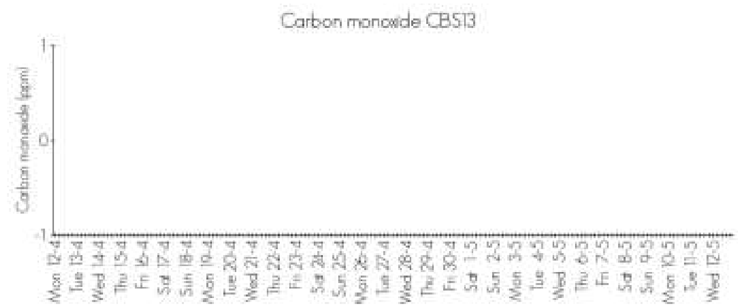
Nitrogen dioxide concentrations in this range have been shown to cause breathing problems in people with lung disease, such as asthma.

Measurements increased: > 250ppb

This level of nitrogen dioxide concentration causes discomfort and potential health problems for everyone, regardless of health and age.

AirTeq

CBS13 (Carbon monoxide/CO)



Detail report CBS13 (12-04-2021 - 12-05-2021)

CO 100%

<35ppm 35-70ppm >70ppm **min.: 0.0ppm** **max.: 0ppm**

Average CO-value during office hours	0.0 ppm
Highest daily average during office hours	0.0 ppm
Highest measured value	0 ppm

Measurements: 0 - 35ppm

This is a safe level of exposure to carbon monoxide. In most people, there are no symptoms when exposure is up to 70 ppm over an 8-hour period. The maximum exposure for 1 hour is 35 ppm by the US standard, which should not be exceeded by more than one exposure per year.

Measurements: 35 - 70ppm

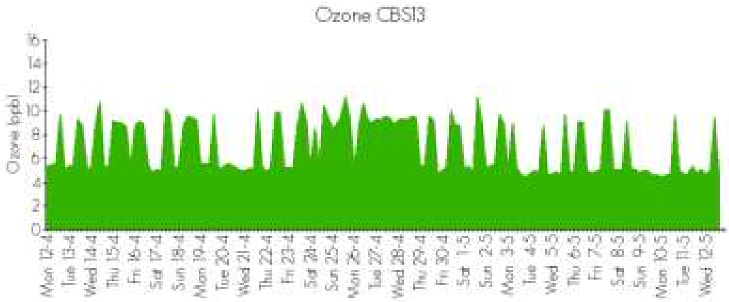
People may begin to experience headaches, fatigue and nausea as soon as CO levels exceed 100 ppm during an 8-hour exposure period. Those with heart conditions may begin to experience chest pain.

Measurements: 70 - 100ppm

Exposure to this level of carbon monoxide is dangerous and can lead to disorientation. Exposure to 400 ppm for 3 hours can be life-threatening, causing unconsciousness and eventually death. At 800 ppm, just one hour of exposure can lead to unconsciousness, with death at 2 to 3 hours.

AirTeq

CBS13 (Ozone/O3)



Detail report CBS13 (12-04-2021 - 12-05-2021)

O3 100%

<30ppb 30-70ppb >70ppb **min.: 4.3ppb** **max.: 10.8ppb**

Average O3-value during office hours	7.2 ppb	
Highest daily average during office hours	9.5 ppb	26-04-2021
Highest measured value	11.2 ppb	25-04-2021 19:21

Optimum readings: 0 - 30ppb

With ambient values of up to 70 ppb, comparable to levels in nature, ozone is effective at neutralizing odors and reducing volatile organic compounds, mould, air and surface bound bacteria and viruses. However, the sensitivity to ozone depends on each individual. More sensitive individuals may experience dry throat, headache, nausea, and shortness of breath.

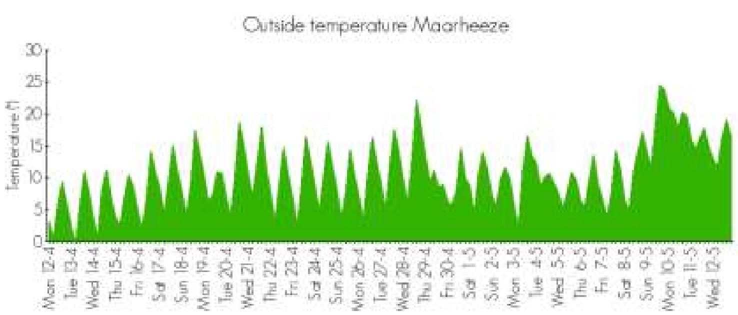
Measurements acceptable: 30 - 70ppb

Those who are sensitive to ozone may experience allergies, nausea, headaches or dryness of the throat.

Measurements increased: > 70ppb

High ozone concentrations can increase the risk for certain lung diseases and lung damage for all demographics. Respiratory levels of Ozone (O3) above 70 ppm can cause a variety of health problems, particularly for children, the elderly and people of all ages who have lung diseases such as asthma.

AirTeq



Appendix 5. Participant questionnaire

The questionnaire was developed in Dutch. This version was used in the Netherlands and Belgium. A rough translation was made by DeepL translation software, and subsequently adapted for the German participants.

1. What is the location of your house?

    1 In Amsterdam, Rotterdam, The Hague or Utrecht
    2 Other city
    3 Village in urban area
    4 Village in a rural area

2. What is the year of construction of your house? If you are not sure, try answering question 2a.

    Year built:

2a. If you do not know (precisely), do you know approximately what the year of construction is?

    1 Before 1960
    2 1960-1979
    3 1980-1995
    4 1996-2010
    5 After 2010
    6 Do not know

3. What is the surface of your living room? Do not include an open-plan kitchen, if any. Do you not know exactly? Then try answering question 3a.

    area:

3a. Can you give an estimate of the surface area?

    1 Less than 20 m2
    2 20-24 m2
    3 25-29 m2
    4 30-34 m2
    5 35-39 m2
    6 40-49 m2
    7 50 sqm or more
    8 do not know

4. What type of home do you live in?

    1 Owner-occupied → question 5
    2 Rented accommodation from a landlord → question 4a
    3 Rented accommodation from another landlord → question 4a

4a. What is the total monthly rent? This is the amount you / your household pays to the landlord or owner each month.

