USER EXPERIENCE EVALUATION OF NOVEL AIR QUALITY SENSING TECHNOLOGIES FOR CITIZEN ENGAGEMENT IN ENVIRONMENTAL HEALTH STUDIES

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Doctoral Dissertation
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OCENA UPORABNIŠKE IZKUŠNJE PROSTOVOLJCEV V OKOLJSKO-ZDRAVSTVENIH ŠTUDIJAH PRI UPORABI SENZORSKIH TEHNOLOGIJ ZA SPREMLJANJE KAKOVOSTI ZRAKA

Doktorska disertacija

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To my family here and there

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Abstract

The use of low-cost sensing technologies increasingly used in participatory environmental health studies brings both opportunities and challenges. While previous research mostly focused on technical aspects, this thesis brings participants to the foreground and articulates their experiences. It aims to evaluate if low-cost sensing technologies are fit-for-purpose in environmental health studies from a user perspective. This work included studying their motivations, needs, expectations, experiences and changes in behaviour and gaining feedback on the used devices, campaigns and data visualization. The thesis reviews the citizen science literature and summarizes functional features of tools that meet volunteer expectations and help retain their long-term interest in citizen science projects.

This thesis also draws from the experience of three relevant EU-funded projects: CITI-SENSE, SMURBS and ICARUS. A combination of qualitative and quantitative methods was used to collect and analyse the data from campaigns held in Ljubljana, Slovenia, and a user-centred approach was used to design a results report. Altogether 101 volunteers participated selected using non-probability sampling based on pre-defined criteria.

The most common motivations of participants were to learn about one's living environment and help science and society. The participants were expecting to obtain insights into air quality about the places they live in and frequently visit, and evaluate the results. For example, the data show that involvement leads to behavioural change and that this change would be even greater if the results were communicated in real-time. It also shows that participants struggled and were frustrated with low-cost prototype sensor devices they evaluated as difficult to use, bulky, and disrupted their daily lives. They also reported being disappointed with frequent data gaps or when real-time displayed air pollution data did not meet their expectations. These findings are why campaigns using such technology should not exceed 14 days; otherwise, the study would become obsolete due to usability issues and since the novelty of participation wears off quickly. Commercially available technologies faced fewer usability issues and were more acceptable to participants. A user-centred design process can help to ensure a product (e.g., a sensor, web page, phone app, or report) is well accepted. This outcome was evidenced by participants being involved in an iterative co-creation process, resulting in a more comprehensible, well-received results report.

Furthermore, data from low-cost sensor devices must be meaningful to the user, i.e., capable of meeting their expectations and providing data promptly to keep them actively interested. When developing new low-cost sensor devices, resources should be allocated to perform user research to test and improve a product prior to full-scale implementation within a cross-disciplinary consortium. The empirical findings from these case studies, supported by theoretical findings from the literature review, highlight the need to align technology and information output to end-users needs. The user experience evaluation methodology developed herein demonstrates the need for iterative user-centred approaches and the importance of collecting user feedback about novel air quality sensing technologies for citizen engagement in environmental health studies. If resources are not available for user-centric approaches, known fit-for-purpose technologies should be used.

Povzetek

Nizkocenovne senzorske tehnologije, ki se vse pogosteje uporabljajo v participativnih okoljsko-zdravstvenih študijah, prinašajo številne priložnosti in izzive. Medtem ko so se raziskave v preteklosti posvečale predvsem tehničnim vidikom uporabe senzorskih tehnologij, to delo v ospredje postavlja prostovoljce in njihove izkušnje s sodelovanjem v takšnih študijah ter ocenjuje, ali so nizkocenovne senzorske tehnologije, z vidika uporabnika, primerno orodje za okoljsko-zdravstvene študije. Ta disertacija proučuje uporabnikove motive, potrebe, pričakovanja, izkušnje in vedenjske spremembe ter pridobiva povratne informacije o izkušnjah z napravami, študijami in vizualizacijo podatkov. Poleg tega vključuje tudi pregled dosedanje literature o ljubiteljski znanosti in povzema funkcionalne značilnosti orodij, ki izpolnjujejo pričakovanja prostovoljcev in pomagajo ohranjati njihovo dolgoročno zanimanje za projekte ljubiteljske znanosti.

Disertacija izhaja iz izkušenj, pridobljenih v treh evropskih projektih: CITI-SENSE, SMURBS in ICARUS. Za zbiranje in analizo podatkov iz študij, ki so bile izpeljane v Ljubljani, je bila uporabljena kombinacija kvalitativnih in kvantitativnih metod, pri oblikovanju poročila o rezultatih pa je bil uporabljen pristop, usmerjen na uporabnika. Skupaj je pri študijah sodeloval 101 prostovoljec, izbran s pomočjo vzorčenja brez verjetnosti na podlagi vnaprej določenih meril.

Prostovoljce je za sodelovanje v študijah najbolj motiviralo spoznavanje lastnega življenjskega okolja ter doprinos k znanosti in družbi. Udeleženci so pričakovali, da bodo dobili vpogled v kakovost zraka v krajih, v katerih živijo in ki jih pogosto obiskujejo. Podatki kažejo, da vključenost v takšne študije vodi do vedenjskih sprememb in da bi bila sprememba vedenja še večja, če bi bili o rezultatih obveščeni v realnem času. Udeleženci so bili nezadovoljni z nizkocenovnimi prototipnimi senzorskimi napravami, ki so jih ovrednotili kot zahtevne za uporabo, okorne in moteče. Poročali so tudi o tem, da so razočarani nad pogostimi vrzelmi v zbranih podatkih oziroma podatki o onesnaženosti zraka, ki se niso skladali z njihovimi pričakovanji. Te ugotovitve so razlog, zakaj študije, ki uporabljajo takšno tehnologijo, ne smejo trajati več kot dva tedna; sicer študija ne bi uspela zaradi težavnega rokovanja z napravami in minljivega navdušenja nad sodelovanjem. Komercialno dostopne naprave so se izkazale za veliko bolj primerne. Dobra uporabniška izkušnja ima pomembno vlogo pri tem, kako je izdelek (npr. senzor, spletna stran, aplikacija za telefon ali poročilo) sprejet. To je bilo razvidno tudi pri iterativnem procesu soustvarjanja, ki je udeležencem podalo razumljivejše in tako boljše sprejete rezultate.

Poleg tega morajo biti podatki, pridobljeni s pomočjo nizkocenovnih senzorskih naprav, za uporabnika smiselni, torej sposobni izpolniti njegova pričakovanja in razpolagati z informacijami, ki ga v tistem trenutku zanimajo. Pri razvoju novih senzorjev je treba veliko pozornosti nameniti prav zagotavljanju dobre uporabniške izkušnje ter predhodnemu testiranju in izpopolnjevanju naprav. Empirične ugotovitve študij primerov, podprte s teoretičnimi ugotovitvami iz obstoječe literature, poudarjajo pomen usklajevanja tehnologij s potrebami končnih uporabnikov. Tu razvita metodologija ocenjevanja uporabniške izkušnje kaže na potrebo po iterativnih, k uporabniku usmerjenih, pristopih in na velik pomen zbiranja povratnih informacij o novih senzorskih tehnologijah za spremljanje kakovosti zraka v okoljsko-zdravstvenih študijah ljubiteljske znanosti. V primeru, da k uporabniku usmerjen pristop ni mogoč, je priporočljivo uporabiti preizkušene tehnologije, ki ustrezajo namenu.

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Abbreviations

API	... Application Protocol Interfaces
APIN	... Air Pollution Indicator
AQI	... Air Quality Index
AQ	... Air Quality
CI	... Confidence Interval
CO	... Carbon monoxide
COs	... Citizen Observatories
CO_2	... Carbon dioxide
CS	... Citizen Science
EO	... Earth Observation
GPS	... Global Positioning System
HCD	... Human-Centred Design
HCI	... Human-Computer Interaction
NO_2	... Nitrogen dioxide
IAQ	... Indoor Air Quality
O_3	... Ozone
OR	... Odds ratio
PAHs	... Polycyclic Aromatic Hydrocarbons
PM	... Particulate Matter
PPM	... Portable PM Meter
SAT	... Smart Activity Tracker
SDGs	... Sustainable Development Goals
STEM	... Science, technology, engineering, and mathematics
TAD	... Time activity diary
UCD	... User-Centred Design
UI	... User Interface
UX	... User Experience
VOCs	... Volatile organic compounds
WHO	... World Health Organization
WP	... Work Package

Chapter 1

Introduction

Air pollution is a major public health concern accounting for over seven million deaths per year globally (WHO, 2020). However, environmental health is a complex issue where many factors must be considered (Grossberndt & Liu, 2016; Keune et al., 2016; Reis & Spencer, 2019). For example, these can include the physical environment, a person's health status, income, social status, genetics, access to health services, education, gender, and behaviour, to mention a few (Caplin et al., 2019; WHO, 2017). Therefore, in order for the public to make informed decisions about their health, i.e. to have evidence-based information to weigh the benefits, risks and alternatives taking into account individual preferences, beliefs and values, the public should be involved in inclusive, deliberative decision-making processes (Grossberndt & Liu, 2016; Renn & Schweizer, 2009). To this end, the Aarhus convention (United Nations Economic Commission for Europe, 1998) provides everyone with the right to access environmental information and participate in environmental decision-making. For instance, Renn & Schweizer (2009) clarify how the public can participate in inclusive risk governance and make valuable contributions with their local knowledge to solve problems that directly influence them.

Air quality (AQ) is traditionally communicated by the governmental sector, responsible for preventing or reducing the harmful effects of air pollution on human health and making information available to the public (European Commission, 2008). However, the public seldom searches for information about their environment (Elshout et al., 2007) but they are nonetheless exposed to the abundantly available information through news channels and the internet. Air quality is particularly elusive, and the majority of the public perceives it as an impersonal risk without short-term health effects, which makes communication challenging (Elshout et al., 2007). The public is often unaware of the negative impact of personal choices on air pollution and its implications on their health and can have low acceptance of measures to reduce air pollution (Stauffer, 2017). However, it is known that even low levels of air pollution affect people's health and daily lives (Brunekreef et al., 2021). While the information on air quality and measures to reduce pollution can be of interest to the public, they can also be subject to public scrutiny or apathy (Xu et al., 2017). In order to improve the acceptance and support for air quality measures, it is essential to increase public awareness of health impacts (Stauffer, 2017).

Air pollution results from several actors, and it should not be considered a government problem solely. While government policies have a paramount role in reducing air pollution, individual choices can also reduce exposure (Carlsten et al., 2020). Besides communicating air quality information, some cities provide recommendations on what to do when air quality is low and try to influence the public's behaviour (Stauffer, 2017). However, as Reis and Spencer (2019) point out, the social impact of science communication remains unresolved, and according to Stauffer (2017), many cities, despite all their efforts, find it difficult to measure behavioural changes in the local population. The same applies to the use of Air Quality Indices (AQI), where the evidence of their

efficacy in influencing personal decisions to minimize exposure is limited (Carlsten et al., 2020).

1.1 A Paradigm Shift in Air Quality Monitoring

The recent advancement and proliferation of novel technologies, such as smartphones and small, low-cost personal air quality sensor devices, have resulted in a paradigm shift in air quality monitoring (Campbell, 2009; Kumar et al., 2015; Morawska et al., 2018; Snyder et al., 2013). These devices enable greater spatio-temporal resolution than traditional air quality monitoring solutions with improved personal estimates of air pollution concerning location and activity (Singla et al., 2018). Such information helps experts understand where and when exposure to air pollutants occurs (Nieuwenhuijsen et al., 2015). Data from personal low-cost air quality devices can also be useful to environmental health scientists and epidemiologists, as they provide insight into environmental drivers of human health (Dons et al., 2017; White et al., 2012). In addition to fixed sensor networks, the development of personal portable monitors has enabled the coverage of even wider spatial contexts, e.g., covering private places such as vehicles and homes, otherwise not reachable by governmental monitoring systems and with greater granularity.

The public's increasing awareness of environmental issues and personal health provides an opportunity to involve them in more personal and hands-on air-quality monitoring campaigns. Ferrer and Klein (2015) show how interventions that successfully engage participants can change risk perceptions and increase positive health behaviours. Furthermore, citizens are more interested in their air pollution exposure than overall air quality, which portable, low-cost sensor systems enable (Hu et al., 2014). This more personal approach might be especially welcome in an era of fake news, where the participants can act as part of the scientific process, which helps build trust (Hubbell et al., 2018). Similarly, being spatially closer to the problem and perceiving a distant risk more personally could promote more sustainable behaviour by stimulating environmental affection (Sheng et al., 2020; Spence et al., 2012). Knowledge and attitudes of the public towards air quality and their influence on environmental behaviour has been studied by, for example, Sheng et al. (2020) and Xu et al. (2017), with the latter describing how a lack of concern could be explained by a feeling of uncontrollability, especially in cities where the impact and responsibilities are shared across the population. According to Ajzen's theory of planned behaviour (1991), perceived behavioural control affects the intentions to perform a behaviour when the perceived behavioural control is strong, which also speaks for the benefits of using personal air quality monitoring devices. Similarly, stationary monitoring of air quality does not seem to satisfy the curiosity of the public, and therefore has a lower empowerment potential than portable monitoring equipment (Kim & Paulos, 2009).

A common framework to involve the public in community-based monitoring is a so-called citizen science approach (Castell et al., 2017; Snyder et al., 2013; Thompson, 2016; White et al., 2012). Citizen science involves non-expert volunteers, e.g., the general public, to collaborate in scientific research activities, and was originally conceived as a method to help scientists gather large amounts of data across time and space (Bonney et al., 2009). The field constantly evolves, and there is a wide array of definitions depending on the type and level of participation (Haklay et al., 2021; Sanz et al., 2014), among other sources further discussed in Chapter 3.2. For example, in the field of air quality, in its basic form, the public is invited to carry or host a device and contribute data through

crowdsourcing. Out of several definitions, Haklay's (2013) definition of four levels of public participation demonstrates that the variety of participation exceeding the basic form of crowdsourcing is one of the most used ones. These levels include the following:

Level 1) Crowdsourcing: The public makes passive observations, such as carrying a sensor *(volunteer computing)*.

Level 2) Distributed intelligence, where the public can also participate as basic interpreters *(volunteer thinking)*.

Level 3) Participatory science: The public participates in problem definition and data collection *(co-production)*.

Level 4) Extreme citizen science where the public collaborates with science and co-designs the problem's definition, collects data, and analyses it *(collaborative science)*.

The European Commission supports and encourages the use of the CS approach in its Action Plan for nature, people and the economy, Action 3 (European Commission, 2017); the Action Plan for streamline environmental reporting, Action 8 (European Commission, 2019), and the Action Plan on environmental compliance, Action 7 (European Commission, 2018). Similarly, CS has synergies with the UN Sustainable Development Goals (SDGs), and currently, two of the SDG indicators are linked to air quality, i.e., (1) Indicator 3.9.1: *Mortality rate attributed to household and ambient air pollution*; and (2) Indicator 11.6.2: *Annual mean levels of fine particulate matter (e.g. PM2.5 and PM10) in cities (population-weighted)* (Fraisl et al., 2020; *Global Indicator Framework for the Sustainable Development Goals and Targets of the 2030 Agenda for Sustainable Development*, 2021).

The European Citizen Science Association (ECSA) proposes ten citizen science principles that set out the basic concepts and principles and underline good practices in citizen science research (ECSA, 2015). These ten principles are as follows:

1. "*Citizen science projects actively involve citizens in scientific endeavour that generates new knowledge or understanding. Citizens may act as contributors, collaborators, or as project leader and have a meaningful role in the project.*
2. *Citizen science projects have a genuine science outcome. For example, answering a research question or informing conservation action, management decisions or environmental policy.*
3. *Both the professional scientists and the citizen scientists benefit from taking part. Benefits may include the publication of research outputs, learning opportunities, personal enjoyment, social benefits, satisfaction through contributing to scientific evidence, e.g. to address local, national and international issues, and through that, the potential to influence policy.*
4. *Citizen scientists may, if they wish, participate in multiple stages of the scientific process. This may include developing the research question, designing the method, gathering and analysing data, and communicating the results.*
5. *Citizen scientists receive feedback from the project. For example, how their data are being used and what the research, policy or societal outcomes are.*
6. *Citizen science is considered a research approach like any other, with limitations and biases that should be considered and controlled for. However unlike traditional research approaches, citizen science provides opportunity for greater public engagement and democratisation of science.*
7. *Citizen science project data and meta-data are made publicly available and where possible, results are published in an open access format. Data sharing may occur during or after the project, unless there are security or privacy concerns that prevent this.*

8. *Citizen scientists are acknowledged in project results and publications.*
9. *Citizen science programmes are evaluated for their scientific output, data quality, participant experience and wider societal or policy impact.*
10. *The leaders of citizen science projects take into consideration legal and ethical issues surrounding copyright, intellectual property, data sharing agreements, confidentiality, attribution, and any environmental impacts."*

1.2 Towards Meaningful Air Quality Participatory Sensing

Low-cost air pollution sensors, requiring non-expert operation, that are easy to set up and capable of real-time monitoring, are needed to complement conventional air quality monitoring and to democratize air pollution monitoring by providing more personalized information on exposure and increasing communities' awareness of air quality (Kumar et al., 2015; Rai & Kumar, 2016). However, many challenges must be addressed before their practical use.

Until now, devices incorporating such sensors have been tested primarily for their technical capabilities and limitations, focusing on their performance in laboratory settings or outdoors (Broday et al., 2017; Castell et al., 2017; Languille et al., 2020; A. C. Lewis et al., 2016; Rai et al., 2017; Spinelle et al., 2015; Zimmerman et al., 2018), including studies that explore their feasibility for personal exposure assessment (Borghi et al., 2017; de Nazelle et al., 2013; Hu et al., 2014; Jerrett et al., 2017; Loh et al., 2017; Piedrahita et al., 2014). However, even if the aim is to democratize air quality measurements, offering increased information on air pollution with a higher spatial and temporal resolution, their usability and acceptability amongst the public rarely go beyond proof of concept and are not as inclusive as they could be, leaving, for example, user experience (UX) unstudied. As exemplified by Stevens et al. (2021), the involvement of the public in air quality monitoring is usually limited to three objectives from the participants' perspective: 1) to provide more localised data than currently available, 2) to raise awareness on air pollution and its health impacts, and 3) to empower individuals to take action to reduce their exposure.

Rotman et al. (2012) and Wiggins (2013) revealed that resource limitations in CS projects often require adopting sub-optimal tools, which may come with hidden costs stemming from poor usability and underwhelming functionality, thus reducing volunteer's motivation. Rai & Kumar (2016) acknowledge that many challenges concerning maintaining user engagement must be addressed before crowdsourced monitoring campaigns using low-cost sensors can be widely adopted. Several authors (Aspuru et al., 2016; Barcellos et al., 2016; Botteldooren et al., 2013; Busch et al., 2016; Castell et al., 2015; Havlik & Schimak, 2014; Kotovirta et al., 2015; Simpson et al., 2014) say that CS tools should be usable, versatile, appealing, engaging, easy to use and intuitive, which ease not only participation acceptance but also long term project sustainability. Following this, Mahmood et al. (2000) and Wright et al. (2015) emphasise that practitioners can meet volunteer expectations by designing information technology tools with functional features and nurturing their motivations, fostering long-term participation and contributing to project sustainability. However, details on such motivations and desired features are lacking, and the "user-friendliness" seems to be self-assessed by CS practitioners rather than through usability testing.