    Amount:

5. Do you have an open staircase in the living room? Yes/no

6. What type of kitchen do you have?

1 Open kitchen
2 Semi-open kitchen
3 Closed kitchen

7. What type of cooker do you use?

1 Gas
2 Electric

8. Does your house have a whole-house ventilation system, such as mechanical or balance ventilation? With both systems, the dirty air is removed to the outside. With balanced ventilation, clean air is also brought back in. The clean air is heated by the polluted air that goes outside again. A heat recovery system is often used.

1 No
2 Yes, mechanical ventilation
3 Yes, balanced ventilation
4 Do not know

9. What type of extractor hood do you use[8]?

1 Recirculation
2 Motorless on ventilation system
3 Motor directly to the outside
4 Do not know

10. How is your house heated? (more answers possible)

1. A "normal" central heating boiler (HE boiler or VR boiler)
2. A wood or pellet boiler
3. A heat pump
4. Block, district or city heating
5. A wood-burning stove or pellet fire
6. A gas stove or gas fire
7. Something else
8. Not applicable: no heat supply

11. Does your home have a fireplace or stove that can burn wood or wood pellets? Fireplaces with 'fake wood' that burn gas or gel are not included.

[8] The answer category 'I do not have an extractor hood' was not provided but was sometimes added by the respondent in the questionnaire, that was made in a format that respondents could freely add comments to the questions and their answers.

1 yes → questions 11a and 11b
2 no → question 12

11a. You have indicated that you use a wood or pellet-fired boiler, stove or fireplace. What do you have? (multiple answers possible)

1. A wood fired boiler
2. An open fire
3. An insert or built-in wood fire (with door/glass panel)
4. A freestanding wood stove
5. A pellet boiler
6. A pellet stove

11b. During the past 2 months, since the installation of the uHoo, on how many days did you / your household burn wood or pellets?

1. Not a single day
2. 1 to 5 days
3. 6 - 20 days
4. 21 to 60 days

12. How often is the extractor hood turned on when cooking in your home?

1 Rarely or never
2 Sometimes
3 About half the time
4 Most of the time
5 Always

13. How often is the window opened during cooking?

1 Rarely or never
2 Sometimes
3 About half the time
4 Most of the time
5 Always

14. How often do you (stir) fry in the morning?

1 never
2 Less than once a week
3 1-2 times a week
4 3-4 times a week
5 5-6 x per week
6 daily

15. How often do you (stir) fry in the afternoon? (same answering categories)

16. How often do you (stir) fry in the evening? (same answering categories)

17. How often is the oven used? (same answering categories)

18. How often do you use an airfryer? (same answering categories)

19. How often are candles burned? (same answering categories)

20. How would you rate the air quality in your home on a scale of 1 to 10? 1 is extremely bad, 10 is extremely good: [1..10]

21. How do you rate the air quality in your neighbourhood on a scale of 1 to 10?

22. Are you concerned about the air quality in your home or living environment?

1 never
2 rarely
3 Sometimes
4 regularly
5 always

23. Is your home insulated? (several answers possible)

1. Yes, the facade / exterior walls
2. Yes, the roof
3. Yes, the floor
4. No, none of these

24. What type of glass are most of the windows in your living room made of? If it is HR(+/++) glass, this is usually mentioned on the aluminium strip between the glass panes. In case of Triple glazing / HR++ glass, there are 3 glass panes and therefore also 2 aluminium strips.

1. Single glazing
2. Normal double glazing
3. HR(+/++) double glazing
4. Triple glazing / HR++ glass
5. Do not know

25. What type of glass do most of the windows in the bedroom(s) have?

1. Single glazing
2. Ordinary double glazing
3. HR(+/++) double glazing
4. Triple glazing / HR++ glass
5. Do not know

26. How satisfied are you with your home?

1. Very Satisfied
2. Satisfied

3. Not satisfied, but not unsatisfied either
4. Dissatisfied
5. Very dissatisfied

27. Is it possible to get the house comfortably warm? Yes/No

28. Do you experience any draughts in the house? Yes/No

29. Do you suffer from moisture or mould in your home?

1. Yes → question 29a
2. No → question 30

29a. In which room(s) do you suffer from mould? (more than one answer possible)

1. Bathroom
2. Toilet
3. Kitchen
4. Bedroom(s)
5. Living room
6. Hallway/Corridor
7. Cellar (box)
8. Other room(s)
9. No room at all, only trouble with dampness

30. How many people in the household? [n]

30b. Are there children in your household? Yes/No

31. In general, how is the health of you and your housemates? [matrix for n household members]

1. Very Good
2. Good
3. Not bad
4. Sometimes good and sometimes bad
5. Bad

32. Are there any lung diseases in your household?

1. No
2. COPD
3. Asthma

33. Where did the uHoo stand in the first month of the measurement period

1. In the living room
2. Between the living room and the kitchen
3. In the kitchen
4. in another place

34. Did the uHoo stand at the recommended height of about 1.5 meters?

1. yes
2. no, higher
3. no, lower

35. In your opinion, did the uHoo always measure?

1. yes → question 36
2. no, there have been periods in which the uHoo did not measure → question 35a

35a. What was the reason that there were periods during which no measurements were made?

1. the uHoo was disconnected from the power supply
2. the WiFi connection was broken
3. other reason, namely:

36. Did you look at the measurements of the uHoo on your app?

1. Very often
2. Regularly
3. Occasionally
4. Rarely
5. Never

37. Have you changed your behaviour as a result of the measurements?

1. Yes → question 37a
2. No → question 38

37a. What did you change? [open]

38. Do you find the uHoo measurements privacy sensitive? Yes/No

Appendix 6. LISS indoor environment questionnaire

The following are some questions about air quality in and around your home.

1. How would you rate the air quality in your home environment on a scale of 1 to 10?

1 is very bad, 10 is very good [1..10]

2. How would you rate the air quality in your home on a scale of 1 to 10?

1 is very bad, 10 is very good [1..10]

3. How often, if at all, do you worry about the air quality in your home or living area?

1 Never
2 Rarely
3 Sometimes
4 Regularly
5 Always

4. How satisfied are you with your home?

1. Very satisfied
2. Satisfied
3. Not satisfied, but not dissatisfied either
4. Dissatisfied
5. Very dissatisfied

5. Do you manage to get the house comfortably warm? Yes/No

6. Do you suffer from drafts in the home? Yes/No

7. Do you suffer from moisture or mould in your home? Yes/No

8. How many people does your household consist of, including yourself? [..]

9. In general, how is the health of you and your household members? (Matrix for N persons, see question 8)

1. Very Good
2. Good
3. not good, not bad
4. bad
5. Very bad

10. Do you or any of your household members have a lung disease? (matrix for n persons)

1. no

2. yes, COPD
3. yes, asthma

11. It is well known that air quality has a great impact on our health. This applies to the air quality outside, but also inside the house. There are small devices that can measure the air quality in your home, such as the amount of CO2, nitrogen and particulate matter. We would like to install such a device in your home to do research on the relationship between indoor climate and health.

To get a good picture of the air quality in your home, the device must measure the air quality #location for two months. The results will show you #why. #Feedback. #Picture. #Edit.

May we place such a device in your home? Yes / No

See below for the variants of each of the #location, #why, etc. imputations.

#location

1. measure in the living room.

2. measure, including one month in the living room and one month in your bedroom.

#why

1. whether the air quality in your home is healthy.

2. whether the air quality in your home is healthy, what, if anything, is wrong, and what you can do about it.

#feedback

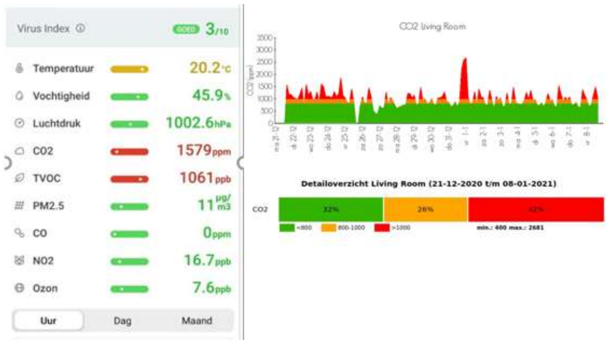
1: Via a smartphone app, you can check the air quality at any time.

2: At the end of the two months you will receive an extensive overview of the air quality during the measuring period.

#picture?

1: [empty]

2: Here is an example of the type of information you will receive:



#edit

1. [blank]

2. You can decide after two months if we can use your indoor climate data for research.

12. Can you tell us a bit more about why you do or do not want to put a device in your house to measure the air quality? [open]

14. You have just answered the question about whether CentERdata may place an air quality meter in your home. Below we will ask this question a number of times, but always with small variations in the text. Please read the question carefully, and indicate how likely it is that you would place the device in your home, if you were invited with this text.

Another 4 times random assignment of the 31 remaining combinations.

variant2

How likely is it that you would place the device with this invitation on a scale of 0 to 5 where 0 = definitely not and 5 = definitely yes. [0..5]

15: variant3

How likely is it that you would place the device with this invitation on a scale of 0 to 5 where 0 = definitely not and 5 = definitely yes. [0..5]

16: variant4

How likely is it that you would place the device with this invitation on a scale of 0 to 5 where 0 = definitely not and 5 = definitely yes. [0..5]

17: variant5

How likely is it that you would place the device with this invitation on a scale of 0 to 5 where 0 = definitely not and 5 = definitely yes. [0..5]

(if possible with paradata to show if they indeed read carefully, or skipped to the answer)

18. Finally, some questions about technology use.

Do you have a smartphone?

1. Yes
2. No --> Q21

19. Do you normally use your smartphone for the following activities on occasion [Matrix: Yes/No]:

Visiting websites
Reading or writing emails
Taking photos
Taking videos
Using social media, e.g. posting or reading messages, photos or videos on Facebook, Twitter, Instagram
Installing new apps, e.g., through Apple's App Store or the Google Play Store
Using GPS/location apps, e.g. Google Maps, Foursquare, Yelp
Playing music or video via the Internet

21. How would you describe yourself in terms of adapting to new technological developments on a scale of 1 (I'm a forerunner) to 5 (I'm a follower), where 3 means 'I'm not the first, but I'm not the last either?

[1..5]

22. In general, how concerned are you about your privacy?

1. Very concerned
2. Concerned
3. Not concerned
4. Not concerned at all

(standard CentERdata thanks)

Appendix 7. Destatis test report

Test Report: Qualitative Findings on Fielding the "uHoo" Air Quality Sensor

ESSnet Smart Surveys – WP 2.4. Living Conditions

Johannes Volk, Daniel Knapp, Anja Sommer

Destatis – Sect. B 22
January 2022

About this Report

- As part of the ESSnet "Smart Surveys" project, Destatis evaluated indoor air quality sensor devices ("uHoo") in regards to its possible future usage in official statistics. This report documents our findings of the test.
- The report focuses on qualitative aspects obtained by conducting several focus groups. It provides insights into device and app usage of respondents, possible impacts on their behaviour, expectations and required functionalities by participants, as well as privacy and data security concerns, thereby revealing potential barriers that have to be overcome before fielding smart sensor devices for official statistics.
- The first part of this report presents a short summary of the main findings. In the second chapter, we briefly describe the methodological aspects of this study. Afterwards, in-depth results of the four main areas of concern are provided: interest and app usage, impact on behaviour, expectations and required functionalities and privacy and data security concerns.
- Please consider that this test was conducted internally with 20 Destatis colleagues, not with random external test persons.

Agenda

Summary

Starting with this test we could easily find colleagues who were interested to take part, which means to have an indoor air quality sensor (uHoo) for seven weeks in their flat. Nonetheless, the interest in indoor air quality varied. Especially persons with issues (like mould in their apartment or health problems) had a greater interest in indoor air quality. In our focus groups we learned that using a device for measuring the indoor air quality can increase the interest in this topic, at least for some time. In the beginning, participants retrieved their values in the app almost every day but for almost all the use of the app decreased during the test phase. That was mainly because there were no new findings anymore. Therefore, the interest in long-term measurements is rather low.