Moreover, Grainger (2017) states that CS projects should benefit society rather than science alone. Developing user-friendly and meaningful tools for CS with the help of user feedback is, therefore, of utmost importance. In order to make sure that the tools used in

CS are of scientific value and provide meaningful information to the volunteers, many authors call for more user involvement in the design of the services (Y. N. Golumbic et al., 2019; Preece, 2016; Sanz et al., 2014; Skarlatidou et al., 2019). Examples exist of air quality sensing solutions where potential end-users were iteratively involved in the development process, e.g., Bales et al. (2012); Jiang et al. (2013); Willett et al. (2010); Zappi et al. (2012), but these studies lack detailed insights. Few authors, e.g., Jennett and Cox (2014), Skarlatidou et al. (2019) and Luna et al. (2018), have attempted to create guidelines and recommendations to facilitate the overall design process of CS tools, yet with a limited focus on web interfaces or apps, and agree that there is a lack of systematic knowledge exchange of the development process.

The literature is extensive on field trials and case studies of newly developed, low-cost sensor devices where the information chain, e.g. pairing the sensor system with the user's smartphone to collect and visualise the data with a central server collecting and storing data, is in the spotlight. Also, the case study participants consist of students or colleagues rather than the public in many cases. However, as Havlik & Schimak (2014) caution, it can be demotivating for the volunteers if crowdsourcing is limited only to a proof of concept and if the infrastructure runs only for a short campaign period. Golumbic (2020; 2015; 2020; 2017, 2019; 2020) found how projects which have goals beyond scientific goals, i.e., educational or social ones, are more likely to be successful and how such projects facilitate participation by creating easy-to-use and access platforms for data collection and nurturing the relationship between science communication and CS practices.

Lewis & Edwards (2016) question the accuracy of such devices, calling for a demonstration of their fitness for purpose. Similarly, Bales (2019) recognized that "*it remains a challenge to provide people with the information they need to be able to make health-conscious choices*". This finding means information needs to meet the needs of the participants. However, as Hubbell et al. (2018) and Rosenbaum et al. (2000) point out, the researchers involved in CS and exposure studies often have a background in natural sciences and lack knowledge on why and how to implement user research and help map the user needs. Druschke & Seltzer (2012), Hubbell et al. (2018) and Tauginienė et al. (2020) talk about the power of interdisciplinarity, and how consortium members with a social science background are needed in order to understand the participants, their needs and behaviour. Golumbic et al. (2017) also encouraged exposing scientists to public engagement, especially in their early careers, to adopt citizen science practices to overcome barriers to engaging with the public.

1.3 User Research and User-Centred Design

Personalized air quality information based on data from low-cost portable sensor systems can help people make informed decisions on their exposure (Wong-Parodi et al., 2018). For this reason, this technology should be designed with and for the public. The human-centred design (HCD) landscape allows the public to be involved in iterative design cycles (Sanders & Stappers, 2008). For example, ISO 9241 Ergonomics of human-system interaction – Part 210: Human-centred design process for interactive systems provides comprehensive guidance on human-centred design. ISO 9241 defines usability as "*the extent to which a system, product or service can be used by specified users to achieve specified goals with effectiveness, efficiency and satisfaction in a specified context of use*". It guides project managers to allocate time and resources for human-centred activities. It also includes iterative cycles to collect user feedback, which is then incorporated in the

design phase to evaluate whether the design satisfies user requirements. According to ISO 9241 (2008), four key activities which should take place in a human-centred design are:

1. Understand and specify the context of its use.
2. Specify the user requirements.
3. Produce design solutions to meet user requirements.
4. Evaluate and reiterate where appropriate.

Fischer (2000) acknowledges that public involvement should be reserved for cases where it is reasonable. There is no need to involve everyone in the design process, and according to Virzi (1992), five participants are sufficient to identify the majority of usability issues. Further, if the cost and benefit of involvement are taken into account, Nielsen and Landauer (1993) suggested that for a "medium" efficiency, no more than 16 participants are needed. Nor would everyone be interested; according to participation inequality, or the so-called 90-9-1 rule described by Nielsen (2006), only a small percentage of volunteers are actively contributing, while the majority are less involved.

Høegh et al. (2006) emphasize how important it is to involve the developers of the systems in the feedback loop to aid their understanding of usability issues and improve the systems. Following this, Gulliksen et al. (2003) explain that far too often, the user interface (UI) design is conducted by "hobbyist" coders rather than professional interaction designers, and hence, the development process should contain conscious design activities. Similarly, many of the devices are designed to address a simple problem (to display value) and fail to take into account the third dimension (people/user), which according to Albers (2004), brings complexity to the problem and goal. More importantly, Degbelo et al. (2016) urge learning from previous studies to avoid making the same mistakes and reinvent the wheel. Rosenbaum et al. (2000) identified and categorized obstacles for applying user-centred research (UCD) into seven groups as reported by usability practitioners. These include:

1. Resource constraints, e.g., time and money.
2. Resistance, e.g., having a belief that the developer already understands usability.
3. Lack of knowledge about usability, e.g., is seen only as testing activity.
4. Better ways to communicate the impact of work and results, e.g., having greater visibility and credibility of the impact.
5. Lack of trained usability experts, e.g., lack of experience of usability issues.
6. Lack of early involvement, e.g., brought in too late to have a real impact.
7. No economic need – customers not asking for usability, e.g., no negative market consequences identified for not including usability in the process.

In addition, Gulliksen et al. (2003) recognise that applying UCD can be challenging even in projects that aim to do so from the beginning. Namely, user focus can be an attitude issue and face organisational obstacles.

According to Gulliksen et al. (2003), UCD should extend beyond hardware and software and represent a holistic approach that includes supporting activities to be developed in parallel. This approach also includes, e.g., user manuals, web interface reports, and, eventually, work practices.

1.4 User Experience Evaluation Methodology

This section introduces projects that provided a working background, materials and volunteers and describes the specific activities that contributed to this thesis. These activities collectively comprise the user experience evaluation of novel air quality sensing

technologies for citizen engagement in environmental health studies. The methodology and its reasoning are also further discussed.

1.4.1 Working ground within EU projects

1.4.1.1 CITI-SENSE

The first project, CITI-SENSE,[1] "Development of sensor-based Citizens' Observatory (COs) Community for improving quality of life in cities" (2012-2016), aimed at developing, testing, demonstrating and validating a community-based environmental monitoring and information system using innovative and novel Earth Observation applications. The project's overall aim was to develop, test, demonstrate, and validate a set of static and portable low-cost air quality sensor devices used in its Citizen Observatories (COs) (Liu et al., 2014, 2018). To this end, participants were engaged in various project activities at different levels of involvement. The overall project could be claimed to belong on the highest level in Haklay's hierarchy of participation involvement as COs aim to go beyond the usual scope of CS projects. Several authors have tried to characterise this newer term, e.g. (Liu et al., 2014). However, Grainger (2017) emphasises that it is important to distinguish between CS and COs, in which also CITI-SENSE project falls. The two differences between the two are that 1) the information generated in CO projects must directly benefit citizens and society generally, rather than science alone, and 2) CO projects will be co-created or collaborative projects rather than contributory projects. However, classification is not straightforward since the project had a complex structure and multiple activities within multiple cities, out of which many were collaborative or even extreme. Specific activities discussed in this thesis and their alignment with the ten principles of CS are detailed in Table 1.1. In particular, the CITI-SENSE urban air quality empowerment initiative developed, employed and tested a low-cost portable air quality unit. The measurement results were expressed as the Air Pollution Indicator (APIN) displayed in a corresponding mobile application (ExpoApp) and on the Citizens' Observatory web portal. The project provided grounds for identifying the problems in the field for this thesis, including the usability challenges arising from using the sensor technologies. More specifically, comprehensive user research as part of the project empowerment evaluation of the tools was carried out to gain insights into participant motivations, needs, experiences, and feedback on the low-cost portable air quality sensor device (Figure 1.1). This feedback from the Ljubljana participants was promptly communicated to the project development teams and further.

[1] https://social.citi-sense.eu/

Table 1.1: Alignment of CITI-SENSE case study activities with the ECSA 10 Principles of Citizen Science.

ECSA's ten principles	Case study activities descriptions
1.	Participants carried a portable low-cost sensor device.
2.	The participants tested and evaluated the sensor device, and their feedback was collected.
3.	Participants benefit by learning opportunities regarding air quality and satisfaction from contributing to the science.
4.	Participants tested and evaluated the device, associated phone app and data visualization portal. Their feedback influenced the design of the next version of the tools.
5.	The participants had access to real-time data and could see their data retrospectively from the visualization portal. They were aware that their feedback would influence the design of the next versions of the tools. Participants signed a user agreement and a privacy policy document.
6.	Participants were given a demonstration of how to use the devices and a user manual for the sensor device. In case of issues, the researchers were available for advice. The technical limitations of the devices and following data visualizations were communicated, e.g., the display of APIs instead of pollution concentrations.
7.	Some general unidentifiable data was available on the visualization portal. The individual results were not shared due to privacy restrictions. The scientific article from this case study was published open access.
8.	The participants were acknowledged in publications.
9.	The participants evaluated the tools, and their experiences were evaluated. Conclusions were drawn for future similar campaigns.
10.	All legal and ethical issues were taken into consideration.

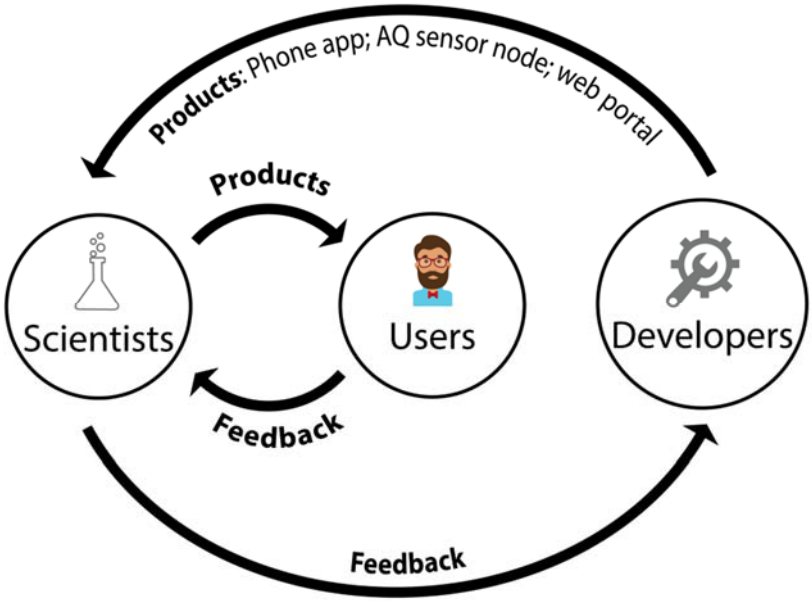

Figure 1.1: User research carried out in the CITI-SENSE project (Robinson et al., 2018).

The CITI-SENSE urban air quality initiative had ambitious aims of empowerment, and despite having co-design features, the participants who carried the portable sensor units were mainly crowdsourcing. However, with the final evaluation of the tools, their involvement became more participatory as they could express their desires and concerns regarding the technology and its empowerment potential. Other evaluations regarding sensor performance within the CITI-SENSE project stated that despite them being sensitive to varying environmental conditions and not being sufficiently accurate for legislative purposes or other purposes which require high accuracy, they have great potential for empowerment and raising awareness by displaying values in relative and aggregated forms (Broday et al., 2017; Castell et al., 2017). This thesis, however, demonstrates that using these low-cost sensor devices even for empowerment and awareness-raising purposes is not straightforward. Moreover, the importance of involving participants in the design process of low-cost air quality sensor devices became evident. The specific outcomes can be found in Section 3.1.

Even if the ten principles appear to be aligned within the presented case study, it is arguable that they do not meet them to the fullest possible extent. For example, regarding the second principle, the project initially aimed at providing the participant's individual-level exposure estimates, yet, due to the nature and developmental stage of the low-cost sensor device, mainly aggregated values were displayed at the end. Similarly, the fourth principle describes different levels of involvement, and even though the project aimed high regarding co-design aspects, the participants had the freedom to carry the sensors where they wished, and therefore answer their research questions. They also participated in the feedback process regarding the tools. There could have been even more involvement prior to and after these activities. Also, this work has the strongest alignment with the ninth principle regarding evaluation. Here the evaluation process took place on two levels. First, the participants evaluated the devices, and second, their participation experience was studied and evaluated.

1.4.1.2 SMURBS

The SMURBS project[2] "SMart URBan Solutions for air quality, disasters and city growth" (2016-2021) aimed at promoting and coordinating the "smart city" concept into a European network of cities through the integration of Earth Observation (EO), serving the need for a common approach to enhance environmental and societal resilience to specific urban pressures with an emphasis on air pollution, natural disasters, urban sprawl and migration pressures. The objectives included setting the stage for integrating the still fragmented, multi-scale and multi-temporal Earth Observation resources into information and decision-making tools for individuals and local governments in support of GEOSS and the Sustainable Development Goals. Citizen science and Citizen Observatories are considered important approaches in EO smart urban solutions.

As part of this project, technical, social and practical aspects for deploying COs from the literature were inventoried (Robinson, 2019). This work gave rise to an overview of citizen science and features of tools that affect volunteer motivation and retention in a review paper as presented in Chapter 3.2 (Figure 1.2). An important part of the review was the description of characteristics of CS projects together with CS terminology and classifications of projects according to their levels of engagement. The literature review served as a *vade mecum* for all SMURBS cities where concepts or particular aspects of COs were adopted (e.g. participatory sensing and reporting), tailored according to the particularities of the specific SMURBS city implementation under real-world conditions and was later used to evaluate the pilot city implementations.

Figure 1.2: Five motivational factors for citizen scientists' participation (Robinson, Kocman, et al., 2021).

1.4.1.3 ICARUS

ICARUS project[3] "Integrated Climate forcing and Air pollution Reduction in Urban Systems" (2016-2020) aimed to develop innovative tools and win-win strategies for urban impact assessment in support of air quality and climate change governance in the EU to improve air quality and reduce the carbon footprint in seven European cities. It aimed to reach this with an integrated approach for air pollution monitoring and assessment combining ground-based measurements, atmospheric transport and chemical

[2] https://smurbs.eu/
[3] https://icarus2020.eu/

transformation modelling and air pollution indicators derived from satellite, airborne and personal remote sensing.

Specific activities discussed in this thesis are related to a multi-sensor personal air pollution exposure monitoring campaign conducted within the ICARUS project in Ljubljana. The sensor campaigns were initially a crowdsourcing activity, where participants passively hosted at their homes or carried various sensor devices. For this thesis, additional activities were introduced. The sensor campaign enabled the study of participant experiences (Figure 1.3) and included the participants in a user-centred design of a final result report (Figure 1.4). A detailed description of the campaign and participant experiences can be found in Chapter 3.3, while the description of the UCD can be found from the manuscript in Chapter 3.4. The introduction of these feedback loops increased involvement from crowdsourcing to participatory science according to Haklay's participation hierarchy.

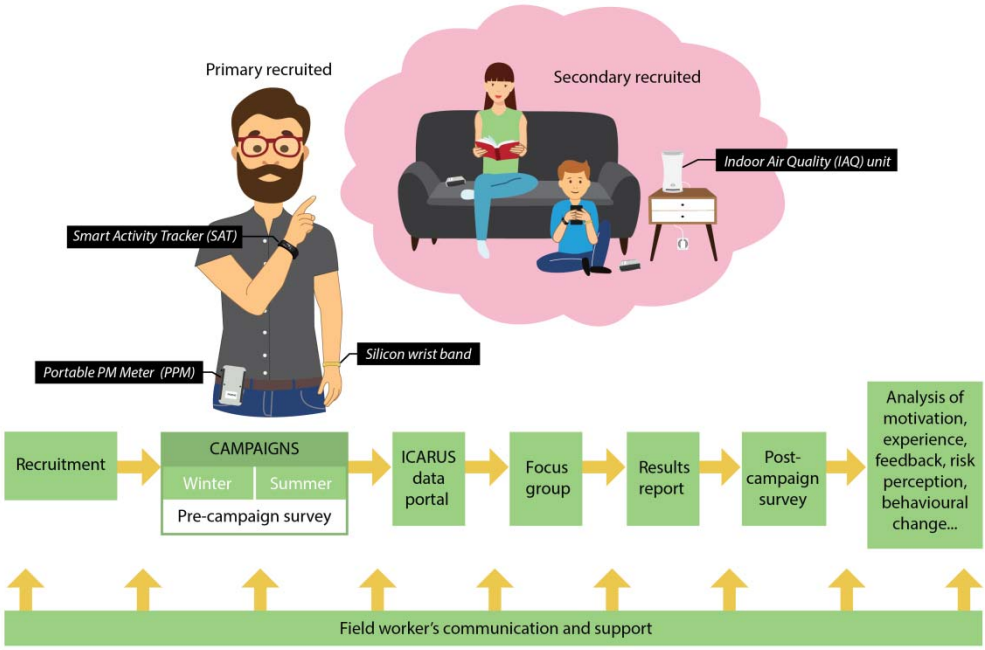

Figure 1.3: Overview of the ICARUS sensor campaign (Robinson, Novak, Kanduč, Sarigiannis, et al., 2021).

The overview of alignment of ICARUS case study activities with the ECSA Ten Principles of Citizen Science is detailed in Table 1.2. Like CITI-SENSE, ICARUS project case study aligns the most with the ninth ECSA principle of CS. Even though the ICARUS case study appears to be aligned with all the principles, at the same time, there is room for improvement to increase their extent. For example, even if the role of the participants in the EU level multi-sensor personal exposure campaign was predefined regarding data collection, the additional activities enabled the participants to share their experience from participation and express their wishes for data visualization. Due to technical challenges with the data coming from low-cost devices, some trade-offs had to be made in reports. Another example is the fifth principle. Here, the participants received individual reports and did not have access to data from other participants. However, this was due to privacy issues, yet, could have been solved discretely.

Table 1.2: Alignment of ICARUS case study activities with the ECSA 10 Principles of Citizen Science.

ECSA's ten principles	Case study activities descriptions
1.	Participants carried portable low-cost sensor devices and hosted stationary indoor air quality units at their homes.
2.	The expected outcome in a multi-sensor personal air quality exposure study was to assess exposure to air pollution at the individual level. The user experience was also evaluated.
3.	Participants benefit by learning opportunities to gain insight about their exposure based on individualized time-activity profiles and through the satisfaction of contributing to science.
4.	Participants could recruit their family members. Participants were encouraged to share their participation insights with their social networks. Participants could provide feedback about the type of data they want to see in the results report and participate in the UCD of the result report design.
5.	The participants gave informed consent and received comprehensive information on the project aims prior to the start of the campaign. The participants received a results report at the end of the study, including information about their individual results.
6.	Participants followed a predefined protocol to use the devices. In case of issues, the researchers were available for advice. The technical limitations of the devices and following data visualizations were communicated, e.g., the display of average daily values.
7.	The individual results were not shared due to privacy restrictions. Pseudoanonymized ones were used for publications. The scientific articles from this case study were published as open access.
8.	The participants were acknowledged in publications.
9.	The participants evaluated the sensor devices, and their participant experience was extensively studied. The wider societal impact was discussed.
10.	All legal and ethical issues were taken into consideration.