Concerning the app's functionalities and content we can report that, overall, test persons were satisfied with the evaluations offered by the app. While the reported values were a surprise in some few cases, it was particularly the increasing of TVOC (which is a rather unknown parameter) that concerned the participants. Here, participants wanted more information, to identify the source of the increase in this value and to get recommendations on how to react.

During the seven week field phase the majority of participants was not (constantly) aware of the device in their apartments and of those who were, most did not experience a stronger feeling of 'being watched'. Reasons being a general trust in this research study and a mostly unobtrusive design of the uHoo device used. In future studies, a device should therefore be designed as small and unobtrusive as possible, and ideally not resemble any commercially available, well-known smart home devices.

Besides the awareness of the device, a potential change in behaviour was an important topic we brought up in the focus groups. As soon as participants receive reports of poor values regarding their indoor air quality, it must be assumed that they will adjust their behaviour. There are some differences if participants are not familiar with the reported indicator and if they are not convinced that another value is aspirational. But in order to avoid influences on the data due to the fact that there is a measurement, a survey design should be chosen in which the test subjects do not see the data (immediately) but, for example, only at the end of the survey. Unfortunately, we can only speculate about the willingness of participation in such a setting.

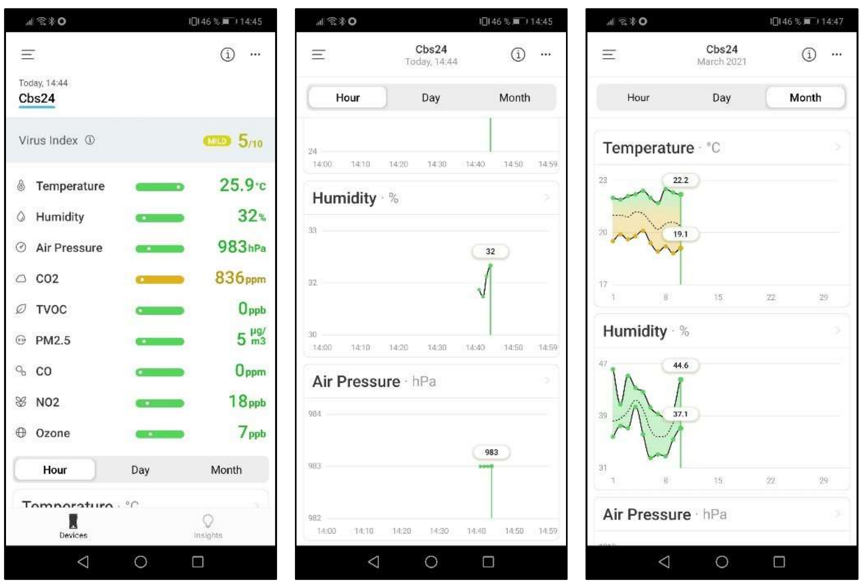
Data sensitivity is another factor, which potentially influences participation. In our test it is considered mostly uncritical or rather low when it comes to indoor air sensor data per se, as opposed to other forms of sensor measures, e.g. smartphone data. We can therefore conclude that this will not be an impediment to participating in future studies or even national surveys. It is important however that the assessment varies depending on whether and how much context data has to be supplied. Context data that is needed should therefore ideally be collected independently of the sensor device, and not via a third party app. To further reduce or even eliminate concerns and increase willingness to participate, data should ideally be stored offline on the device and not be sent via WiFi to a cloud, and third-party suppliers should be avoided or at least chosen according to their publicly perceived trustworthiness.

Methodology

About the "uHoo" test devices

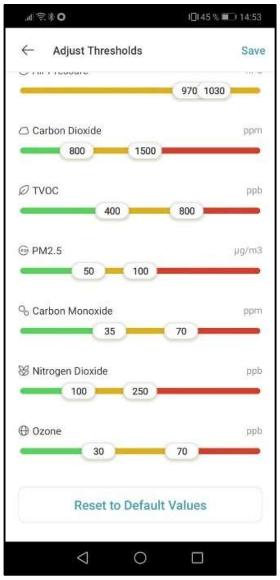
The "uHoo" test device is a low-budget, commercially available sensor to track indoor air quality. It stores data on a European cloud, thereby assuring adherence to European GDPA requirements, and allows access and download of the generated raw data.

- Via a set of algorithms, the device transforms data measured into a user-friendly app display that is easy to understand.
- It measures the indoor quality 24 hours a day and provides real-time feedback, made possible by having it connected to the local WiFi of the user.
- The device comes with a user-friendly app (available in the common app stores), which is required to install the uHoo at home.
- The app allows to examine and interact with the air quality measurements at any given moment:



App-screenshots show: all nine air quality indicators with their current measures and limit exceedances in colour (left), as well as fluctuation of specific values within either one hour (middle) or one month (right).

- The uHoo app defines a range of appropriate values for every indicator. This range is marked green. In subsequence there is a range marked orange and afterwards a range with bad values marked red. All these thresholds can be adjusted by the user for every indicator and can also be reset to the default values easily.



This App screenshot shows the surface for the adjustment of desired warning thresholds for all values.

- Other than showing real-time measurements, the app also allows setup of push-notifications, changing settings, and provides additional information about the sensors.
- The app comes in various languages, including German, which allowed us to include the app as it is, without having to adapt any translation.

Test persons (TP)

- n = 20 Destatis colleagues participated as test persons.
- TP varied both in … ○ demographics (sex, age, household size) ○ as well as their interest in the topic of air quality and how tech-savvy they were.

Setting and field phase

The test consisted of two phases:

  - (1) TP installed the device in their apartment and had it collect data for seven weeks.
  - (2) We conducted focus groups with the TP afterwards, asking about their experiences.
- (1) Field phase ○ TP were handed out the devices and asked to install both the device and the app on their own in their apartment (a manual was provided).
  - The uHoo device remained in the apartment for 7 weeks.
  - We asked all TP to place it in the living room for the first four weeks, and then to change location to the bedroom for another three weeks.

Disclaimer: Views and opinions expressed are however those of the author(s) only and do not necessarily reflect those of the European Union or Eurostat. Neither the European Union nor the granting authority can be held responsible for them.

- At the end of the field phase, we sent out a questionnaire to all TP, asking them for context information about their apartment, as well as their experiences in the field.

- (2) Focus groups ○ To gain more insights into their experiences, we conducted focus groups after the 7week field phase.
    - Each focus group consisted of 2-4 TP.
    - Conducted as semi-standardized interviews, featuring a predetermined set up, key questions and some screenshot material to be shown during the discussion.
    - All interviews were done remotely, via video conferences, and were recorded audiovisually.
    - Sessions lasted about 90 minutes and took place between 16th. and 22th Nov. 2021
- No incentives were paid.

Field phase: Technical issues

- Over the course of the seven-week long field phase, we encountered a few technical issues with the uHoo devices.
- For one TP, the device did not work at all, a replacement uHoo had to be sent.
- For five TP, the device itself worked, but could not be coupled with the local WiFi or stopped working after trying to update the device (replacement was sent):

This screenshot displays an error message in case of an update-failure

- An additional two TP could not see their data in the app, the device itself worked and generated data about their indoor air quality though. As we did not have replacement devices left, we kept it this way for the 7 weeks, but shortened the focus group with these two TP at the end.

- Rarely, we encountered minor functionality problems that could be solved by restarting: For example, one TP had to go restart the app several times, until it finally prompted for the (automatic) WiFi setup.

I. Subject interest and app usage of participants

Interest in "indoor air quality" (IAQ) before the test

The level of interest in the IAQ of their own home varied among the participants. A few TP had already shown quite some interest before they took part in the uHoo test. That turned out to be more likely the case when they had a personal issue related to IAQ, e.g. concerning health, high or low humidity or mould in their living spaces. Some TP also mention they had already given some thought to the air quality in their apartment, because there is a busy street right next to their apartment. Several other TP, however, have not thought about this topic before at all.

Interest in IAQ during the test

Most of the TP developed a significant increase in their interest at the beginning of the measurements in their living spaces. Reasons for interest:

- Being intrigued by the many parameters (9) shown for assessing air quality
- Interest in the actual status of their indoor air quality / values in the app
- Interest in the development of these values over time
- Interest in connections between behaviour and measured values, e.g. with certain activities (cooking, ventilation) or presence of other people.

For many TP, however, this interest is not permanent. If there are no personal issues (e.g. health problems or mould in the apartment) and the measured values during the test were rather inconspicuous, TP did not show sustained high interest in monitoring the measurements of the air quality in their own living space.

In the case of TP with problems and TP whose measured values were repeatedly above the thresholds, the interest usually remained on the increased level. However, there were also a few TP whose individually measured values were sometimes increased, but their interest was nevertheless not permanently increased.

The change of location (from living room to bedroom) of the air sensor increased the interest temporarily for some TP. Some found it interesting to compare the readings with those in the living room. Some are interested in the development of the measured values during the night in the bedroom.

Interest in IAQ after the test

Most of our TP do not plan to purchase a sensor to track indoor air quality in the future. Especially if the TP have no personal problem (e.g. mould in the apartment), the interest in the permanent measurement of the air values is rather low.

During the test phase several TP considered purchasing a device and researched the price of the uHoo. However, the price of over € 300 was too high for them. '*Just to show that the air is okay it is too expensive'*.

Some already have a simple measuring device (temperature and humidity) that is sufficient for them.

Other TP are more interested in purchasing a combination device that not only measures but also has a positive effect on air values, e.g. filtering or dehumidifying.

A few TP could imagine purchasing an air-measuring device that is connected to a smart home system. This device should not only measure air values, but also switch the heating on and off or open the windows.

Frequency of app usage

Almost all TP reported that the frequency of app usage changed during the test. At the beginning of the test phase, TP called up their measured values in the app at least several times a week. At the beginning of the test phase, many TP even checked the app every day or several times a day. Over time, TP look at the app less often.

Reasons for decline of the usage:

- Measured values were always good
- No great or unexpected changes in the measured values (any more)
- No more new findings how to influence the measured values
- Behaviour has been optimized (ventilation, heating)

Evaluation of sensor values

TP were asked if they were surprised by the data. Overall, TP were satisfied with the measured values displayed. Nonetheless, some of the values displayed in the app surprised TP:

Neutral reaction

- Surprised about causal dependencies e.g. that heating lowers air humidity

Negatively surprised

- Measured values (especially CO_2) deteriorate quicker than thought if you do not ventilate (e.g. overnight)
- Scope of the Total Volatile Organic Compounds (TVOC) values
- Higher humidity than expected
- Values improved rather slowly through ventilation

Positively surprised

- Values for fine dust were decent, despite a busy street next to the house • Humidity was lower than assumed

Virus index (VI)

The VI received varying degrees of attention by TP. A few TP did not notice it at all, some others only later during the course of the seven week field phase. On the other hand, the remaining TP noticed it either right away, while others got aware of it once the VI value increased and got worse for the first time. Generally, though, TP state their VI was mostly consistently in the green area.

Positive remarks about the VI were that it offers a quick summary, thus serves as a good general warning sign. Some TP see it as an “entry” – a first look at VI to see its values, and if needed, TP check individual values to see where the alarming VI value is coming from.

Some TP criticized it as being hardly noticeable visually (especially those who only in the focus group learned about this feature). Generally, the information about the VI is often not seen or read. TP say the composition of the value is unclear for them. It remains nebulous how the value is composed, so some participants doubt its validity and meaningfulness. Several TP also stated that their interest in individual values is far greater than in the VI.

As an interesting side note, some TP thought the VI was introduced especially because of Covid 19.

II. Impact on participants' behaviour

In the following chapter, we will discuss possible impacts of a sensor measurement on participants' behaviour. To do this, we first explored if and how respondents perceive the device in their daily life, e.g. if they are constantly aware of the sensor.