1.4.2 Development of the methodology

Evaluation or validation of a tool confirms that it meets the requirements of specific intended use (ISO, 2008), while mere usability as functional testing may prove that it meets the specifications set by the technical team (Hudson, 2001). An interest in studying the empowerment potential of the tools means that it is important to choose an approach that enables an exploration of the participants' intended uses and evaluate whether they were met. This approach meant that traditional forms of UX from the Human-Computer Interaction (HCI) field, e.g. pre-existing UX questionnaires that focus on quick feedback under laboratory conditions (Laugwitz et al., 2008) to improve a system, were not applicable. First, they do not provide insights into holistic user experience, and second, the wider social aspects of their use were also studied.

As described previously, user research was applied to low-cost air quality sensor devices designed for the campaigns of the respective studies and commercially available ones used during the ICARUS project campaign. It was impossible to influence the initial choice and development process of the used low-cost sensor devices within the large projects. However, it was possible to introduce additional activities as sub-studies to complement the evaluation of the used low-cost sensor devices.

Following Gulliksen et al. (2003) guidance for a holistic approach, the whole system was evaluated. This guidance included user manuals, web interface, reports and work practices evaluated within the respective case studies, where applicable. All this was done in addition to gaining feedback on the low-cost sensor systems. User experience was studied under real-world field conditions for holistic user experience where volunteers carried the low-cost sensor devices in their everyday life for approximately one week.

Tauginienė et al. (2020) suggest that using methodological spectrum from social sciences and humanities helps to understand the human dimension in CS projects; this thesis explored the ethnographical aspects of the use of low-cost sensor devices (Kujala, 2003); the social dimension of product design, having the user in the spotlight and exploring the empowerment potential of these devices. In this thesis, ethnographic user research enabled the capture and articulation of real-life lived experiences, i.e., their environment, rather than setting up a usability lab and studying how such systems affect their daily lives. By adding an ethnographical aspect to UX, the aim was to understand current practice amongst users of low-cost sensor devices. The ethnographical UX aspects include how they experienced interaction with the technology, their challenges, and what frustrated them. The fact that case studies included long-term use called for qualitative data collection. The use of surveys, focus groups and interviews was seen as appropriate to capture the participants' long-term lived experiences with the low-cost technology and the campaign as a whole. The collective experiences were further analysed and interpreted into larger themes with the help of coding. This analysis enabled the articulation of the user point of view.

Ethnography is *"about telling a credible, rigorous and authentic story. Ethnography gives voice to people in their own local context, typically relying on verbatim quotations and a "thick" description of events. The story is told through the eyes of local people as they pursue their daily lives in their own communities. The ethnographer adopts a cultural lens to interpret observed behaviour, ensuring that the behaviours are placed in a culturally relevant and meaningful context.* The ethnographer is focused on the predictable, daily patterns of human thought and behaviour. Ethnography is both a research method and a product, typically a written text" (Fetterman, 2009).

Moreover, knowing the importance of UCD means that it is possible to introduce iterative UCD in a results report development, which, just like low-cost sensor devices, works as a communication medium of individual exposure (Figure 1.4). Participants were involved in three iterative cycles within the UCD process of a results report within the ICARUS project. In Chapter 3.4, a model is suggested, and the UCD process is demonstrated.

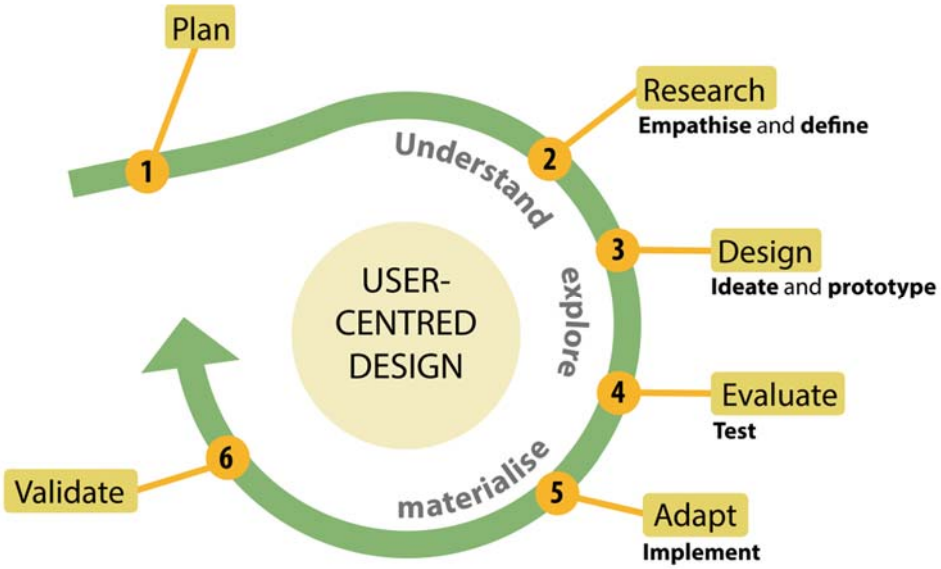

Figure 1.4: Life cycle model of a user-centred design (Robinson, Novak, Kanduč, Maggos, et al., 2021).

In this work, sometimes the word *user* (or end-user) is used, as defined by ISO 9241: "*person who interacts with the product*," but here, the word *participant* is used to emphasise the participatory nature of their involvement as volunteer users. Here the term *end-user* refers to the participants. For example, Rai et al. (2017) consider scientists as the end-users, which might partially explain why the low-cost sensor devices developed for many CS projects are designed for researchers in mind, rather than the public, even though in literature it is emphasised over and over again how these devices can mobilise the public and democratise air pollution monitoring. This research emphasises the *real* end-user needs and involves them in case studies to identify design faults relevant from their perspective. This thesis will avoid using the word *citizen*, as it strongly refers to a person's status as a national of a particular country while excluding those who are not citizens but still living in the country. To refer to a crowd of people, i.e. a local community, the phrase "*the public*" is used.

It is commonly observed that CS projects attract a limited demographic profile and are generally over-represented by older white males with above-average education levels and higher socio-economic backgrounds. At the same time, groups from other sociocultural backgrounds, socio-economic status, literacy levels, religious affiliations, minority groups, gender, age, people with disabilities, etc., are mostly underrepresented (Butkevičienė et al., 2021; Paleco et al., 2021). Edwards et al. (2018) propose that encouraging participant diversity in citizen science projects will benefit scientific outcomes by delivering them to a wider population and hence growing science capital. Some scholars even argue e.g. (Paleco et al., 2021), that inclusiveness should also entail

the composition of the project team, e.g. women to assume leadership. While inclusiveness and equity are important factors in the democratisation of air pollution monitoring, especially since AQ affects everyone, it was not the focus of this thesis. Namely, while acknowledging that only those who want to participate in environmental health studies will participate, recruitment strategies can try to reach less represented vulnerable groups. Still, in the end, it is up to them whether they volunteer. Details regarding the profile of recruited participants in the case studies can be found in Chapters 3.1. 3.3. and 3.4., and summarised here. In any case, the nature of volunteering meant that the diversity in the profile of participants could not be fully controlled, and the relatively small number of volunteers does not allow for in-depth exploration and conclusions to be drawn within individual groups or profiles, respectively. To this end, the two case studies originally attracted a certain profile of people inclined to participate, i.e., well-educated individuals. However, especially with the ICARUS case study, the secondary recruitment method enriched the typical CS participant profile, and also elderly, children, mothers with young children and people with existing health conditions were represented. The socio-economical spectrum was also more diverse. In the CITI-SENSE case study, males were overrepresented, while in ICARUS, they represented just over half. In the ICARUS campaign, the number of under-aged participants was high, while in CITI-SENSE, all were adults. Third, participants in the ICARUS case study mentioned having a pre-existing health condition. The majority of people in the ICARUS campaign had an average or low level income. More technically oriented people were eventually intentionally recruited in the CITI-SENSE campaign, as the low-cost portable AQ device and the accompanying phone app had issues recognised by the researchers at the campaign's onset (e.g. re-connections, forced stops, and reinstalling the app had to be performed frequently).

Chapter 2

Hypothesis and Aims

The goal of the thesis is to study end-users of low-cost air pollution sensor devices in environmental health studies; their experiences, needs, expectations, motivations, behavioural changes, and to gain feedback in order to contribute to the next-generation monitoring and sensing technologies, assess their fit-for-purpose for environmental health studies, and to examine the conduct and outcomes of these studies from the participant's point of view.

2.1 Specific Aims

- To gain insight into volunteer motivation by performing a literature review and empirical case studies.
- To perform user experience evaluation of low-cost air pollution sensor devices from case studies and investigate the need for co-design.
- To investigate which features inhibit or nurture participation.
- To understand user needs, expectations, experiences, behavioural changes, and their underlying factors.
- To document, demonstrate and evaluate the user research process conducted in the context of multi-disciplinary environmental health study campaigns.
- To understand the role and scope of participation from a work practice point of view.
- To understand to what extent the low-cost sensor devices can be used in environmental health studies (fit-for-purpose).

2.2 Hypothesis

This thesis tests the following hypotheses:

1. Prototype low-cost sensor devices are not sufficiently adapted to user needs.
2. Commercial low-cost sensing devices are more readily accepted amongst participants than prototype ones.
3. A positive user experience will positively influence user motivation and satisfaction.
4. Participation in environmental health studies as a sensor device user causes participants to adopt pro-environmental behaviour.

5. Participation in environmental health studies increases the participant's knowledge and interest in the subject.
6. Including participants in the design process of a results report leads to increased use and understanding of the report.

Chapter 2

Publications

Publications included in this thesis consist of three scientific articles: two published, one submitted for publication, and a published review article. The publications have resulted from three EU-funded projects, and the candidate's contributions to each scientific article are described. The selected publications appear in the following order:

Robinson, J. A., Kocman, D., Horvat, M., & Bartonova, A. (2018). End-User Feedback on a Low-Cost Portable Air Quality Sensor System—Are We There Yet? *Sensors*, 18(11), 3768. https://doi.org/10.3390/s18113768

Robinson, J. A., Kocman, D., Speyer, O., & Gerasopoulos, E. (2021). Meeting volunteer expectations—A review of volunteer motivations in citizen science and best practices for their retention through implementation of functional features in CS tools. *Journal of Environmental Planning and Management*, 64(12), 2089–2113. https://doi.org/10.1080/09640568.2020.1853507

Robinson, J. A., Novak, R., Kanduč, T., Sarigiannis, D., & Kocman, D. (under preparation). Articulating user experience of a multi-sensor personal air quality exposure study.

Robinson, J. A., Novak, R., Kanduč, T., Maggos, T., Pardali, D., Stamatelopoulou, A., Saraga, D., Vienneau, D., Flückiger, B., Mikeš, O., Degrendele, C., Sáňka, O., García Dos Santos, S., Visave, J., Gotti, A., Persico, M. G., Chapizanis, D., Petridis, I., Karakitsios, S., Sarigiannis, D.A., Kocman, D. (2021). User-Centred Design of a Final Results Report for Participants in Multi-Sensor Personal Air Pollution Exposure Monitoring Campaigns. International Journal of Environmental Research and Public Health, 18(23), 12544. https://doi.org/10.3390/ijerph182312544

3.1 Scientific Article: "End-User Feedback on a Low-Cost Portable Air Quality Sensor System—Are We There Yet?"

This section is a scientific article authored by Johanna Amalia Robinson, David Kocman, Milena Horvat and Alena Bartonova. The article was published in Sensors in 2018. The article results from the EU-funded CITI-SENSE project and describes participant feedback of a low-cost portable air quality sensor system tested in Ljubljana, Slovenia, covering user experience, user needs and motivations. It demonstrates the need for including end-users in co-designing CS tools and confirms hypotheses one and three. The candidate conceptualised the idea for the manuscript, interviewed the participants (individually or in focus-group settings), performed data analysis, prepared visualisations and wrote the original manuscript.

Link to the article: https://doi.org/10.3390/s18113768

sensors

MDPI

Article

End-User Feedback on a Low-Cost Portable Air Quality Sensor System—Are We There Yet?

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Abstract: Low-cost sensors are a current trend in citizen science projects that focus on air quality. Until now, devices incorporating such sensors have been tested primarily for their technical capabilities and limitations, whereas their usability and acceptability amongst the public rarely goes beyond proof of concept, leaving user experience (UX) unstudied. The authors argue that UX should be taken into account to make sure that products and services are fit for purpose. Nineteen volunteers tested and evaluated a prototype device and provided feedback through semi-structured interviews and during focus group sessions. Their UX was then coded using mixed coding methods regarding device functionality and recommendations for future product development. The results indicate that UX can identify potentially problematic design aspects while giving deeper insights into user needs. For example, UX recognized that one of the most important aspects of user involvement and motivation was successful data harvesting, which frequently failed. This study recommends that future developers of low-cost portable air quality sensor systems prioritize reliable data transmission to minimize data loss. This will ensure an efficient and positive UX that supports user engagement in citizen science based research where collecting sensor-based data is the primary objective.

Keywords: low-cost portable sensor system; user experience; user needs; air quality; citizen science

1. Introduction

An increasing number of research projects requiring the use of portable low-cost air quality sensor systems [1] means there is a need for user experience (UX) feedback to sensor systems developers, and to those who deploy them. Our central argument is that developers of low-cost, portable air quality sensor systems and the scientists deploying them in participatory studies will benefit from considering end-user experience. Moreover, the trend in miniaturizing and mobilizing air quality sensor devices has influenced rapid development in the field of low-cost portable air quality sensor systems. In recent years, a large number of sensor developers and users have emerged, including commercial and research laboratories, reflecting the appeal of these devices for engaging various end users. There now exists a number of field studies characterizing such devices [2–10] including studies that explore their feasibility for personal exposure assessment [4,11–14]. Similarly, low-cost sensing devices utilizing IoT platforms designed for real–time indoor monitoring have been published [15–19] with indoor air quality being an important part of a holistic approach to exposure assessment. Many studies now focus on citizen science type experiments where volunteers carry or host an air quality sensor device [3,7,20–22].

Citizen science approaches have led to innovative methods of data collection, data processing, and data sharing both as a result of technological advances and an increased interest by the public

to participate in gathering information about their environment [12,21–24]. Even if low-cost portable sensors can bring new opportunities for observing air pollution at higher spatial resolutions while providing personalized air quality data [25], there are many challenges preventing the wide-scale implementation of such devices. Some of these challenges relate to low-quality data deriving from the use of low-cost sensors and the lack of meaningful information that they provide to the public [3,8,21,26–29]. It is also recognized that although the involvement of citizens increases spatiotemporal coverage of an area [30], data collected by non-experts might be considered less reliable [31].

The added complexity created by involving citizens also adds to the challenges for the practical application of the technology. This problem has been addressed in several studies: For instance, Morawska et al. [32] provided an overview of the steps involved in successfully deploying sensor systems, whilst Thompson [22] pointed out a new technology should not be expected to work flawlessly, and encouraged researchers to develop not only accurate devices but to test them prior to deployment. Lewis et al. [7] also recommended caution when using newly developed sensor technologies and to first demonstrated their fitness for purpose, and Kumar et al. [26] raised questions about the future directions of low-cost sensors. In addition, Aoki et al. [25] questioned why participatory sensing is treated merely as a technical feasibility experiment, leaving the social aspect unstudied, whilst Hubbell [33] provided examples of what should be done and called for more social science research at the individual and community level.

Many authors e.g., [25,27,34–36], and review papers [21,22], have touched upon the user side of the technology. Most studies involving participants or studies describing a sensor-based solution for participatory sensing, however, discuss data processing, data transfer and data visualization [37–40], while few studies focus on the response to the information gathered, and how it can increase awareness and foster behavioral change [14,27,41]. Despite this, there remains a lack of literature from the perspectives of volunteers of systems which have not been designed with the potential end user in minds, yet have been deployed in citizen science research. Bales et al. [34,37] and Zappi et al. [36], as well as Willet et al. [35], provide examples of air quality sensing solution where the potential end users were iteratively involved in the development process, but these studies lack detailed insights.

Hart and Martinez raised usability issues as a challenge back in 2006 [42], and how sensor system networks are designed for research platforms used solely by scientists, while Moore [43] emphasized how high-tech products must meet end-users' needs. However, devices reported in literature (see for example [8]) are still designed for those who have capabilities to perform co-location and calibration of the units, e.g., technically capable members of the public, professional communities or scientists. Furthermore, scientists often recruit the public to use a research device they consider as a "finished" product, yet in reality the device is a prototype. The present trend is to create user-friendly sensor systems for public use, yet there is lack of literature validating those claims. It is surprising how few sensor systems have been evaluated by potential end users. Studies show that the more the end user is involved in the process of designing and testing a product, the more satisfied they are with the final product as summarized by Mahmood et al. in their meta-analysis [44]. Commodore et al. [21] confirmed the importance of community involvement in all stages of the research process in the field of air quality related participatory research, and Reed [45] emphasizes that participation should start as early as possible in the design phase and involve relevant stakeholders to provide a comprehensive understanding of societal needs.

Without end-user involvement, it can be difficult for a designer to know intuitively what is required from a product. The benefits of learning about user behavior, needs and motivations through UX research far outweigh the risk of failure when users are not involved in the design process [46]. A key concept of citizens adapting new technology is "ease of use". Scientist can study these aspects through usability testing, based on the landscape of Human-Centered design domain [47,48]. Documenting the interactional experience of the end user, can lighten technically oriented designers who commonly see the failure of the user to use the product correctly as the users

fault e.g., by using Problem Exists Between Keyboard And Chair (PEBKAC)-type phrases. A human centered design approach can help make useful and user-friendly products [49] and contributing products that are fit for purpose.

This paper, provides a close examination of UX in relation to a prototype of a portable low-cost air quality sensor system based on a field study conducted within the EU funded CITI-SENSE project [50]. Our aim was to describe the outcomes of UX study regarding a product which would have otherwise not been tested by potential end users and hence identify potential improvements. To do this, volunteers were each given a device for one week to test and evaluate, after which they provided feedback through semi-structured interviews and focus group sessions. The feedback was then coded to obtain a structured summary of their experiences. The study maintained a constant discussion between researchers and the development team, and the volunteers' feedback was provided promptly to the development team in order to contribute to the next generation of sensor systems. Ultimately, this paper discusses the types of features that the citizen science community desires, i.e., user needs as well as the pitfalls in design, which developers can avoid in order to create a positive user experience.

2. Methods

2.1. Study Design

Nineteen volunteers were recruited to test and evaluate a prototype low-cost portable sensor system in Ljubljana, Slovenia between 21 April 2016 and 24 June 2016. One sensor system was given to each of the volunteers for one week. The purpose of the study was to have volunteers to test and evaluate the sensor system during their daily routine rather than in a usability laboratory. As the sensors in the device were targeting outdoor air pollutants, the volunteers were recommended to carry the device on them when leaving the house, therefore they were not requested to carry the sensor unit at all times as is usually the case in exposure studies. Out of the 19 volunteers, 67% were male, and 37% female. 5% had finished secondary education as their highest level of education, 37% had an undergraduate degree, 5% had a master's degree, and the remainder 53% had a doctoral degree. Ages ranged between 25 and 57 with 26% under 30 years old, 53% between 31 and 40 years old, and 21% were 41 years old or older. Volunteers included representatives from local technology-based businesses and national organizations, i.e., individuals with a better than expected average technological background, and individuals with a research background. This may have introduced some bias into the study, since the group of volunteers is not representative of the public. Initially, the study recruited public volunteers at the yearly Jožef Stefan institute's open day event, and local stakeholders during project meetings. Other volunteers contacted the research team after they saw a presentation of the project (short-video) by the Slovenian Press Agency in their news feed. No incentives for participation were given, and all volunteers signed a user agreement and a privacy policy document.