Awareness and perception of the uHoo device

Awareness in everyday life

After the initial setup, most participants quickly lost awareness of the uHoo device in their apartments during the seven-week test period and generally did not consciously recognize it anymore. Reasons being that the device is not too large, fits into the interior, or – due to lack of better options – because respondents had placed it at the wall or corner of a room where it was barely noticeable.

A few participants report otherwise, a major factor being a more prominent placement of the device. Some respondents placed it in a central position because they wanted to fulfil the "ideal setup" instructions as much as possible (centrally placed, in roughly 1,5 m height), so it was constantly in their field of view and therefore reminded them of the device more frequently. Other, less often mentioned reasons include: respondents were reminded by frequent app-push-notifications and then remembered that there is a device at home tracking the indoor air quality, the device stood out as it did not fit to the other furniture, or it was considered too large.

The latter was the exemption though, which speaks for the mostly unobtrusive design of the uHoo device and plays an important role in potentially eliminating or at least minimizing possible impacts on the behaviour that could influence the data (such as increased ventilating).

Perception of 'being watched'

Going beyond the awareness of the device at home, a very important aspect is whether participants actually perceive a feeling of 'being watched' due to the device at home. This could lead to noncompliance or dropouts, as participants might experience a privacy intrusion; it could also result in a more socially acceptable behaviour and as a result produce biased, non-representative data. In our study, this turned out to rarely be the case, in a limited fashion. As mentioned above, the majority was not (constantly) aware of the device, and of those who were, most did not experience

such a stronger feeling of 'being watched', citing a general trust in this research study.[9]

However, one participant felt a bit uncomfortable at the start of the test period, another participant felt somewhat being observed throughout the test period whenever she was in the same room as the device. The reason for this was that the device appears similar to commercially available ones,

[9] Please note that this study was conducted internally with colleagues, which likely helped build trust into the study setup.

such as Amazon Alexa, which can track far more than the uHoo device (such as voice activation/recognition).

Albeit we can conclude that for most, this was not a problem, the abovementioned issue should be kept in mind when building or choosing a sensor device for a national study. To avoid this feeling of 'being watched' as much as possible, the device should be designed as small and unobtrusive as possible, and ideally not resemble any commercially available, well-known smart home devices.

Reported changes of behaviour

In our focus groups, we asked participants about the influence of the uHoo device and the uHoo app on their behaviour. Some participants report that the uHoos influenced their behaviour strongly; others say that they were influenced only in a minor way; few state, that they did not change their behaviour at all. Participants who were influenced, changed mainly their ventilation behaviour, e.g. they ventilated more often or ventilated for a longer time. Some participants also changed their heating behaviour.

For some participants the influence on their behaviour is enduring and they developed new routines, e.g. they started to ventilate the bedroom before going to sleep. Others changed their behaviour only for the time the uHoo was in the specific room and fell back to their normal behaviour as soon as the uHoo was in another room. For some participants the influence on the behaviour was stronger in the beginning of the test and declined by time. In the following, we try to identify processes and reasons which lead to changes.

Getting informed about indoor air quality

The beginning of a change in behaviour was always that participants had a look at the app and were informed that their indoor climate is not optimal, i.e. that the app reported data which was classified outside the green comfort range for any indicator.

Participants who did not change their behaviour or only very slightly, often report that the measurement data in the app did not show values outside the green threshold. Moreover, they say that they were confirmed in their behaviour by the reported data and that they therefore did not see a reason to change their behaviour.

As reported, we also had participants without a working app so that they did not have the information about their IAQ. Without this information, they did not change their behaviour, as they did not know if their IAQ is good or not. This was interesting because one might think of influences on the behaviour only through the uHoo standing in a flat in the sense that participants maybe try to have a better IAQ and ventilate more often. In our pretest we could not find such behaviour, our TP needed to know about their IAQ before they changed their behaviour.

Knowing indicators and values

Knowing about poor IAQ values is not a sufficient prerequisite to change one's behaviour.

Participants also have to understand how to influence the value and must be convinced that another value is better, otherwise they are not inclined to change their behaviour.

If participants got bad values of well-established indicators such as humidity, temperature or carbon dioxide, they mostly reacted by ventilating or changing their heating behaviour. The underlying reason for that could be that participants care about their health: avoiding high concentrations of carbon monoxide, nitrogen dioxide or carbon dioxide seems to be quite obvious. Avoiding a high humidity value and therefore mould in the flat could be due to health reasons or because persons care about the flat and building stock. One participant reported that she normally turned down the heating when she left her flat and that she was surprised how fast the room cools down if she is not at home. She thinks that a constant temperature is better. Therefore, she did not turn down her heating that much anymore when she left her flat. So, the underlying reasons for a change might differ but there was always a reason why they thought another value would be better and why they should react and change their behaviour.

In other cases, participants had poor values for some indicators and decided consciously not to change their behaviour. They did not trust the thresholds in the app or knew the reasons for their poor values and decided to accept it. Participants had e.g. the uHoo in their bedroom and the app was telling them that it is too cold in the room. But they did not change their behaviour because they simply like to sleep in a cooler room or do not see the necessity to heat the sleeping room more. Others were well informed about humidity and said that their humidity value is absolutely fine according to other sources while it was outside the threshold in the uHoo app. Therefore, they did not change anything. A last example is a participant who has an automatic air refresher in her flat, which sprays some well smelling liquids in the air at regular intervals. She saw the influence of this air refresher in the data, which, temporarily, got worse with every spray. However, she likes the air refresher and was not worried about the air quality, so she had no reason to change something. All examples show that participants who are not convinced of a change in behaviour, as suggested by the uHoo app, do not change their behaviour either.

Besides these well-known indicators there are others which were less known or even completely unknown, predominantly TVOC. Participants did not know how to influence specific unknown indicators. Some participants did some research and tried to ventilate when the reported TVOC value was outside the thresholds. But they could not understand how and why the value is rising. Some state it seemed to change randomly, others speculated it is related to having a dog around, freshly washed laundry, new furniture and television, and others. Participants with high TVOC values were uncertain and wanted to do more research on this topic (e.g.: Where does it come from? What can I do?) because they wanted to avoid any negative consequences for their health. One participant reported that she was ventilating twice a day for a long time (more than 30 minutes) because of high TVOC values. But other participants simply ignored the indicator as they got the impression of it being rather random values. The awareness and uncertainty with this indicator depended on the reported values: unsurprisingly, persons were more concerned when the TVOC values were outside the thresholds repeatedly. So, without knowing the indicator and how it can be influenced, participants reacted differently. In the end, most of them did not change their behaviour, even if some would have liked to do so.

To sum it up: Participants changed their behaviour when they were informed about bad IAQ values for a well-known indicator and were at the same time convinced that for any reason another value would be better. If participants were not convinced that a well-known indicator should have better values or if participants had no information at all about their IAQ they did not change their behaviour. If the indicator was unknown, there was uncertainty about how to react on bad values, but most of those participants did not change their behaviour either because they ignored the values or they did not know what to do.

Taking on a researchers' perspective, this means: If we want to avoid a change in behaviour related to the use of an air quality measurement device like uHoo, according to our test the best way would be to not inform participants immediately about their air quality, as knowing about ones values oftentimes leads so such changes in behaviour. To gauge such a setting, we subsequently asked our participants if they would also participate without such information.

Motivation to participate

The data collection for official statistics should take place without influencing the collected data.

However, the process of collecting data with an air sensor can affect participants' behaviour, as seen above. Therefore, we also discussed with TP, if they would also take part in the air measuring if they do not see the values directly in the app.
Some TP would nevertheless participate 'for the sake of official statistics'. But it is important that TP know who is getting the data and what happens to it. Several TP would only participate if there was a personal report at least at the end of the measurement phase. TP want to know what data is being recorded on them.

Two of our TP could not see their measurements in the app due to technical problems. They still left the device for the 7 weeks in their rooms. However, they previously assumed that they would receive information directly during your participation.

And again: We did this test with Destatis colleagues who might have different motivations to participate than the general population. Therefore it is really hard to make any statements about the willingness to participate if participants do not have direct access to their air measurement values. Maybe it would be a compromise to have a first period without direct information and only a report in the end of this period, and afterwards a second period where participants have full direct access to their data.

Push Notification

Receiving push notifications

Through the uHoo app every participant should receive push notifications for every indicator as soon as the measured values cross the thresholds (if users have allowed push notifications). The text of the notifications for each indicator differ for each threshold. Users get one notification if an indicator's value reaches the first threshold and another, more pressing notification if it reaches the next threshold. User can decide for which indicators they want to receive push notifications. By default, notifications for all indicators are activated.

Please note: In our test, not every participant received push notifications. We assume that this is because the uHoo devices, together with the accompanying pre-set uHoo accounts to log into the app, were used before in other countries, and resetting the device (as was done) apparently does not reset the in-app setting concerning push notifications for a given uHoo account. Unfortunately, we realized this problem only during our focus groups.

In our focus groups, participants expressed different opinions about push notifications in general and from the uHoo app in particular.

Some of those participants who did not receive push notifications really would have liked to receive them and reported that they could have been useful, especially in the beginning of the test. Within the group of participants who received push notifications, some participants deactivated them right from the start or quite early on. For them push notifications are annoying in general, while the app was not relevant enough to allow push notifications. Others opened the app when they saw push notifications – at least in the beginning. So, one could argue that they were better informed about their IAQ. One participant's behaviour was influenced strongly by notifications – but also only in the beginning of the test. As participants got used to the test and the app, they got the impression that there are too many und too unimportant push notifications (e.g. when the temperature is declining:

A participant opened the window and therefore it was obvious that it was getting colder in the room. A push notification saying that it is (too) cold now was deemed pointless).

Some participants said that they want to receive push notifications only if a value is really bad and could cause health issues like high carbon monoxide values. Otherwise – if there are too many notifications – notifications are annoying, are not taken serious anymore, get ignored and in the end deactivated. Another participant pointed out that the app cannot be a sufficient warning system for perilous situations as mobile phones might be turned off or lie in another room and push notifications will not wake you at night. This could be an argument to remove this functionality altogether, as it should not give a false impression that the app can be seen as a warning system.

Nearly all participants did not realize that the thresholds, which trigger notifications, can be adjusted individually and that one can choose for which indicators notifications should be sent and for which not. In the focus groups, a lot of participants requested exactly these functionalities – being able to adjust the notifications according their own preferences and stated that and they might use them. With this result in mind, it would be interesting to do another test where participants are explicitly informed about these functionalities.

Concerning push notifications' text, participants would like to get clear, easily understandable messages with concrete advices what to do to improve the IAQ, especially for unknown indicators like TVOC.

III. Expectations and required functionalities by participants

Feedback on the current app design

While we only discussed this aspect briefly, TP generally were satisfied with the content visible in the app. Mentioned positively were mainly:

- The number of indicators is sufficient
- A traffic light system is helpful to quickly see where there is a problem.
- Textual recommendations for possible actions to generally in- or decrease values are considered mostly helpful.
- As mentioned before (see chapter I.), the design of the Virus Index could be improved upon.

Ideas for improvements of the TP

Evaluations in the app

- The representation of the data in the 24 hours log is not user-friendly. TP criticize that the time course in the app is not so smooth. Instead they would prefer if there was no cut at 12 o'clock at night, so that not only separate days can be viewed but a timeframe of ones one choosing.
- Some TP would have liked to view weekly reports.
- Some TP missed a function to export the data.
- One TP would like to have an additional measured value for pollen exposure.

More information about air values

- TP want to have more background information: What is this parameter? What are reasons for increasing? What can I do? Especially information to TVOC are desired because the reason for increasing of this values is often unclear.
- Some TP wish more recommendations for action and advice tailored to their own situation • Information about the values should be easier to find within the app

IV. Privacy and data security concerns

Assessment of indoor air sensor data privacy: In need of protection?

A key step in determining data privacy and security concerns of future survey participants is whether the sensor data obtained is actually considered sensitive, i.e. in need of protection, and if so, to what degree.