Volunteer training involved a demonstration of how to use of the device during a face-to-face session. Each volunteer also received a link to a video tutorial [51] and a user guide [52] describing the use of the device, the main functionalities as well as troubleshooting including instructions on how to charge the device. Throughout the trial, volunteers had access to on-demand technical support by phone and email with the project researchers. All technical issues encountered were reported to the development team during the participation phase in order for the team to make the necessary adjustments. After the field trial, researchers provided a summary of the feedback to the development team.

The field trial was followed by UX research to gain an in-depth understanding of user needs and from the analysis of user feedback to systematically describe what worked well and what improvements are needed. The project team conducted six focus group sessions with volunteer numbers ranging from two to five volunteers. In addition, they conducted two open ended individual interviews with those volunteers who could not join the focus groups, one of them through an online GoToMeeting. The focus groups and interviews followed the same semi-structured form and were

conducted at the volunteers' workplace and moderated by the lead author. Volunteers were told in advance that they are expected to provide their feedback of the sensor system, however, they were not given any questions in advance. Face-to-face feedback sessions lasted approximately 20 min and the focus group sessions and interviews were recorded and transcribed. Four of the sessions were held in the Slovene language and were translated into English after transcription. The information gained provided feedback to the development team and research material for the current paper.

2.2. Low-Cost Portable Sensor Unit with Smartphone Visualization

This study, made use of a prototype low-cost portable air quality sensor system developed within the CITI-SENSE project (2012–2016). CITI-SENSE also developed hardware and software sensing platforms, which allowed individuals to participate in collecting air quality information. One of the developed sensing devices was the Little Environmental Observatory (LEO) developed by Ateknea [53]. It is a prototype with an indicative market price below 500€. The sensor system measures nitrogen monoxide (NO), nitrogen dioxide (NO_2) and ozone (O_3) using Alphasense A4 series electrochemical microsensors [54]. The unit contains a built-in ambient temperature (°C) and relative humidity (%) sensors (Sensirion SHT11, Stäfa, Switzerland) in addition to a Pt1000 sensor used for temperature compensation of gas measurements. Table 1 gives the specifications of the Alphasense electrochemical microsensors, while Figure 1 shows the dimensions and the location of the sensors in the device. Depending on the model, the wearer could clip the device on a belt/pocket (weight 164 g) or have it attached to an armband (weight 185 g). The battery lasts up to 20 h depending on Bluetooth usage and sampling frequency. Details regarding testing and performance evaluation of the LEO are given elsewhere [2,55,56]. The testing comprises sensors evaluation in the laboratory against traceable gas standards under controlled ambient conditions, against each other during co-location as well as comparison with stationary air quality monitoring reference data under field conditions.

Table 1. Specifications of the Alphasense electrochemical microsensors [57].

Parameter	Sensor Name	Operational (Measurement) Range	Response Time	Diameter	Weight
NO	NO–A4	0–20 ppm	<25 s	20.2 mm	<6 g
NO_2	NO2–A42F	0–20 ppm	<60 s	20.2 mm	<6 g
O_3	OX–A421	0–20 ppm	<45 s	20.2 mm	<6 g

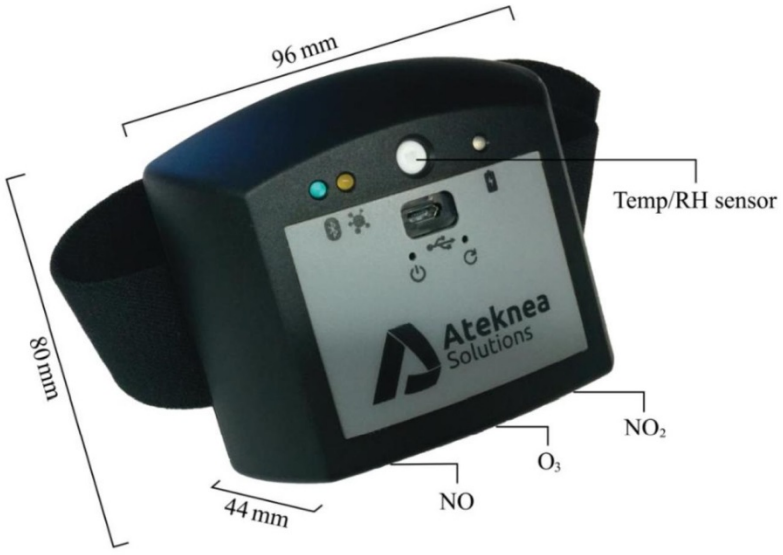

Figure 1. Little Environmental Observatory (LEO) portable sensor system.

For data collection, the LEO device was paired via a Bluetooth 2.1 connection with an Android smartphone. An app (ExpoApp) allowed the smartphone's Global Positioning System (GPS) unit to log the user's geolocation while collecting data. With a 10 s sampling frequency, the smartphone was capable of sending 1121 bytes of data every minute to a Web Feature Service (WFS) server via Wi-Fi or cellular data. A time-stamped signal of the individual sensors, GPS coordinates and accelerometer data were also sent to the server where the data was stored and processed. The data was visualized back to the user in near real time through the ExpoApp app, as a 5 scale Air Pollution INdicator value (APIN). Figure 2 shows the data flow of the system.

Figure 2. Data flow from the sensor system to the user via a smartphone and the server.

The APIN was calculated using all three measured pollutants, using a procedure based on the Common Air Quality Index (CAQI) approach developed as part of the CITEAIRII project [58]. There are important differences between CAQI and APIN. To provide sufficient temporal granularity, APIN uses 1 min averages instead of hourly data, and further, the low-cost sensor data are of unknown- or low-quality [3], while the CAQI is based on air quality monitoring made in compliance with the requirements of EU Directive 2008/50/EC [59].

ExpoApp is also able to display two hours of historical data as time plots of APIN and Activity index. To calculate the Activity index, ExpoApp used the smartphone's own accelerometer. In addition, the user was able to access an online web visualization tool [60] that shows their own tracks based on GPS data. See also Figure 2. These tracks were only visible to the user who generated them via a unique user ID defined during the pairing phase between the sensor system and ExpoApp. The public was able to see the last location of the units colored according to the last recorded APIN, together with the available data for the city, using project specific web visualization features.

The project team members provided initial feedback about the systems prior to the field campaign, and the necessary changes and updates were made.

2.3. Data Analysis

To analyze the UX data, the transcripts from the focus groups and interviews (a 65-paged textual corpus) was coded. This was achieved using mixed coding methods that combined Magnitude coding, Descriptive coding, In Vivo coding, and Recommendation coding in the Evaluation coding method as described in [61]. For traceability, all the entries were numbered both in the textual corpus and in an excel file. The mixed coding process was used as follows; every entry received a main code (Descriptive coding), which emerged during the first round of coding and was accompanied either by a descriptive sentence or a citation (In Vivo coding). Where appropriate, a Magnitude coding indicated whether the feedback was positive (+) or negative (-). Recommendations were tagged with a "REC" (Recommendation coding). A second round of coding followed where similar entries from the first round were further clustered and re-organized.

3. Results and Discussion

Twenty-eight categories based on user experience emerged (Table 2). Several entries were also classified under multiple categories, e.g., when volunteers gave feedback with suggestions about ExpoApp, the feedback was categorized both under "app" and "REC".

Table 2. Number and frequency of codes in each coding iteration (coding rounds R1 and R2).

	Main Codes	R1/R1 f Total	*R1: REC*	R2	*R2: REC*	R2 f Total
	Recommendation (REC)	84	*100*	45	*56*	103
	App	50	*35*	27	*20*	53
	Barriers for further action	43	*3*	15	*3*	45
	Possibilities (if improved)	37		21		45
	Hardware	24	*17*	16	*9*	27
	Motivation	22		14		25
	Positivity about the general idea	18		8		21
	Data loss	14	*3*	5	*1*	18
	Web visualization	13	*5*	9	*2*	16
	General user experience	13		9		13
	Expectations	7		4		8
	Privacy	7	*2*	2	*1*	7
	Quitting (reasons)	6		4		7
	Battery	7	*5*	2	*4*	7
	Length of use	4		4		6
	Data connection	6	*5*	2	*3*	6
	App visualization	3	*2*	4	*2*	4
	Data quality	4	*1*	4	*1*	4
	GPS	4	*6*	3	*4*	4
	Optimal participation time	4	*3*	1	*1*	3
	Product price	2	*2*	3	*1*	3
	Behaviour	3		[1]		
	Time	10		[2]		
	Data visualization		*8*		*4*	
	External people	2		[3]		
	LEO	26	*3*	[4]		
	CityAir	25		[5]		
	Uncategorized	5		[6]		
Total	28	443	*100*	202	*56*	425

[1] Under "Possibilities" in R2; [2] Mostly covered by "Barriers for further action" in R2; [3] under "Possibilities" in R2; [4] covered by other categories in R2; [5] Excluded as it is outside the scope of this paper, pertaining to another data collection tool used in CITI-SENSE; [6] categorized in R2.

The main categories were further modified in the second round (R2) of coding, which meant that several categories from the first round were reclassified, e.g., Behavior, Time, External people, LEO, and Uncategorized. This resulted in 22 categories of UX. We then restructured REC to reflect the target of the recommendation, e.g., hardware and app. In addition, a new category, Data visualization, was

created to extend the codes App visualization and Web visualization. Table 2 gives the code frequency for each round. The coded more detailed feedback is available in the Supplementary Materials.

The coding process worked as a tool to form a structured overview for the final evaluation, and many of the main categories complement each other. When writing the manuscript, the final, most aggregated, categorization emerged and comprised the following four themes: (1) User experience, (2) Feedback on the sensor system and its functionalities, and (3) User needs and recommendations and (4) Possibilities.

3.1. Structured Feedback

3.1.1. User Experience

The volunteers were positive towards the idea of portable low-cost sensor systems, and the idea that individuals can measure air quality wherever they are. They thought the idea was interesting, nice and beneficial and were interested in having such data. Volunteers thought that crowd-sensing methods are a good way to obtain higher resolution data, and being able to monitor indoor conditions was seen as especially useful compared to static air quality monitoring stations. They also felt positive that such projects exist and hoped that there would be a follow-up study. Some volunteers were surprised to learn that it is possible to measure air quality with such a small device.

Feedback revealed that user-friendliness was one of the main issues. This was not surprising since the device and accompanying software was a prototype designed for researchers rather than for the public, and hence did not meet the needs of the end user (public). In addition, the software was developed by a hobbyist programmer, rather than experienced software developer. Even the more technically oriented volunteers proposed thought ExpoApp needed simplifying. Several volunteers stated that the device in its current form is not ready for citizen science activities. The volunteers felt that the units did not perform well in everyday use, as various technical issues, e.g., the app crashing, having unstable connection and short battery life, kept hindering their use, which reduced the volunteers' motivation to continue using the device. Many were frustrated that it took a long time to pair the device to the smartphone in the morning when they had the least time (ID1). The volunteers wished for a simpler solution, e.g., a simple start/stop button for continuous data collection. This is in agreement with Thompson [22] who emphasized the need for an effortless interaction in the data collection process.

> ID1: "*If it only took few seconds to fix the problem it would be fine. It took a minimum of five minutes, which in itself is already too much. And it usually freezes right when you do not have the time. E.g., when you already have dressed your kids in the winter clothes and are ready to go to the car*".

UX also highlights issues with ExpoApp, which is a necessary component of the monitoring system. Volunteers were disappointed, frustrated and annoyed with the app, and noted that the phone app did not work properly and did not collect data successfully. Further, they pointed out that, the information provided by the device (categories of APIN) did not match the perceived air quality. Volunteers were also frustrated with the time and effort required to set up the device and to overcome technical issues. Some volunteers were happy to learn how to work with the new technology even if it meant learning to use a force-stop function. Overall, the results reveal that the volunteers expected the system to be user-friendly and older volunteers commented that perhaps, young people might have more time to experiment with a constantly failing technology. Despite this, even after encountering technological issues, several volunteers remained optimistic. Volunteers also sympathized with us about how the sensor system did not work as promised and wished the device could have helped them learn about local air quality.

For many volunteers, their motivation to participate was the idea of experimenting with a new emerging technology and gaining insight into air pollution, especially near their home. They also expected to see spatial differences in air pollution when moving between areas with perceived lower and higher air pollution. They were also interested in monitoring air quality alongside their daily

life, while others mentioned that this type of research is important because they want their children to live in a clean environment, and they wanted to check the air quality in their neighborhood. Several volunteers also liked the idea that their participation would contribute to the development of the technology, i.e., towards meeting user needs. These motivations are similar to the findings of Commodore et al. [21], who summarized related studies, and found that the primary motivations behind participation are related to a perceived risk to health, proximity to pollution sources, urban sprawl, living in unmonitored areas, and a desire to know more about air quality. Furthermore, volunteers in our trial emphasized that they were interested in the technology. Hu et al. [12] found that people are more interested in their own personal air pollution exposure than in overall air quality. Our findings were similar, and suggested that people were more interested in personal exposure and air quality in their immediate surroundings, especially near to their home. Hence, it is valuable that mobile devices can collect and receive information about one's immediate environment.

Once the volunteers began to use the device, technical issues resulted in volunteers becoming demotivated about continuing to use the device, but fortunately this did not affect their desire to fulfil their task, which was to test and evaluate the device. Many of the technical issues encountered were also barriers for further action, for instance, several volunteers stopped using the device after several failed attempts to fix a technical issue, or when fixing the problem took too long (ID12). Five of the volunteers reported using the research prototype only for three to four days instead of the suggested seven days. For many of the volunteers it was not interesting enough to see only one or two APIN values displayed on their smartphones. However, the webpage provided some additional air quality information for their city, based on data obtained from other devices. Accessing an additional webpage to see additional visualization was too much effort for some volunteers.

> ID12: *"It crashes already at the settings. When they released a new update after a few days I got excited that perhaps it would work, but it didn't".*

Many volunteers pointed out that this device would not be useful or have any benefit in daily life, and that, although the sensors in the device were useful outdoors, people spend a lot of time indoors and so such measurements would not be useful. The device was also considered burdensome, especially since the device needed frequent attention. Several of the volunteers were also unconvinced as to whether or not the device could empower a user to change their behavior, and some could not see the added value in having such a device since "common sense already tells you the time and locations to avoid air pollution" (ID17). The volunteers did believe in the "power of the masses" and suggested that a wide-scale simultaneous deployment was needed to make the data useful for others, rather than just for the individual with the device. There was a belief that substantial actions towards air pollution reductions are needed at the city level, e.g., closing roads, before any changes would be seen on a citywide air pollution map. Nearly all emphasized that such a device must work flawlessly before they are ready for the public. In terms of study length for future studies, one month was considered a suitable time-scale for exposure studies since one month was considered sufficient to capture the diversity of one's behavior. They believed also that interest in the experiment involving a new gadget would wane within a month and continuing to carry the device would become an obligation. Interestingly, privacy was not a huge issue, albeit volunteers were aware of and agreed to have their movements tracked. They considered it normal in these kinds of projects. Several of the volunteers pointed out that if any data was to be made public, they would not want to be identified or for anyone to be able to know where they live.

3.1.2. Feedback on the Sensor System and Its Functionality

The LEO device received mostly negative feedback, even if some volunteers commented positively about its compactness and how it was a "cool" gadget. They also thought that having an armband as a carrying option was a good solution. Most volunteers were satisfied with the selected air pollutants although several would have liked to have additional parameters and to cover also the indoor spectrum.

Most negative feedback was about the device being bulky and clumsy to transport even with the existing attachment options and its tendency to fall to the ground if not attached properly. It was also pointed out that one had to constantly remind oneself to carry it.

When using the device, volunteers had several issues including the time it took for the sensors to stabilize, which resulted in the APIN not changing rapidly enough. Volunteers found this inconvenient, since it meant that they had to remain at one location for a significant length of time to allow the device to adapt to its environment, and that the data was no longer representative when having moved from one location to the next. Also disappointing was that when they expected there to be a difference in air quality, e.g., when moving from a park to a busy street, the device did not register any change in air quality. Moreover, many volunteers were not sure if the device was actually collecting data (ID2), which led to data losses and more disappointment. In addition, due to the app crashing and connection issues between the device and ExpoApp the device had to be frequently reset. This led to data loss—a main source of frustration. The battery life of the hardware lasted longer than the phone battery, yet the volunteers found it ran out of charge quickly, unexpectedly and without warning, hence it was important to remember to charge it regularly. The device also had a blinking LED that indicates data acquisition, Bluetooth connectivity (when established) and the charging state of the battery. Some of the volunteers were bothered by this, especially in the evening in the dark. One volunteer even covered the LED indicators with electric tape.

> ID2: "*It would be good if one would know for sure if the device works or not. I know there are those indicating LED lights, but they do not always work the way they should. It leaves the user confused. There should be a clear indication if it works or not*".

ExpoApp was described as unstable, unreliable, buggy, non-useful, bad, complicated, clunky, non-self-explanatory and slow. Only one volunteer claimed it was easy to use. The volunteers reported that the app constantly kept crashing or froze without any obvious cause, and this often happened when not having attended to the phone for some time, e.g., while sleeping or at work. They also complained that once the app had crashed, it then took several steps and an unreasonable amount of time to get it to work. Sometimes just restarting the app was sufficient, but other times the app had to be force-stopped and the app reinstalled. Data was also lost in various ways, which disappointed the participants. Sometimes data was erased because of having to delete the app, but mainly data was lost because the user thought the device was collecting data, even though it was not. Apparently, it was not obvious when the device was either collecting data or transferring data to the server. The data connection was also said to be poor. Curto et al. [62] also reported various data gaps, e.g., missing values or repeated zeros with various other low-cost sensor systems which are already on the market, which opens a discussion on how to reduce the failure or malfunction rate of such devices. Data connection issues also resulted in ExpoApp crashing multiple times a day, which meant that the volunteers had to create multiple usernames. This became an issue when a volunteer wanted to access the data portal retrospectively, who then had to remember all of their user names and associated dates. This led to them not being able to access all of their data.

Volunteers also experienced various Bluetooth connection issues. The connection between the sensor system and the phone was difficult to establish and maintain. For this reason, the phone and the hardware needed to be kept in close proximity, but unfortunately not everyone remembered this all the time. The connection was supposed to be automatic once the phone and the sensor system unit were in close proximity, but this was not always the case, which caused ExpoApp to freeze. In addition, some of the volunteers could not participate because the app was only available on the Android operating system, and in some cases even with an Android phone, the app would not work. This left volunteers frustrated because they were promised that it would work on a certain version of Android regardless of the phone's make. Volunteers also commented that overcoming these constant technical issues with ExpoApp would be even more challenging for a less technically minded person. Battery life was also an issue. Not only did the GPS and Bluetooth connection rapidly drain the phone's battery, but the device kept shutting-off unexpectedly because there was no clear indication of battery life.

The data itself was considered interesting and many volunteers would have liked to discover more about their immediate surroundings and the places they frequently visit. For some volunteers, the five scale APIN color codes were sufficient, while others would have preferred a much finer-scale and would have like to see the values actually changing. This finding agrees with that of Zappi et al. [36], where the EPA color guideline and number also did not provide a sufficient level of detail for the participants. Many volunteers in our study would have liked to see numeric data and graphs of individual pollutant concentrations rather than an index. In a similar initiative performed by Bales et al. [37], air quality was visualized as an air quality index while a more detailed analysis was provided for more involved users.

Calibration issues means that data from low-cost sensor systems show mostly either relative values (higher and lower pollution levels) or an aggregated level of air quality [3], which raises questions whether showing numeric data to the end users will be done in the near future (also see reference [1]). Data quality on its own was rarely a topic of discussion, but a lengthy sensor stabilization time significantly lowered their trust in the measurements making the device ineffective as a mobile unit. Questions also arose concerning the quality of the data, noting that it differs from official data, and whether it makes sense to calculate the APIN using data obtained from low-cost sensor systems. There were also opposing views about whether increasing the number of low-cost air quality sensor systems in a city for modelling purposes would result in better data.

The web visualization portal was mainly perceived positively and described as being OK, nice, interesting, and that it was easy to use and navigate. Some volunteers did not see any need for improvements, yet others would have liked the ability to examine individual pollutants and their concentrations instead of having just an index value. Unfortunately, some volunteers were using the portal when updates took place and reported how the portal was unreliable, while others did not know that they can display multiple user tracks. It was also not obvious that they needed to enter the user ID from the app, and not the hardware ID.

3.1.3. User Needs and Recommendations

The volunteers' recommendations reflect the user needs of low-cost portable air quality sensor systems. All volunteers made recommendations concerning the used sensor system as well as general recommendations for future low-cost portable sensor systems throughout the focus group discussions. These included the fact that volunteers would prefer a self-explanatory device, but if it did require a user manual, they would like it to be clear, simple, concise and accurate: on demand technical support was also deemed for future studies. The volunteers also thought the hardware should have multiple transport options and that the device should be much smaller than the one used in the study. Many volunteers suggested integrating the sensors in a device that a user would be already carrying with them, such as a phone or a smart watch. Other suggestions included having additional sensors, like particulate matter (PM), carbon dioxide (CO_2), and that the device should be able to detect and display differences in air pollution concentrations. Temperature and humidity are also parameters of interest. However, they were not visualized in the used sensor system despite them being part of the sensor unit, as they were only used for temperature compensation of gas measurements. Bluetooth and GPS issues should be solved and battery life maximized, e.g., by using low energy Bluetooth. Other suggestions included having the data frequency set automatically to a lower sampling rate and the GPS and Bluetooth in stand-by mode when the person is static. Another suggestion was to send data to the server at least twice per day to avoid having to be constantly connected to the 3G network with an option to require real time data on demand. In addition, there should be a battery level indicator either on the device or in the app. Some volunteers expressed a wish to control the hardware.

Volunteers also expressed a desire for information on exposure and on the spatial distribution of air pollution. They suggested developing an app that is more intuitive, self-explanatory, simple and user-friendly than the use one, meaning a device that is "good to go" and needs as little button pressing as possible. Having only an on/off button was suggested. In addition, Bluetooth, GPS and 3G could

be turned on automatically rather than manually, and for it to be obvious when the device is collecting or sending data to avoid any misunderstandings and to prevent data loss (ID17). A smartphone app should also be made for iOS to include more volunteers. It was also suggested that the app could have other functions, such as, a function which would alarm the user when air pollution is too high. In order to have context for the data, the volunteers suggested a function that would tag and add frequently visited locations and activities, e.g., home, work, exercise, etc. They also wanted to be able to use the same user ID upon each restart of the device, with the option to change it if they wish. The option to have a phone app that combines subjective air quality and measured objective values was raised multiple times. For example, the user would indicate their subjective estimation of air quality at their location followed by a verification of the current measured air quality.

> ID17: "*I would like that there were as few steps as possible. That it would be automatically connected and sending the data. There needs to be as little such extra pressings of buttons like "OK", "save", "confirm" etc. It would be good that once you press the stop button, you would get a notification that you had been measuring successfully. That you get a feeling everything went well*".

To improve the data visualization experience, volunteers suggested having mobile friendly data visualization similar to the web visualization. More granularity was also desirable, since with the used system (5 scale APIN) the values did not vary sufficiently to be of interest e.g., (ID3). Many said they would prefer to see individual pollutant concentrations with indicative limit values. Also, access to historic data of the user's tracks is considered important, but the visualized data should be anonymized.

> ID3: "*I was disturbed by the fact that it only showed number 3 all the time, regardless where I went*".

Considering that the used device was not collecting data autonomously or being used constantly, the volunteers suggested it would benefit from having a reminder function. Kefalidou and Sharples [63] recommends that users are reminded to use a device with a pop-up function, but such reminders should be kept to a minimum. The volunteers agreed that the appropriate length to carry such device is one month, and also implied that they were not ready to integrate it permanently into their daily lives. However, if the device was much smaller, like the size of a wristwatch, they could see themselves using it more frequently. According to a recent review on wrist wearable devices, current air quality sensor technology is not sufficiently mature and hence, is not yet part of mainstream wrist wearable devices [64].

Finally, the volunteers suggested the price for a similar commercial device should be under 100€, although some would pay 150€, but 200€ was considered too expensive.

3.1.4. Possibilities

The volunteers brought up various options and suggestions regarding what could be done in the future with low-cost portable air quality sensor systems. Similarly, Barzyk et al. [65] collected Newark's Ironbound community's suggestions on what would be the next steps with regards to sensor technologies. The volunteers in our study suggested that such devices have the potential for raising awareness about the spatial distribution of air pollution, which could affect preferred routes and places to spend time and live in, and hence, improve one's quality of life. Such devices could be used also for monitoring indoor air quality, e.g., in the home and in the car. Crowd sourcing projects, industrial air pollution monitoring and estimating property values were some of the applications suggested. Vulnerable groups, such as asthmatics, were seen as possible target groups who could receive information about their exposure from such devices. In addition, city authorities, nongovernmental organizations and kindergartens were listed along with schools that could use them to perform various experiments. Ideas about attaching the devices to city bikes or busses, or google street-view cars were raised. Having such data publicly available was seen as self-evident, and the city authorities were seen as the most obvious contact point to make data

available. The volunteers also mentioned how such devices could open up discussions with polluters and decision makers. In order to reduce costs for the end users of low-cost portable air quality sensing systems, a rental service operating through either a company or a research institute for individuals and schools was suggested. A sensor loan program for public use has already been suggested by Barzyk et al. [65]. Moreover, volunteers expressed their interest in wanting to know about the air quality in their own neighborhood, and wished for such devices to be used to determine where the air quality is poor and how to improve it.

3.2. Redesign of the Low-Cost Sensor System for Air Quality

During the field campaign, running feedback was provided to the hardware and web developers, pointing out the issues that the volunteers were having. At the end of the campaign, the feedback from the interviews and the focus groups was aggregated, and sent to the development team. The volunteers' feedback contributed to a new version of the hardware (see reference [66]). The resulting unit, called the Ateknea Air City monitor (AACM), is half the size of the original unit used in this study, has a lower energy draw Bluetooth connectivity, and improved battery life, and is one-step closer towards meeting the end-user needs. The field evaluation of the AACM occurred at the end of the CITI-SENSE project and neither new software nor visualization tools were implemented during the project, nor was the new sensor system tested afterwards.

3.3. Limitations

This study had several limitations. For example, by gathering volunteers' feedback retrospectively and relying solely on what they reported, might have led to details getting lost on how the volunteers operated the sensor system. During the focus group sessions, certain volunteers dominated the discussions and this may have prevented other volunteers from voicing their opinions. The profile of the volunteers group was not reflective of the general population, and the volunteers were clearly more research minded and technically capable than a cross sample of the public. In contrast, the profile of the volunteers in this study might well represent the reality of a possible citizen scientist profile. Our recruitment goal was to obtain feedback from people outside of the project and our institute. Moreover, any generalizations are based on volunteers' evaluation of a single prototype sensor device with an associated phone application. Hence, many more portable low-cost air quality sensor systems should be studied in the future to evaluate them from the point of view of the public. Moreover, the end users should be included in the earlier design of the sensor system [46]. The lack of earlier end user involvement in the design process in our case study highlights the importance of doing so. Malfunctioning of the sensor system was an issue, and in some cases prevented the seamless collection of data and meant that several volunteers could not use the device to its fullest potential. Questionable data quality from low-cost sensors [67] can also be seen as a limitation. Finally, since the translation and coding of the interview data was done only by one person, which can have led to subjective bias. Despite these limitations, based on personal communication with other project investigators the authors believe that the results present an accurate representation of UX.

4. Conclusions

This paper evaluates UX with respect to a prototype of a low-cost portable air quality sensor system from a citizen scientists' perspective and provides user experience feedback for future developers. The sensor system comprises a sensor device, accompanying phone app and web visualization. Due to the issues related to the app design, e.g., freezing, crashing and having connection issues, the app received more comments than any other components of the system. Our paper brings insights into user experience with a sensor system which was considered ready for public, yet, as it lacked user involvement in an earlier state, the collected feedback had a negative tone and various necessary improvements were suggested. Consequently, we were able to map the user needs of future low cost-portable sensor systems. Personalized air quality information based on data from low-cost

portable sensor systems can potentially help people to make informed decisions on their exposure. For this reason, this technology should be designed with and for the public.

By including volunteer feedback, this study uncovered issues relating to usability that commonly used methods of self-evaluation by project members could not provide. Our results showed that the tested low-cost portable sensor system was perceived as non-user friendly and not ready to be widely deployed by end users, even though comments provided by the project team members were taken into account by the device developers prior to the field campaign. The feedback from volunteers highlighted meaningful changes and features, which can be used to improve the next generation of such devices and contribute to understanding the limitations and opportunities of technology that is fit for purpose.

The root cause of the negative feedback can be associated with the poor operational performance of the phone app, while most of the positive feedback of the sensor system related to its potential. The prototype sensor system used in this study frequently complicated the volunteers' lives: they desired a simpler, less visibly prominent, and, not least, a more reliable device with additional visualizations. They especially did not like the results to be in conflict with their perceived air quality. Key recommendations are as follows:

- Involve potential end-users early in the development phase in iterative cycles;
- The device should be "good to go" providing results immediately when activated;
- Minimal effort to operate with a simple start-stop button;
- Using the device should be self-explanatory and intuitive;
- It should come with a functional and user-friendly smart phone app capable of running on different mobile operating systems (iOS, Android, Windows, etc.);
- The app should display near real-time data with reliable and stable data transmission;
- The device needs to indicate successful data collection and battery levels;
- The device should detect and visualize differences in air quality at a higher resolution than the 5-level scale APIN which is too coarse to be interesting;
- The sensor system should provide a visualization which is in agreement with users perceived air quality i.e., indices might mask out individual high air pollutant concentrations which the user detects;
- The visualization should be tailored and adapted for different user groups, e.g., to include different levels of visualization for basic and advanced users;
- Users would prefer to see individual pollutant concentrations with indicative limit values;
- Default visualization should include present and past data linked to the user's location.
- Smartphone apps should be developed by professional mobile app developers.

Despite the negative feedback, it was evident that the volunteers liked the idea of a portable low-cost air quality sensor device and could see the potential of such a device, albeit there remains significant room for improvement. The volunteers in this study were optimistic about the future of the technology, even though the prototype device did not work as they hoped. In short, the users remain interested as long as the technology works. To keep costs down, a rental option should also be made available for individuals and interested groups such as schools. This would satisfy the need to explore and use the device only as long as the user remains interested.

This study illustrates that initiatives, such as citizen science projects, aimed at improving data availability (coverage, temporal resolution, value to users) should not only focus on improving data quality, but also UX. This case study demonstrates that it is not enough simply to test a prototype amongst project team members, since end users will highlight the most pressing design faults which need further development prior to the device being ready for wider deployment. Therefore, the authors recommend testing prototypes of low-cost portable air quality sensor devices with a small number of volunteers prior to data sampling campaigns, if their purpose is to go beyond proof of concept.

Supplementary Materials: The following are available online at http://www.mdpi.com/1424-8220/18/11/3768/s1, Table S1: Coding round 1; Table S2: Coding round 2; Table S3: Additional coding iterations for "REC" in R1; Table S4: Additional coding iterations for "REC" in R2; Table S5: Statistics of "REC"; Table S6: Code frequency statistics; Table S7: Volunteers statistics.

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3.2 Review Article: "Meeting Volunteer Expectations — a Review of Volunteer Motivations in Citizen Science and Best practices for Their Retention Through Implementation of Functional Features in CS Tools"

This section is a review article authored by Johanna Amalia Robinson, David Kocman, Orestis Speyer and Evangelos Gerasopoulos. The review article was published in the Journal of Environmental Planning and Management in 2021. The article resulted from the SMURBS project and was inspired by the project deliverable 3.5, "Citizen Observatories (COs) implementation", authored by the candidate.

The review article contributes to bridging the gap between theory and practice in implementing CS projects, commonly managed by scientists from various backgrounds, while pointing directions to facilitate public engagement in scientific research. The review concentrates on practices and experiences from several projects to deliver substantial insight in understanding and meeting volunteer motivations, needs and expectations, while it also provides a thorough review into different approaches to retain volunteers in the long term.

Managing expectations through meeting volunteers' needs with suited functional features facilitates the success and sustainability of CS projects. Overall, the paper guides CS practitioners on pursuing the interplay between well planned and managed projects and tools and the volunteers' motivation and satisfaction and works as a resource for CS practitioners who might not have the knowledge or resources to perform in-depth user studies. The review brings insights into how the tools for citizen science should be designed to provide citizen scientists with an efficient and positive user experience. At the same time, while designing products fit-for-purpose, one creates win-win situations for both CS volunteers and CS practitioners, thus linking environmental research with societal benefits. The results confirm hypothesis three.

The candidate coordinated the literature review, analysed and synthesised the findings textually and in table format and wrote the manuscript.

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Review Article

Meeting volunteer expectations — a review of volunteer motivations in citizen science and best practices for their retention through implementation of functional features in CS tools

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Citizen Science (CS) projects vary greatly. The aims and goals of a CS project determine the type of citizen involvement and the tools to be used, which in most cases also entail information and communication technology (ICT) that facilitates public participation in scientific research. Resource limitations in CS projects often require adopting suboptimal tools, which, however, may come with hidden costs stemming from poor usability and underwhelming functionality, thus reducing volunteers' motivation. Meeting the volunteers' expectations by designing or using existing tools with functional features which fulfill and nurture their motivations, will foster long-term participation and contribute to project sustainability. This paper reviews the types of CS projects, volunteer motivation and retention strategies from the literature and classifies them thematically. This is distilled into guidance that can help CS practitioners to design and implement CS tools and plan and manage CS projects, which better serve their scientific and volunteer-related goals.

Keywords: citizen science; volunteer motivation and retention; expectation management; sustainability of CS projects; tools for citizen science

1. Introduction

Citizen Science (CS) refers to the voluntary public engagement in scientific research activities, such as, collecting and processing environmental data and helping to answer real-world scientific questions with their intellectual effort, knowledge of their surroundings or tools and other resources (Bonney, Cooper, *et al.* 2009; Sanz *et al.* 2014; Silvertown 2009). Methods to practice CS have undergone a revolution over the last two decades, mainly due to the advances in Information and Communication Technologies (ICT), sensor technologies and social networking, which has resulted in new tools which foster open, efficient and agile systems (Sanz *et al.* 2014; Silvertown 2009; Wald, Longo, and Dobell 2016). Many CS projects rely on surveys completed

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by volunteers who report objective or subjective observations about their environment; a task made ever-easier using modern technologies such as smartphone apps that facilitate the interaction between scientists and volunteers. Many projects require volunteers to submit data on, e.g. biodiversity and environmental phenomena or conditions using image acquisition, web- and smartphone-based applications and surveys (Couvet and Prevot 2015; Havlik and Schimak 2014; Wallace, Snedigar, and Cameron 2015). More and more CS projects also explore the use of low-cost devices, including handheld or portable sensor systems (Aspuru *et al.* 2016; Thompson 2016; Uhrner *et al.* 2014). Data collected are increasingly visualized in web-based portals or via smart phone apps in near real time. Moreover, there is a gradual shift toward participatory, bottom-up and co-design processes, where citizens are not just data collectors and where communication is only one way, as in traditional contributory crowdsourcing projects, but are involved in advanced participatory communication models addressing community needs (Mominó, Piera, and Jurado 2016; Sanz *et al.* 2014; Shirk *et al.* 2012). In these more reciprocal and inclusive projects, such as Citizen Observatory (CO) projects, the aim is to directly benefit the citizens and society generally, rather than science alone (Grainger 2017). These projects strengthen social capital, collective intelligence, scientific capacity, and inclusiveness in local decision making (Aspuru, Herranz-Pascual, and Santander 2016; Dickinson *et al.* 2012; Wehn *et al.* 2018). They also provide the public with scientific information, which is accessible in forms they can understand and utilize (Golumbic, Fishbain, and Baram-Tsabari 2019).

Making sure that the tools used in CS are of scientific value and provide meaningful information to the volunteers, many authors call for more user involvement in the design of the services (Golumbic, Fishbain, and Baram-Tsabari 2019; Preece 2016; Robinson *et al.* 2018; Sanz *et al.* 2014; Skarlatidou *et al.* 2019). It is frequently reported that the lack of user involvement can cause problems both for the volunteers as well as for the scientists, affecting motivation and data quality, and to this end, it is suggested that Human-Computer Interaction (HCI) research should be incorporated in Citizen Science (Preece 2016). If data collection is too complicated, or too time-consuming, volunteers often lose their initial desire and drive to participate (Robinson *et al.* 2018; See, Fritz *et al.* 2016).

The advantages of well-designed ICT products are numerous; for example, they enable CS projects to engage volunteers more efficiently, increase scientific productivity and keep volunteers engaged for a longer time (Wald, Longo, and Dobell 2016). Further, involving users in the product design process increases their satisfaction with the final product (Mahmood *et al.* 2000). Moreover, understanding volunteers' motivation and fulfilling their expectations increase their satisfaction, which in turn determines their level of participation (Wright *et al.* 2015). Consequently, involving the citizens at various design stages and incorporating their feedback increases their expectations and capacity for participation, while conversely, failing to do so inhibits satisfaction and participation (Mahmood *et al.* 2000).

Despite the apparent benefits of involving citizens in the design process of CS projects and tools, their involvement is not yet the mainstream practice. Resource limitations in projects usually constrain inclusive involvement of citizens, leading to the use of tools which might lack appropriate functionality (Wiggins 2013). Furthermore, limiting crowdsourcing only to a proof of concept level e.g. to test and develop a new CS tool might be de-motivating for the volunteers, who are otherwise altruistic and ready to substantially contribute (Havlik and Schimak 2014). Knowing certain features

of tools which are known to work can help to bridge the gap for those who do not have the resources to involve volunteers in the design process, yet acknowledge the benefits. Few authors have attempted to create guidelines to facilitate the overall design process. For example, Jennett and Cox (2014) provided guidelines for virtual CS projects focusing on website interfaces. Similarly, Skarlatidou *et al.* (2019) summarized best practices for CS applications, with a focus on web interface features based on a systematic literature review. Our paper extends the scope of these technical guidelines covering a broader topic of volunteer motivation, which is the driving force that determines the types of technical features CS tools need to meet volunteer expectations and retain their interest long-term. The aim of the paper is to make a synthesis of current knowledge from the CS literature with respect to i) understanding types of CS related projects and the characteristics of the volunteers involved, including participation patterns, ii) grouping common volunteer motivations according to functional categories, and iii) summarizing strategies for retaining volunteers, with examples of functional features for CS tools.