Results of the focus groups reveal that views on this subject differ. The majority does not consider air measurement data to be sensitive per se (without context), some respondents however do rate such data as personal, and thus consider it sensitive and in need of protection. Reasons brought up as to why such data could be considered sensitive are:

- It is data about one's personal space, it therefore belongs per definition to one's private data.
- Sensor data does not simply refer to a non-personal object (my apartment), but depends on the personal behaviour, and therefore indirectly displays the personal indoor behaviour at home.

On the other hand, the majority does not consider raw air sensor measurements as sensitive data:

- Such data does not reveal aspects about one's personality.
- Data without context is not meaningful (e.g. an increased level of carbon dioxide can have a multitude of reasons).

This only holds true though, as long as it does not include any personal data or context information.

- If context information (even WiFi could potentially allow identification of someone's residence) is supplemented, it could allow inferences about someone's indoor behaviour: If an address is included or traceable, one might indirectly infer when someone is at home, how many household members live in a specific apartment, or when someone wakes up or goes to bed. This would then be quite sensitive data.
- Similarly, if data gets into the 'wrong hands', it bears risk of misuse: a landlord or an insurance could theoretically deny payment of mould removal, citing a lack of ventilation by the residents.

Overall, indoor air sensor data is considered uncritical by most when it comes to data sensitivity, while few rate it as personal data in need of protection. However, even among the latter, the level of data privacy is judged as rather low. This includes one important prerequisite however: It only applies as long as no context data or otherwise related data is also being collected (on the same device). If this is the case, for most such indoor air sensor data becomes sensitive private data in need of protection, as it allows inferences about one's personal living space, behaviour, or household specifics.

To gauge the general view and get additional context information when it comes to data privacy and security concerns, we also discussed similarities and differences of such an indoor air sensor device in comparison to other smart devices, such as smartphones or smartwatches.

Here we could obtain a clear distinction. Nearly the whole sample affirmed that smartphone sensor data is more critical than the uHoo measurements. Reasons being that a smartphone or similar device has a lot more sensor options, with microphones / audio recording being one of the predominantly mentioned especially critical aspects (that also apply to devices such as Amazon Alexa). While the uHoo device itself is somewhat of a black box (where one has to trust that it does not include more sensors), with a smartphone one definitely knows that it packs many more options, albeit not having an idea about details either – some mentioned the sentiment that such devices can track far more than we can imagine. Furthermore, much communication is done via these devices, so they potentially also store and give access to information to these data, including everything shared on social media. This together makes sharing or tracking data via smartphones and similar devices much more sensitive than an indoor air quality sensor such as the uHoo device. Only one respondent does not see a difference between smartphone and indoor air sensor data. This can be attributed to

a high level of trust in official statistics to handle the data confidentially, e.g. safe data collection/transmission and storage, no data transfers or usage for a specific purpose only, or anonymous publishing.

To put participants' statements into context, we also asked them about their settings of their personal devices, e.g. whether respondents took measures to reduce the data collected. When it comes to their usage of smartphones, our sample shows variation as well. Some respondents are concerned and try to minimize data tracking on their smartphones. Actions mentioned were: GPS turned off by default, offline mode during the night, and generally as little sensors as possible within the own apartment (several respondents stated they would not use smart home devices with voice recognition/activation). Others however either do not mind (rather the exemption though) or see it as a 'necessary evil' that comes with using the devices and having its benefits.

Generally, we can summarize that for most respondents, using sensors in their everyday life follows a trade-off between costs (possible data collection) and benefits (using e.g. Google Maps to navigate). While this shows that our sample included participants from a broader spectrum of opinions, is it still very possible that on average our participants are more sensitized than the general public, due to the data protection standards (and knowing the restrictions in place) working in official statistics. However, this might be more assuring, as most of our respondents still rate indoor air data as mostly uncritical and not in (strong) need of protection.

Data Privacy and Security concerns in our study

Now we wanted to apply this to the participation in our study, and possibly in future studies. Given that air sensor data per se was not considered to be (highly) sensitive data by many (see above), most participants therefore had no concerns taking part in this study. This means aspects of data security and data protection played a role only for the subset of participants who did consider these type of data to be (somewhat) sensitive, with such judgement being a prerequisite of having data security concerns.

For those who consider indoor air sensor data in need of protection, yet again only a small subset had slight concerns in our study (and more generally, in the context of official studies). These concerns refer to the usage of a third party (the manufacturer of these uHoo devices) and the data being uploaded via WiFi to this third party's cloud. These participants would have preferred a local offline storage, and were a bit concerned about their personal data being uploaded/transmitted. Other than that, none had actual data privacy or security concerns in this study or in the general context of participating in official studies, one major reason being their trust in official statistics:

- Trust in official statistics … ○ … to handle data with the highest standards in data privacy and security. ○ … to not add hidden sensors (e.g. microphones) into the sensor devices.

- … to not use data in any other way than stated and to publish it anonymously (some mentioning this in contrast to private firms)
- Along these lines, participants mentioned the aspect of risk assessment: The damage, if an official institution (knowingly or unknowingly) violated their promises or regulations and it became public, is considered higher for the institution than the damage for oneself, if these type of data were to be accessible by others.

- Trust due to our study setup: Participants mention they felt safe because they were given anonymous accounts for the uHoo device, and therefore no retracement to their own identity was possible, i.e. no personal context information had to be entered.

In summary, we have learned that data sensitivity is rather low when it comes to indoor air sensor data per se. We can therefore conclude that this mostly will not be an impediment to participating in future studies or even national surveys. It is important however that the assessment varies depending on whether and how much context data has to be supplied. Context data that is needed should therefore ideally be collected independently of the sensor device, and not via a third party app as was done in our study. It is also important to create trust in the device (that it only tracks what is absolutely needed and should ideally not represent similar commercially available devices which include additional sensors, such as Amazon Alexa) and into the handling of data, e.g. aspects such as secure data transmission and storage, or anonymous publishing. To further reduce or even eliminate concerns and increase willingness to participate, data should ideally be stored offline on the device and not be sent via WiFi to a cloud, and third-party suppliers should be avoided or at least chosen according to their publicly perceived trustworthiness.