This literature review draws best practices from inclusive CS projects including Citizen Observatories, since the trend is toward collaboration and co-design in line with the level of understanding and involvement of the volunteers. It aims at helping to manage volunteer expectations better and ultimately supporting the planning and management of successful and sustainable CS projects.

The work was conducted within the H2020 SMURBS/ERA-PLANET project[1] under a wider literature review on Citizens Observatories, which covered 352 articles found in SCOPUS, Web of Science and PubMed in July 2018. Detailed methodology can be found in Robinson (2019). For the purpose of this manuscript with a narrower focus on citizen involvement, only articles which address inclusive citizen science were considered. Additional articles were reviewed for the purpose of specific chapters to improve readability and to cover a joint discussion of motivations, volunteer experiences and suggestions for design.

2. Characteristics of CS projects and volunteers

What is common to all CS projects is that they involve both competent communities, i.e. the scientists and the volunteers who are participating as citizen scientists. The experts and CS practitioners involved in the projects include, but are not limited to, environmental scientists, social scientists, hardware and software specialists, and data analysts. Depending on the type of CS project, the target group of volunteers and other stakeholders might involve locals living nearby who are affected by the issue at hand (Grossberndt and Liu 2016; Uhrner *et al.* 2014), schools (Hunt *et al.* 2015; Kobernus *et al.* 2013; Mominó, Piera, and Jurado 2016), representatives of local officials (Mietlicki, Gaudibert, and Vincent 2012) and do-it-yourself (DIY) communities (Busch *et al.* 2016). In addition, external stakeholders such as scientists from other domains, NGOs, and government agencies may want to harness the data for various purposes, such as complementing their own data sets (Cooper *et al.* 2017; Ferster and Coops 2013; Hunt *et al.* 2015; Wehn and Evers 2015). It is observed that people who take part in CS projects are generally highly educated and belong to middle and upper socioeconomic classes (Soleri *et al.* 2016), are retired (Wright *et al.* 2015) or have an already established interest in the topic (Mazumdar *et al.* 2017).

The specific aims and goals of a Citizen Science project are to determine what kind of volunteers it seeks to engage and what kind of tools are best suited for its purpose (Wiggins and Crowston 2011). To meet the expectations of volunteers and CS practitioners, who typically consist of experts with various backgrounds (some without previous experience of CS), communicating the objectives early on is crucial to the process (Grossberndt and Liu 2016). These are commonly written using technical terms and need to be translated into a common language to be easily understood by the layperson (Sanz *et al.* 2014). Understanding and using the correct terminology can help define the aims already outlined in the project proposal at the design stage while reducing misunderstanding later on by clarifying participants' roles, responsibilities and limitations (Grossberndt and Liu 2016; Wiggins and Crowston 2011). There is currently no single definition of CS, but there are a plethora of different types of CS projects that reveal the dynamics of this evolving research field (Sanz *et al.* 2014). The terminology used in the literature is summarized in Table 1. The definitions provide additional information about the level and type of participation.

In addition to the terminologies, CS projects can be classified according to different levels of engagement, e.g. contributory, collaborative and co-designed CS projects (Bonney, Ballard, *et al.* 2009; Shirk *et al.* 2012). The involvement of the public and the amount of control over different steps of the project increases in this classification. In contributory projects the volunteers are merely involved in data collection, where as in collaborative projects, in addition to data collection, they can also analyze and disseminate data and participate in the project design. Co-designed projects present the highest degree of engagement including the co-design phase, as well as active involvement in most or all aspects of the research itself. While some projects aim at long term volunteer commitment (e.g. birding communities [Sullivan *et al.* 2009]), others might rely on event-driven volunteer contributions, e.g. monitoring ash fall (Wallace, Snedigar, and Cameron 2015), earthquakes (Dell'Acqua and De Vecchi 2017), and invasive species (Crall *et al.* 2011).

The level and pattern of volunteer participation, as well as satisfaction, is known to vary and evolve (Ferster and Coops 2013; Grainger 2017; Houghton *et al.* 2019; Jennett *et al.* 2016; Wright *et al.* 2015). Some contribute consistently, others in bursts of activity, while others contribute more sporadically (Ferster and Coops 2013). Moreover, as Grainger (2017) points out, some of the observing activities are regular and thus advocates that the volunteers' activities need to become institutionalized in the sense of having reoccurring patterns. However, in reality this might be disrupted due to unforeseen incidents such as an illness or other causes which hinder routine. Volunteers' contribution levels might indeed plummet due to loss of interest or time, or because of changing prioritizations (Jennett *et al.* 2016). The decision of volunteers to contribute is influenced by whether the particular activity fits with the volunteers' needs and goals (Clary and Snyder 1999; Wright *et al.* 2015). That is why understanding volunteer psychology, e.g. their motivations, will promote the efficient gathering of quality data while optimizing the benefits for the volunteers (Wright *et al.* 2015). Familiarity with the theories that explain participation patterns, e.g. the Technology Acceptance Model (TAM), Theory of Diffusion of Innovations (DIT), Theory of Planned Behavior (TPB) and the 90-9-1 rule for participation inequality, will help CS practitioners to understand the different roles and characteristics as well as the information needs of citizen scientists (Haklay 2016; Lai 2017). The TAM by Davis in 1986 focuses on acceptance of information technologies explaining user behavior. It is

Table 1. Citizen Science terminology.

Term	Definition	Reference
Citizen Science (CS)	The umbrella term of the voluntary involvement of the wider public in scientific research from data collection to research design	(Bonney 1996; Bonney, Cooper, *et al.* 2009; Hand 2010; Silvertown 2009)
Citizen Observatory (CO)	CO is an information ecosystem where citizens are empowered in community-based environmental monitoring with the capability to collect, report, access and share environmental information and connect and interact with other citizens, scientists and stakeholders to discuss, intervene and make decisions with the help of ICT enabled technologies.	(Degrossi *et al.* 2014; Grainger 2017; Lanfranchi *et al.* 2014; Liu *et al.* 2014; Miorandi *et al.* 2013; Mominó, Piera, and Jurado 2016; Montargil and Santos 2017a; Tapia *et al.* 2014; Zaman and Meuter 2015)
Community Remote Sensing (CRS)	Another umbrella term which "combines remote sensing with citizen science, social networks, and crowd-sourcing to enhance the data obtained from traditional sources. It includes the collection, calibration, analysis, communication, or application of remotely sensed information by these community means."	("IGARSS" 2010; Williamson 2009)
Community-Based Monitoring (CBM)/ grass root sensing/ civic or community science	Similar to participatory sensing, but a bottom-up process where concerned citizens, in collaboration with scientists, public authorities and further stakeholders monitor, track and respond to issues that arise from common community concern	(Breen *et al.* 2015; Burke *et al.* 2006; Haklay 2015; Whitelaw *et al.* 2003)
Crowdsensing	A sub-category of crowdsourcing in which individuals with sensing and computing devices collectively share data and extract information to measure and map phenomena of common interest	(Ganti, Ye, and Lei 2011; Miorandi *et al.* 2013)
Crowdsourcing	Outsourcing work to the crowd	(Howe 2006; Howe 2008)
Participatory sensing (PS) (also called citizen-or mobile (crowd)sensing, crowdtasking or participatory mapping)	Volunteers acting alone or in groups observing their environment with smart mobile devices or sensors forming interactive, participatory sensor networks that enable public and professional users to gather, analyze and share local knowledge	(Burke *et al.* 2006; Haklay 2015; Jennett *et al.* 2016)
Passive sensing/ opportunistic sensing/ passive crowdsensing/ Ambient Geographic Information (AGI)/	Automatic data collection through a volunteer's resources without the active engagement of volunteers. E.g. social media harvesting. Passive sensing can also refer to a	(Dell'Acqua and Vecchi 2017; Haklay 2015; Lane *et al.* 2010; Loukis and Charalabidis 2015; Stefanidis, Crooks, and Radzikowski 2013)

(*Continued*)

Table 1. (*Continued*).

Term	Definition	Reference
social geographic data (SGD)/ Involuntary volunteered geographic information (iVGI)	volunteer agreeing to host a sensor device in his/her backyard.	
Public Participation in Scientific Research (PPSR), crowd science, crowd-sourced science, civic science, or networked science	Synonyms for CS	(Bonney, Ballard, *et al.* 2009; Hand 2010; Liu and Kobernus 2017)
Public Participatory Geographic Information Systems (PPGIS)	The use of geographic information systems (GIS) in community participation in a plethora of social and environmental contexts.	(Craig, Harris, and Weiner 2002; Newman *et al.* 2010; Sieber 2006)
Volunteer computing	Volunteers share the unused processing power of their computers and device and allow scientists to run complex computer models when the device is not used.	(Haklay 2015; Jennett *et al.* 2016)
Volunteer thinking	Making use of the volunteers' cognitive resources in parallel with leisure activities or explicitly on their free time where volunteers, for example, classify or identify species or land cover types through a web application.	(Haklay 2015; Jennett *et al.* 2016)
Volunteered Geographic Information (VGI)	Spatially referenced data provided voluntarily by individuals	(Goodchild 2007a; Goodchild 2007b; Gómez-Barrón *et al.* 2016; See, Mooney *et al.* 2016)

comprised of the Perceived Usefulness (PU) and Perceived Ease of Use (PEU) components. The DIT Theory, developed by Rogers in 1995, helps researchers understand the acceptance and adoption of innovations among individuals and organizations over time. Rogers' famous S-shaped curve encapsulates the innovators, early adopters, early majority, late majority and laggers. The TPB was developed by Ajzen in 1991 and theorizes the behavioral intention of the person's attitudes toward a particular behavior, broken down into attitude, subjective norms and perceived behavioral control. Participation inequality or the 90-9-1 rule described by Nielsen in 2006 is the phenomenon where a small percentage of volunteers contribute a significant proportion of information to the total output, while the majority are less involved. To give an example, in the well-known Zooniverse project, only 4–7% of volunteers actively contribute over long periods (Sauermann and Franzoni 2015), which implies that even the most successful projects need robust mechanisms to increase and sustain participation. The upside however is that these "super volunteers" are most likely able to contribute consistently and submit good quality data (Jennett *et al.* 2016).

Similarly, several authors have identified different roles of volunteers and participation characteristics. For example Cooper *et al.* (2017), divides volunteers into two categories, data collectors and data consumers, whereas Mominó, Piera, and Jurado (2016) introduce the so called "makers", "observers" and "analyzers" with different levels and roles of participation. More specifically, the *makers* describe people with abilities and interests in the technologies with the capacity to build DIY observation devices. The *observers* collect observations and the *analyzers* interpret the data. Following a different classification Kobernus *et al.* (2013) have identified six citizen roles. The *Observer* makes the initial observation, the *Publisher* makes the observation discoverable by others, the *Discoverer* finds an existing data resource, the *Service Provider* makes the information accessible to others to use and download, and finally, the *Service Orchestrator* who combines existing services for a distinct purpose i.e. a smartphone application, and the *Decision maker* who exploits the data to make an informed decision.

3. Motivation of CS volunteers

Motivation drives people to take action (Kaufmann, Schulze, and Veit 2011). The higher the motivation, the more the volunteers are satisfied with the project outcomes and are willing to continue to contribute (Clary and Snyder 1999; Wright *et al.* 2015). The nature of volunteerism can be multi-motivational, a volunteer having both altruistic and egoistic reasons to participate e.g. both wanting to selflessly help as well as desire to benefit oneself (Clary and Snyder 1999). Motivation can be classified into intrinsic and extrinsic motivation. Intrinsically motivated individuals might, for example, participate due to the project being fun, while extrinsically motivated individuals might be motivated due to short or long term pay offs, such as direct compensations or improved skills (Kaufmann, Schulze, and Veit 2011). Intrinsically motivated people are more likely to stay committed for longer (See, Fritz *et al.* 2016; Wright *et al.* 2015), while using incentives, such as rewards might have the opposite effect on volunteerism, due to the perception of external control *versus* personal control (Clary and Snyder 1999; Gharesifard and Wehn 2016). Clary and Snyder (1999) indeed observed that volunteerism can be induced on the short term with incentives, i.e. external control, yet the stronger perception of personal control to volunteerism, i.e. participating from altruistic reasons, is the drive for contribution in the long run. The level of participation, as well as the goals and attitudes driving the participation, can vary over time (Kaufmann, Schulze, and Veit 2011; Wright *et al.* 2015). Initial interest to participate might be triggered by e.g. curiosity, interest in science and desire to contribute to research, which are factors that may not necessarily justify ongoing and sustained engagement (Jennett *et al.* 2016).

The motivational factors reported in the literature are thematically grouped and summarized in Table 2. Clary and Snyder's (1999) and Wright *et al.*'s (2015) Volunteer Functions Inventory (VFI) was used to classify the different factors into five categories: (i) Values (ii) Personal development (iii)) Career and recognition (iv) Social, and (v) Recreation. Each are provided with an example that binds them with the concept of CS. Volunteer motivation can be studied through stakeholder and volunteer surveys as well as focus groups and analyzed with qualitative content analyses e.g. with coding, or with quantitative research methods using statistical tests (Clary and Snyder 1999; Kaufmann, Schulze, and Veit 2011; Robinson *et al.* 2018; Wright

Table 2. Summary of volunteer motivations.

Function	Conceptual example in environmental CS	Reference in CS literature
Values	The wish to contribute to science or society (i.e. civic responsibility) while helping the environment	(Bruyere and Rappe 2007; Dickinson *et al.* 2012; Grainger 2017; Grossberndt and Liu 2016; Hunt *et al.* 2015; Jennett *et al.* 2016; Montargil and Santos 2017b; Robinson *et al.* 2018; Wright *et al.* 2015; See, Fritz *et al.* 2016)
Personal development	Learning opportunities (about the scientific subject area and data collecting and analyzing techniques, environmental awareness, familiar places)	(Bruyere and Rappe 2007; Devictor, Whittaker, and Beltrame 2010; Dickinson *et al.* 2012; Grainger 2017; Havlik and Schimak 2014; Hunt *et al.* 2015; Jennett *et al.* 2016; Montargil and Santos 2017b; Robinson *et al.* 2018; See, Fritz *et al.* 2016)
Career and recognition	To gain relevant experience related to their career interests and to gain recognition and other personal benefits for their input	(Grainger 2017; Havlik and Schimak 2014; Hunt *et al.* 2015; Jennett *et al.* 2016; Kotovirta *et al.* 2015; See, Fritz *et al.* 2016; Wright *et al.* 2015)
Social	Social interaction and being part of a community of likeminded individuals	(Bruyere and Rappe 2007; Dickinson *et al.* 2012; Grainger 2017; Montargil and Santos 2017b; See, Fritz *et al.* 2016; Wright *et al.* 2015; Jennett *et al.* 2016)
Recreation	To have fun and to undertake new activities as part of existing recreational activities while commonly being outdoors	(Grainger 2017; Havlik and Schimak 2014; Jennett *et al.* 2016; See, Fritz *et al.* 2016; Tserstou *et al.* 2017; Wright *et al.* 2015)

et al. 2015). Surveys should be designed together with scientists experienced in social sciences, and if necessary, approved by the researchers' ethical committee (Druschke and Seltzer 2012).

Intrinsic motivation drives many people to volunteer. Protecting and improving the environment and making it a better place to live are amongst the most well-documented motivations in environmental CS projects (Bruyere and Rappe 2007; Havlik and Schimak 2014; See, Fritz *et al.* 2016). Many feel a civic responsibility to address certain issues affecting local communities (Hunt *et al.* 2015; Montargil and Santos 2017b; See, Fritz *et al.* 2016) and like to see the impact of their contribution to policy making, fulfilling them with the feeling of empowerment (See, Fritz *et al.* 2016). Contributing to science is also a strong motivation (Dickinson *et al.* 2012; Grainger 2017; Robinson *et al.* 2018; See, Fritz *et al.* 2016; Wright *et al.* 2015).

Citizen science projects can offer informal- (Hunt *et al.* 2015) and indirect community- (Jennett *et al.* 2016) learning opportunities and contribute to robust learning outcomes (Dickinson *et al.* 2012). Some volunteers want to learn more about familiar places, i.e. their neighborhood (Devictor, Whittaker, and Beltrame 2010; Grainger 2017; Robinson *et al.* 2018) and the natural environment (Bruyere and Rappe 2007), while at the same time enabling them to gain valuable and relevant information about

the topics addressed in the project (Grainger 2017; Montargil and Santos 2017b). Others are interested in the science behind the project (See, Fritz *et al.* 2016) and the technicalities of data collection and analysis, which also enables them to make new "discoveries" while exploiting the collected data (Grainger 2017; Robinson *et al.* 2018). Curiosity may also drive many volunteers to participate (Devictor, Whittaker, and Beltrame 2010; Havlik and Schimak 2014).

In addition to informal learning opportunities, CS projects can help people gain valuable knowledge useful for their current or future career, especially in Science, Technology, Engineering and Mathematics (STEM) (Hunt *et al.* 2015). The volunteers also expect to gain some recognition for their input, e.g. through feedback and interaction with the CS community and scientists (Grainger 2017; Havlik and Schimak 2014; Kotovirta *et al.* 2015; See, Fritz *et al.* 2016). Some common incentives are monetary rewards (Kotovirta *et al.* 2015) and prizes (See, Fritz *et al.* 2016). However, Clary and Snyder (1999) and Gharesifard and Wehn (2016) warn about their demotivating effect because of their perceived external control, and counter that a greater perceived personal control will lead to stronger motivations and greater intentions to volunteer. Recognition of volunteers' contribution can also be accomplished by providing them with an opportunity to perform more complex tasks, which in turn also requires more responsibility allowing them to achieve "expert status" in the project (See, Fritz *et al.* 2016). An example of this approach is providing experienced participants the role of moderating discussion forums (Jennett *et al.* 2016). For others, it is important to feel like an active participant and co-owner in the project (See, Fritz *et al.* 2016). Bruyere and Rappe (2007) and Wright *et al.* (2015) emphasize the need to recognize the significance of volunteers' contributions, which will satisfy and enhance the volunteers' intrinsic motivation.

Participating in activities in a community of likeminded people is an important social motivation (Bruyere and Rappe 2007; Dickinson *et al.* 2012; Grainger 2017; Montargil and Santos 2017b; See, Fritz *et al.* 2016; Wright *et al.* 2015). The social interaction with people with similar interests can be perceived as an important means of socializing and making new friends (Bruyere and Rappe 2007; See, Fritz *et al.* 2016).

Being able to connect the CS activity with a volunteer's existing recreational activities will nurture the volunteer's motivation to keep it fun (Grainger 2017; Havlik and Schimak 2014; See, Fritz *et al.* 2016). These activities can take place outdoors while performing observations in the natural environment, e.g. in biodiversity-related CS projects, or by performing tasks using a computer at home (online CS projects) (Grainger 2017; Tserstou *et al.* 2017; Wright *et al.* 2015).

4. Retention of CS volunteers

Retaining motivated volunteers is crucial for the sustainability of a CS project (See, Fritz *et al.* 2016). If citizens do not see any value and usefulness in their participation, loss of interest and abandonment of effort is likely (Ferster and Coops 2013; Wright *et al.* 2015) as is a lack of initial engagement (Gharesifard and Wehn 2016; Wright *et al.* 2015). In addition to the common constraint of lack of time, other barriers for sustained involvement include the tasks' complexity, being mundane, or even apprehension for submitting incorrect data (Jennett *et al.* 2016). See, Fritz *et al.* (2016), and Dickinson *et al.* (2012) suggest communication strategies which take into account both

volunteer recruitment and retention. In order to get the word out in recruiting the volunteers, Dickinson *et al.* (2012) suggest using well-timed press-releases that are picked up by national and local media. Newsletters, blogs, and social-networking groups help to create a sense of community, in addition to active forms of communication, such as contents, badging systems and methods to recognize the effort of the volunteers (Dickinson *et al.* 2012). Providing rapid feedback to volunteers and regular communication on their contributions have also shown to work in terms of retaining a community (See, Fritz *et al.* 2016). Clary and Snyder (1999) emphasize that those recruitment strategies, which address the specific motivational functions underlying behavior and attitudes, are the most successful. Montargil and Santos (2017a) underline the critical balance between the participation effort and return benefits. Many projects lack motivation mechanisms and rely on volunteers' goodwill and interest to assist in research (Kotovirta *et al.* 2015). However, several approaches have been established to motivate volunteers. These approaches are summarized in Table 3, with examples of functional features.

The above-listed features match with the volunteers' motivational functions, which CS practitioners should nurture. For example, Havlik and Schimak (2014) argue that motivation determines the fate of the built infrastructure and therefore an application designed to be used by the volunteers should be fun, nourish curiosity and enable the user to make a difference, in order for them to stay motivated. Table 3 can function as a checklist for CS practitioners, first during the design phase of the project to include as many features as possible, and secondly, to evaluate the project, whether these points were met to allow for correcting actions or a post-evaluation of the user-centricity of the CS project. The analysis, however, should take into account certain tradeoffs between the features of Table 3 and other requirements of the project, such as robustness and scientific integrity of measurements as well as quality assurance (QA) and quality control (QC) procedures.

Resource limitations in CS projects often require adopting suboptimal ICT tools which come with hidden costs from poor usability and lack of appropriate functionality (Wiggins 2013). In order to adapt the tools to meet the various volunteers' motivations and needs, they should be useful, easy to use and versatile (Grainger 2017; Havlik and Schimak 2014; Kobernus *et al.* 2013; Kotovirta *et al.* 2015; Mazumdar *et al.* 2017; Prakash *et al.* 2004; Wallace, Snedigar, and Cameron 2015). The first step to achieve this is to understand and adapt to the citizens' needs as it is not enough to provide them with some arbitrary tools (Lawton *et al.* 2011; Liu and Kobernus 2017). Secondly, it is important to provide data in an easy to comprehend format. As Grainger (2017) points out, data becomes information only after someone understands the method of data generation, knows how to interpret the data and knows how to use the data meaningfully. If data is presented only as lists of figures or spreadsheets that only experts can interpret, the project will lose part of its audience (Kobernus *et al.* 2013). Golumbic, Fishbain, and Baram-Tsabari (2019) suggest to include Human-Computer Interaction (HCI) and User Centered Design (UCD) in the design process, since there is no universal user, and hence no universal interface. In this way, the design process becomes more inclusive and will increase the overall attractiveness of the interface. Nevertheless, in practical terms, many CS projects simply lack the resources to involve users in the design process, or it might not be their aim or priority, in which case, a good tradeoff would be to use preexisting tools, which are already deemed fit for purpose. If the project explicitly aims at developing a new tool, the

Table 3. Summary of approaches to retain volunteers.

Feature	Explanation/Example of a functional feature	Sources
Fun and cool	The project tasks should be cool and tools fun to use while nurturing curiosity	(Castell *et al.* 2015; Grainger 2017; Havlik and Schimak 2014; Kaufmann, Schulze, and Veit 2011; See, Fritz *et al.* 2016; Simpson, Page, and De Roure 2014)
Simple, easy, versatile and user-friendly tools	Tools adapted to different user groups according to their skills	(Druschke and Seltzer 2012; Gharesifard and Wehn 2016; Grainger 2017; Havlik and Schimak 2014; Kobernus *et al.* 2013; Kotovirta *et al.* 2015; Mazumdar *et al.* 2017; Newman *et al.* 2010; Prakash *et al.* 2004; See, Fritz *et al.* 2016; Wallace, Snedigar, and Cameron 2015)
Provide relevance and meaning to volunteers' everyday lives and interests	Address environmental issues, which affect the direct environment of the volunteers	(Ferster and Coops 2013; Grossberndt and Liu 2016; Guillaume *et al.* 2016; Hunt *et al.* 2015; Kotovirta *et al.* 2015; Mominó, Piera, and Jurado 2016; Montargil and Santos 2017b; Williamson 2009)
Rapid feedback on volunteers' contributions	E.g. visualization of the measurements on a map	(Druschke and Seltzer 2012; Grainger 2017; Gutiérrez *et al.* 2016; Kotovirta *et al.* 2015; Liu and Kobernus 2017; Montargil and Santos 2017a; See, Fritz *et al.* 2016; Zaman and De Meuter 2016)
Communication and recognition of the importance of volunteers' contribution and scientific outcomes	Certificates of recognition, communication on how results are being used	(Aspuru, Herranz-Pascual, and Santander 2016; Cohn 2008; Dickinson *et al.* 2012; Druschke and Seltzer 2012; Grainger 2017; Grossberndt and Liu 2016; Havlik and Schimak 2014; Kotovirta *et al.* 2015; Mackay *et al.* 2015; See, Fritz *et al.* 2016; Sullivan *et al.* 2009; Wright *et al.* 2015)
Provide access to volunteers' contributions and the possibility to analyze and share them	Enable volunteers to make discoveries from their data	(Busch *et al.* 2016; Charvat *et al.* 2018; de Assis *et al.* 2018; Gharesifard, Wehn, and van der Zaag 2017; Grainger 2017; Hunt *et al.* 2015; Jirka, Remke, and Bröring 2013; Liu and Kobernus 2017; Mackay *et al.* 2015; Marantos *et al.* 2017; Mazumdar *et al.* 2017; Mietlicki, Gaudibert, and Vincent 2012; See, Fritz *et al.* 2016)
Rewarding and gamification	Reputation ranking, competition between volunteers, prices	(Castell *et al.* 2015; Dickinson *et al.* 2012; Gutiérrez *et al.* 2016; Havlik and Schimak 2014; Kotovirta *et al.* 2015; Mominó, Piera, and Jurado 2016; See, Fritz *et al.* 2016)
Create a sense of community	E.g. discussion forums, social networking groups	(Cooper *et al.* 2017; Dickinson *et al.* 2012; Druschke and Seltzer 2012;

(*Continued*)

Table 3. (*Continued*).

Feature	Explanation/Example of a functional feature	Sources
		Kotovirta *et al.* 2015; Mackay *et al.* 2015; Mazumdar *et al.* 2017; See, Fritz *et al.* 2016; Sullivan *et al.* 2009; Williamson 2009)
Enable feeling of co-ownership and control over the scientific process	Actively involve the volunteers in the design, implementation and dissemination of the project	(Breen *et al.* 2015; Gharesifard, Wehn, and van der Zaag 2017; Grossberndt and Liu 2016; Jones *et al.* 2010; Liu and Kobernus 2017; Mackay *et al.* 2015; Mazumdar *et al.* 2017; See, Fritz *et al.* 2016)
Actively remind volunteers to contribute	Pop-up features in smartphone apps and using geofencing functions near desirable locations	(Kotovirta *et al.* 2015; Mazumdar *et al.* 2018)
Organize training	Adequate information on the data collection procedure either in forms of training or user guides as well as receiving help on demand	(Aspuru, Herranz-Pascual, and Santander 2016; Busch *et al.* 2016; Degrossi *et al.* 2014; Druschke and Seltzer 2012; Grainger 2017; Grossberndt and Liu 2016; Hunt *et al.* 2015; Jones *et al.* 2010; Kotovirta *et al.* 2015; Liu and Kobernus 2017; Mietlicki, Gaudibert, and Vincent 2012; Mominó, Piera, and Jurado 2016; See, Fritz *et al.* 2016; Wehn *et al.* 2015)

volunteers should be involved in the design process, where as if the aim is to collect scientific data, it is more cost-efficient to use existing CS tools proven to be user-friendly.

Druschke & Seltzer (2012) emphasize that it is critical to provide access to the data the volunteers collect, even preliminary ones, as soon as possible, in order to allow them to provide feedback and inquire on an issue that might interest them, while at the same time providing them with a feeling of connectedness to the study and demonstrating the value of their involvement. Providing rapid feedback might even involve utilizing suboptimal tools, but still, this expectation can sometimes be difficult to meet depending on analytical demands combined with time constraints.

See, Fritz *et al.* (2016) emphasize how user needs can change, and there is a need to understand the volunteers' skills, expectations and interest to adjust the developed tools accordingly, which might mean that data analysis, modeling and presentation of results must be adjusted for distinct user groups (Gharesifard, Wehn, and van der Zaag 2017; Grainger 2017; Kobernus *et al.* 2013). Golumbic, Fishbain, and Baram-Tsabari (2019) suggest a multilayer information display to address different user needs. For example, scientists might be interested in the raw data, while the general public might prefer off-the-shelf data visualization products (Prakash *et al.* 2004). An example of adaptation to different user needs in data visualization platforms is given in Table 4

Table 4. Adapting to user needs after Prakash *et al.* (2004).

User groups	Example of visualization
The general public and young children	Simple visualization of processed data
Decision and policy makers	Retrieve data for different scenarios in order to make decisions
Students	Possibility to change input parameters and explore the data to fulfill curiosity
Web and tool developers	Access to archived and near real-time data for web interface and tool development purposes
Researchers	Access to raw and original data for research purposes

and is based on the findings of Prakash *et al.* (2004). However, many features depend on the level of desired participation, e.g. in virtual projects where participants analyze data vs. investigative projects where volunteers submit data, as well as the project goals (e.g. conservation vs. investigation), and physical location (e.g. local, global or virtual) (Wiggins and Crowston 2011).

Citizen science campaigns should allow volunteers to match their interests with those environmental issues that directly affect their environment and provide relevance and meaning to their daily lives (Grossberndt and Liu 2016; Kotovirta *et al.* 2015). They can do this by involving communities, such as schools and other local populations directly affected by the issue (Ferster and Coops 2013; Grossberndt and Liu 2016). While the CS project will provide opportunities for informal training of the volunteers, the scientists will also gain valuable information as these locals will hold valuable knowledge of the study area and related issues and who can be actively involved in solving them (Ferster and Coops 2013; Guillaume *et al.* 2016; Hunt *et al.* 2015; Mominó, Piera, and Jurado 2016; Montargil and Santos 2017b; Williamson 2009). Mobile applications should be used both for extracting and disseminating information. The data should be visible to the end user since it can affect their willingness to participate and is a critical success factor (Montargil and Santos 2017a). The volunteers should receive instant qualitative feedback by, for example, displaying data on a live map (See, Fritz *et al.* 2016).

The desire by the volunteers to contribute to science and society means CS practitioners should frequently communicate the importance of their contribution and how their data is being utilized (Kotovirta *et al.* 2015; Mackay *et al.* 2015; See, Fritz *et al.* 2016; Wright *et al.* 2015). According to Grossberndt and Liu (2016) to foster meaningful participation, it is essential to reassure the volunteers that the results are being used to solve real issues. Similarly, Aspuru, Herranz-Pascual, and Santander (2016) noticed the importance of participants reaffirming that their observations can affect the decision-making process. It is also important to acknowledge their input, e.g. rewarding them with certificates of recognition (Dickinson *et al.* 2012; See, Fritz *et al.* 2016).

Providing access to individual contributions is rewarding for volunteers (Sullivan *et al.* 2009) and will boost their curiosity and personal developmental goals when they are given the opportunity to analyze their data (de Assis *et al.* 2018; Gharesifard, Wehn, and van der Zaag 2017; Hunt *et al.* 2015; Marantos *et al.* 2017). Sharing the data is also an integral part of establishing trust, fairness and value for those who

contribute, while it increases comprehension of environmental issues by the general public (Ferster and Coops 2013; Mietlicki, Gaudibert, and Vincent 2012; Miorandi *et al.* 2013).

Rewarding volunteers is an effective way to encourage and support participation (See, Fritz *et al.* 2016). On the one hand, Clary and Snyder (1999) acknowledge the efficiency of external rewards, yet on the other, they caution that once the external pressures to perform observations is removed, the motivational force to participate might shift and thus advocate for using methods which foster intrinsic motivation. In addition to providing access to individual data, which were classified separately, providing different levels of progression or reputation ranking and introducing elements of competition between volunteers including contests, incentives, and badging systems, might be rewarding to some of the volunteers (Dickinson *et al.* 2012; Kotovirta *et al.* 2015; See, Fritz *et al.* 2016). Increasingly CS projects are incorporating elements of gamification, for example, by asking users to conduct micro-tasks, e.g. classifying images, which is a type of volunteer thinking (See, Fritz *et al.* 2016). Gamification can help to solicit and maintain contributions from wider, already existing, communities, e.g. online communities (Simperl *et al.* 2018). It transforms the crowdsourcing procedure and makes it more engaging and fun (Gutiérrez *et al.* 2016). Gamification can also incorporate educational functions which can both enhance participation and learning (Mominó, Piera, and Jurado 2016). Some volunteers can indeed find playing a game rewarding (Jennett *et al.* 2016).

To support a volunteer's desire to feel part of a community of likeminded people, adding social networking options to the crowdtasking might boost their motivation (Dickinson *et al.* 2012; See, Fritz *et al.* 2016). Creating a sense of community through discussion forums and social networking groups will enable social interactions with people of similar interests, e.g. to be able to connect and share experiences with peer contributors (Kotovirta *et al.* 2015). Enabling volunteers to interact might also lead to scientific discoveries that would have been otherwise overlooked by scientists, the project forum being a key space for such discussion between fellow citizen scientists (Jennett *et al.* 2016). Connecting people to frame and solve issues together will also create a sense of being part of a community (Williamson 2009). In some cases, merely watching submitted online data from other contributors can be enough for others to feel part of a group (See, Fritz *et al.* 2016).

Stakeholders need to achieve sufficient levels of trust, ownership and continuity to achieve the desired outcomes of social learning and engagement (Wehn *et al.* 2018). Volunteers should be offered ways to feel inspired, involved, and active in order to affect educational, attitudinal, behavioral, and scientific outcomes (Druschke and Seltzer 2012). Volunteers need to be actively and iteratively involved in the different aspects of the project, e.g. in the design, implementation and dissemination phases to foster the feeling of co-ownership in the project (Breen *et al.* 2015; Gharesifard, Wehn, and van der Zaag 2017; Grossberndt and Liu 2016; Mazumdar *et al.* 2017). Being involved will also give the volunteers a feeling of control over the scientific process (Grossberndt and Liu 2016). Furthermore, the more aspects of the project the volunteers are involved in, the more likely they are to retain interest; this includes especially the possibility to engage in various activities beyond the main task, such as discussion forums in online CS projects (Jennett *et al.* 2016). Yet, Wright *et al.* (2015) caution that there is a fine line between overextending and supporting participation, and a balance needs to be struck and managed for equitable participation.

With regards to trust, Barcellos *et al.* (2016), Gharesifard and Wehn (2016) and Golumbic, Fishbain, and Baram-Tsabari (2019) suggest providing information about the origin of the data and metadata in the platforms and using disclaimers. The metadata should include, for example, information about the observations, i.e. under what conditions the data were acquired, type and accuracy of the equipment used and how often equipment is calibrated (Gharesifard and Wehn 2016). The disclaimer should inform the user about the reliability of the data (Gharesifard and Wehn 2016).

As discussed in section 2, user patterns and levels of participation are known to vary. To keep users active, or to revitalize their activity, the users can be reminded to contribute, for example, with the help of the geofencing approach (Kotovirta *et al.* 2015; Mazumdar *et al.* 2018). Geofencing can be used to trigger a volunteer to act near a pre-defined location where they will receive a notification on their smartphones and can decide to act or disregard the message.

Volunteers should also receive training and sufficient information before data collection campaigns (Mietlicki, Gaudibert, and Vincent 2012; See, Fritz *et al.* 2016). They need to be provided with adequate information on the data collection procedure and to receive help on demand (Aspuru, Herranz-Pascual, and Santander 2016; See, Fritz *et al.* 2016). The information can be passed on remotely by providing volunteers with user-guides, instruction sheets, guidelines and protocols on the use of the measuring device and observation recording, or face-to-face guidance during a workshop or training session (Grainger 2017; Hunt *et al.* 2015; Liu and Kobernus 2017; See, Fritz *et al.* 2016; Wehn *et al.* 2015). Trained volunteers can then use their gained knowledge to train more users (Kotovirta *et al.* 2015). Training of volunteers will create win-win situations; the volunteers will increase their skills, knowledge and experience while the scientists will receive higher quality data (Aspuru, Herranz-Pascual, and Santander 2016; Jones *et al.* 2010; Liu and Kobernus 2017; Mietlicki, Gaudibert, and Vincent 2012; See, Fritz *et al.* 2016).

Investing time and effort to involve citizens does not guarantee success. Reporting on a project that appeared to be a success, at least regarding scientific outcome, Druschke and Seltzer (2012) warned other CS practitioners that while superficially it may seem that all aspects of CS engagement have been taken into account, it is not enough to provide user-friendly info and tools and to set up a community communication medium. The volunteers need to be actively involved from the design phase onwards. Otherwise the apparent efforts towards engagement of volunteers in scientific data collection does not guarantee dual benefits e.g. positive learning outcomes for the participants.

5. Sustainability

Projects face many challenges concerning their long term sustainability. In CS projects, sustainability is guaranteed when both volunteers and the infrastructure e.g. data platform is maintained over the long term, and therefore retaining motivated volunteers is not the only aspect of sustainability (Ferster and Coops 2013; See, Fritz *et al.* 2016; Tapia *et al.* 2014; Wright *et al.* 2015). Several previously discussed points affect the sustainability of the project, such as creating tools and services which are usable, versatile, appealing, engaging, easy to use and intuitive (Aspuru, Herranz-Pascual, and Santander 2016; Barcellos *et al.* 2016; Botteldooren *et al.* 2013; Busch *et al.* 2016; Castell *et al.* 2015; Havlik and Schimak 2014; Kotovirta *et al.* 2015; Simpson, Page,

and De Roure 2014). However, in order to sustain the infrastructure and other elements of the project, actions should be taken to foster a broader and more longer-lived influence beyond involved volunteers. In addition to providing the volunteers with access to the data, providing access to the general public (Ferster and Coops 2013; Montargil and Santos 2017a) and other interested parties, such as third-party developers (Ferster and Coops 2013; Miorandi *et al.* 2013) in the form of open APIs that extend the project's reach to other platforms and applications, can foster its continuation and long term success. For this, it is important to use open standards for interoperability to complement and re-use existing datasets (Botteldooren *et al.* 2013; Busch *et al.* 2016; Liu and Kobernus 2017). By using standardized parameters and methods, data can be accepted more widely into other data repositories and to reach a wider user base (Busch *et al.* 2016), while interoperability becomes imperative when fusing data from different platforms and developing "universally" operated applications.

Creating a business model, e.g. selling a software license or finding organizations interested in the data or its user groups (Havlik and Schimak 2014), while making sure the data is preserved, curated and documented in a data management plan (Mietlicki, Gaudibert, and Vincent 2012; See, Fritz *et al.* 2016), can sustain the project features beyond its lifetime. Commercially driven projects and cross-financing can help to sustain a project financially (Gharesifard, Wehn, and van der Zaag 2017; Vincent *et al.* 2011). Close collaboration with well-known existing organizations and integrating the interactive features of CS using their infrastructure, such as enabling citizens to contribute observations through their webpage, can further promote the longevity of the project (Cooper *et al.* 2017; Grainger 2017; Sanz *et al.* 2014; Wehn and Evers 2015). This is both an efficient way to reach out to the target audience and at the same time, assure a communication network that can be used for information and support.

Reaching wider audiences *via* mass participation and scaling up the project geographically will increase both the number of observations and their geographical coverage (Gutiérrez *et al.* 2016). Other means to increase a broader uptake are, for example, the promotion of tools and services (Liu and Kobernus 2017) as well as ensuring they provide relevance and meaning to various stakeholders, such as enabling them to influence governance (Montargil and Santos 2017b; Vincent *et al.* 2011). Finally, Grossberndt and Liu (2016) call for close project documentation of both successes and failures for other projects as a mean to learn from, while Sanz *et al.* (2014) emphasize the need for evaluation of the projects.

6. Conclusions

This paper provides a typology of CS projects, and introduces a joint discussion on the motivation and expectations of volunteers, together with functional features of CS tools to retain them, including approaches which help to sustain a CS project over the long term. The broad application areas and types of CS projects make it difficult to describe a one-size-fits-all solution, which is why knowledge and suggestions summarized here should be considered and used as a map and reference point to inspire and guide CS practitioners in adopting specific aspects tailored to their projects. This is further supported, as emphasized previously by Freitag and Pfeffer (2013), by the fact that different CS projects perceive success differently, which also depends on the particularities of the local setting. As the field of inclusive CS continues to grow, the joint discussion presented about volunteer motivation, retention strategies and design aspects is

unambiguously of high value for the CS community. The value cross-cuts scale from the local to the global. Both scholarly and practice-based communities can adopt good practices presented here and in conjunction with the continuous technological innovations make the difference in incorporating CS practices in local use cases, while, given the increasing role of local views for addressing global issues, enhance the international relevance of CS i.e. in support of the Sustainable Development Goals (SDG) frame (Fraisl *et al.* 2020; Fritz *et al.* 2019).

In summary, this paper makes the following recommendations:

1. Clarity of project aims as well as managing expectations early on in the process are vital elements of success.
2. Recruitment of volunteers and stakeholders should be based on relevance criteria and after thorough collection and comprehension of their motivations and needs.
3. Volunteers should be actively involved in all stages of the project and its products.
4. Functional features should match the volunteers' expectations and for this knowledge gained during their implementation should be fed back.
5. The sustainability of projects is better served when relevant factors are addressed early in the design phase and potential exploitation scenarios are foreseen.

Importantly, citizens should have a central role in CS projects. Due to the transdisciplinary nature of CS projects, the focus should not only be on scientific outcomes, but also on the volunteers themselves and the participatory process needed for their efficient involvement. Examining and taking into account volunteers' motivation and needs during the project design stage will result in longer-term participation retention, as long as their motives are fulfilled and a win-win situation is accomplished. Practitioners can achieve this by providing features within the tools used in CS projects which enable the matching of volunteers' expectations and motivation to their benefit. A dynamic balance between co-benefit of volunteers and scientific objectives should be established for best-fit-for-purpose. Overall, for the optimization of CS applications, volunteers and infrastructure should be regarded as one integral ecosystem, whose good health significantly drives long term sustainability and success.

Note

1. Smurbs.eu

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3.3 Scientific Article: "Articulating User Experience of a Multi-Sensor Personal Air Quality Exposure Study"

This section is a scientific article authored by Johanna Amalia Robinson, Rok Novak, Tjaša Kanduč, Denis Sarigiannis and David Kocman. The article is under preparation. The article results from the EU-funded ICARUS project describe participants' user experience in a multi-sensor air quality exposure study. In addition to user experience, the article describes and analyses participants' motivations, expectations, risk perception and behavioural change, and evaluates the used sensor technologies. In addition to the abovementioned it demonstrates the importance of receiving timely information on collected data, as it influences behavioural changes and pinpoints the burden and inconveniences of carrying and caring for immature low-cost technology. The article confirms the hypotheses one to five. The candidate conceptualised the idea for the manuscript, designed pre-and post-campaign surveys, collected user feedback in the campaigns with the other authors, analysed the results, prepared illustrations for the manuscript and wrote the manuscript.

Link to the article: https://portal.ijs.si/nextcloud/apps/onlyoffice/s/eNL4HZNQ5XYi4Hj

Articulating User Experience of a Multi-Sensor Personal Air Quality Exposure Study

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Abstract

Personal exposure monitoring in air quality is more and more often conducted using low-cost sensor devices. Currently, little is known about participants' experiences using such devices and how these studies contribute to behavioural change and risk perception. This study articulates the user experience of participants of the EU H2020 ICARUS project's multi-sensor personal air quality exposure campaign in Ljubljana, Slovenia along with exploring their behavioural change and feedback on the used devices, their motivations, expectations, perceived risk and perceived level of exposure to air pollution. Pre and post-campaign surveys were administered to 87 participants. The participants expected to benefit from the campaign by obtaining information about their living environment and exposure to air pollution. Over half of the participants reported they had changed their lifestyle to reduce their air pollution exposure. If results had been seen in real-time, the participants' intention to change their behaviour was four times higher. Participants experienced inconveniences to their daily lives resulting from their participation in the study mainly due to a prototype device, while off-the-shelf devices were more easily accepted. The results can inform low-cost sensor device developers and exposure campaign practitioners on user-aspects.

Keywords

User experience, air quality, motivation, behavioural change, risk perception, novel sensor technologies

1. INTRODUCTION

Air quality (AQ) and exposure studies have traditionally relied on either monitoring station data or AQ models (de Nazelle et al., 2013; Singla et al., 2018). However, personal exposure to air pollution can vary dramatically and cannot be accurately assessed based solely on data from monitoring stations or respective modelled geospatial data (Caplin et al., 2019). While such studies are essential in advancing scientific understanding of air pollution levels, public involvement has been somewhat limited in traditional air quality studies (Bickerstaff, 2004). A Citizen Science (CS) approach contributes to monitoring air quality in urban areas by using portable, low-cost sensors to estimate personal exposure and is increasing in popularity (Borghi et al., 2017; Campbell, 2009; Castell et al., 2017; Jerrett et al., 2017; Snik et al., 2014; Thompson, 2016) and meets the future directions for human-environment research set by Moran & Lopez (2016), where natural and social-sciences interact and directly benefits society. Moreover, including indoor measurements in an exposure assessment gives a complete picture of an individuals' exposure since, on average, as much as 90 % of the time is spent indoors (Pitarma et al., 2017). As personal "smart" technologies become prevalent, exposure estimates on the personal level enable higher spatio-temporal data covering various microenvironments. Together with activity data and other self-reported information administrated through questionnaires and additional sensors, more relevant personal level data can be obtained, which are a promising component for self-management, and detailed information on the intake dose in exposure models (de Nazelle et al., 2013; Jerrett et al., 2017; Morawska et al., 2018; Novak et al., 2020; Steinle et al., 2015). Many previous air pollution exposure studies or cohorts have limited the research objectives to participant exposure, while the literature on the participants own experiences is limited (Zappi et al., 2012). Citizen science (CS) has the potential to empower participants in pro-environmental behaviour e.g. (Bonney et al., 2009; Cooper et al., 2015), yet the impact of air pollution exposure studies on lifestyle choices is less well studied (Leung & Le, 2019; Skarlatidou, Hamilton, et al., 2019).

The use of personal air pollution sensors for exposure studies have not been widely implemented on a large scale due to their being costly, time consuming, and performance and usability issues (Park, 2020; Rai & Kumar, 2016; Robinson et al., 2018). In order to facilitate a better user experience, several authors have introduced guidelines on designing CS tools (Jennett & Cox, 2014; Robinson, Kocman, et al., 2021; Skarlatidou, Ponti, et al., 2019).

This study is part of the EU H2020 ICARUS project (Integrated Climate forcing and Air pollution Reduction in Urban Systems, 2016-2020) to assess air pollution in nine European cities. The project also included a multi-sensor personal exposure study, which had features of CS in regards that citizens participated in data collection using passive personal sensors (Campbell, 2009). The purpose of this study was to investigate user motivations, expectations, and experiences during the campaign conducted as part of the Ljubljana pilot and included obtaining feedback on the sensor devices. In addition, the aim was to determine the impact of participation on user behaviour and perceived exposure risk to air pollutants.

2. METHODS

2.1 Overview of the Background Study Design

A multi-sensor campaign to collect data on individual exposure to environmental air pollutants was conducted in seven European cities as part of the EU H2020 ICARUS

project[4] . This manuscript focuses on the case study in Ljubljana, Slovenia (Fig. 1). The main objectives were to collect data on external environmental exposure and exposure determinants by combining location, activity and air pollution data in different microenvironments while demonstrating the feasibility of using new sensor- and personal mobile technologies in collecting exposure data. The aim was to achieve two of ICARUS's goals, i.e., raising public awareness about air quality and motivating citizens to adopt pro-environmental behaviours both important for public health. The ICARUS approach is different and considers an individual's exposure to environmental pollutants in different microenvironments, which depends on time-activity profiles and activity levels rather than on ambient concentrations. The information obtained is based on exposure monitoring devices, questionnaires, surveys and time-activity diaries.

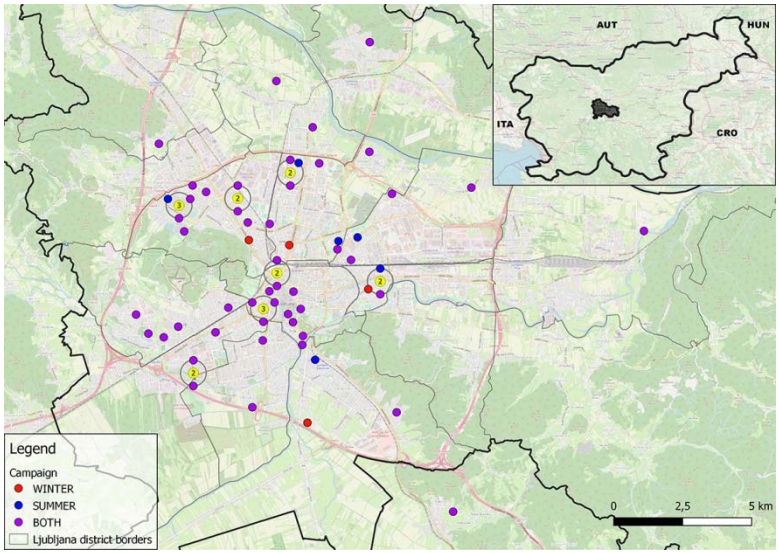

Figure 1: Distribution of households involved in the Ljubljana case study.

Measured data included personal exposure to Particulate Matter (PM) and location data collected using a portable PM meter (PPM) developed within the frame of the ICARUS project (IoTech Telecommunications, Thessaloniki, Greece); organic contaminants including Polycyclic Aromatic Hydrocarbons (PAHs), pesticides, and flame-retardants sampled using a custom-made silicone wristband passive sampler. Indoor air quality was assessed by measuring levels of carbon monoxide (CO), carbon dioxide (CO2), volatile organic compounds (VOCs), particulate matter (PM2.5), ozone (O3), nitrogen dioxide (NO2), temperature, humidity and air pressure using a static commercially available Indoor Air Quality (IAQ) unit uHoo (South Coast Air Quality Management District, 2019). Finally, personal activity data such as heart rate, steps and sleeping patterns were collected using a Garmin vivosmart 3 smart activity tracker (SAT) (Garmin, 2020).

If the participant was a smoker, the silicone wristband was worn on the hand used to hold a cigarette. Both were carried 24/7 and were waterproof. The portable PM meter was carried on a belt or any other means the participant found practical. The static IAQ unit was placed in the participants' living room. The portable and static IAQ devices were co-located for data quality prior to the campaign (Novak, 2019; Novak et al., 2020). A dedicated ICARUS data collection platform collected and stored data in various formats using the devices' Application Protocol Interfaces (API)(UPCOM, 2020), with

[4] https://icarus2020.eu/

each household and participant being given a unique non-identifying user ID. Figure 2 gives a complete overview of the campaign design.

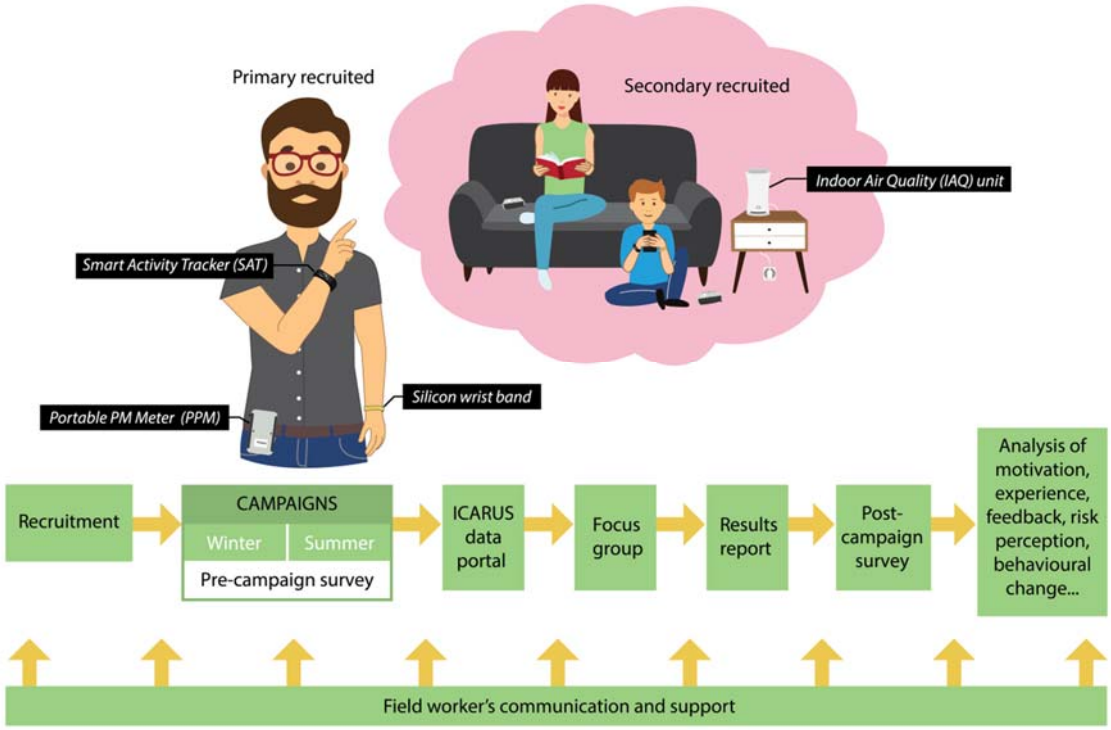

Figure 2. Overview of ICARUS sensor campaign.

The 2019 campaign took place in winter (heating season) and summer (non - heating season) to capture seasonal variations. Each participant had a seven-day timeslot within a campaign period of 34 days in the winter and 24 days in the summer campaigns, respectively. In addition to the sensor data, the participants were asked to fill out an hourly time-activity diary (TAD). This included their relative location (indoor/outdoor/in transit) and activity (leisure, sleep, playing, sports, cooking, smoking, and cleaning), house conditions (candle, open window, AC/fan, fireplace), and if they were active outdoors, whether they were running or doing other sports.

An ICARUS questionnaire about participants' demographics and socio-economic status was given to all participants living in the household. In addition, one adult within each household was asked to complete another questionnaire capturing household characteristics, e.g., type of dwelling, presence of pets, cleaning habits and frequency, the number of smoked cigarettes in the household, sources of pollution in the vicinity of the household, type of kitchen stove, heating type and heating fuel used. Ethical approval was obtained from the National Medical Ethics Committee of the Republic of Slovenia (approval no. 0120-388/2018/6 on 22 August 2018), and all participants gave informed consent.

We aimed to recruit one hundred participants in Ljubljana following the ICARUS study design (Sarigiannis et al., 2018). Recruitment took place six months before the first campaign. It included recruitment on social media, at scientific conferences, during the Jožef Stefan Institute's public open days, on the street with a (market) stand with leaflets and a banner, and by emailing participants from previous participatory projects. Preliminary criteria for selection included (1) a resident of Ljubljana, (2) wireless internet access in the home, (3) owning a smartphone with Bluetooth and 4) adequate

comprehension of the English language. All participants received an information leaflet explaining the study's aims and objectives, and before the start of the campaign, they were contacted by phone to confirm their availability. At the same time, the primary recruits were asked if any other household members would like to participate (secondary recruited). The contact person in each household, i.e. the primary recruit, was sent an informative email about the study and an informed consent form to sign and comprehend. A one-month study slot was outlined to cover all foreseen participants with a limited number of four field workers (researchers) and available sensors, which were rotated between the participants. Visits by researchers were commonly scheduled for the weekend when all participants were at home.

During the first house visit of the winter campaign (held in February and March 2019), the participants signed the informed consent form, and researchers handed out the questionnaires and surveys, set up the measurement equipment in the home, and provided instructions about using the personal monitoring devices. The start and end times of wearing the silicone wristband passive samplers were recorded. The participants were then given a two-page instruction guide containing instructions on how to operate the devices. Field workers were also available by phone or email to offer any additional assistance.

During the campaign, field workers regularly manually observed the real-time data uploaded to the ICARUS data platform. If a device was offline and not sending data, the participant was contacted and asked to reset the portable PM meter or move to an open space to receive a clearer GPS and mobile network connection.

The participants were expected to charge the PPM each evening or whenever they were stationary, e.g. in an office, since the expected battery life was approximately seven hours. A small red led light indicated the low charge status of the device. The SAT typically lasted five days before having to be charged. The participants did not have to operate the static IAQ sensor unit nor do anything with the silicone wristband. The participants did not have access to the data during the campaign.

After seven days, the field workers collected the devices. In a few cases, the participants decided to deliver the devices to the research institute. The researchers needed at least 12 hours between the participants' switching off their devices, backing up the data, deleting data stored in the device, reassign new user IDs, and charge the devices. The silicone wristbands were sealed in small amber vials and kept in a freezer until analysis. The whole procedure was then repeated during the second (summer) campaign in April and May 2019. Participants were provided with a pre-campaign survey about their experience, and researchers were available to discuss the initial results. A Final result report was then co-developed with the participants and based on participant feedback and focus-group discussions (Novak, Petridis, et al., 2021; Robinson, Novak, et al., 2021). The participants received the final result report 12 months after the campaign, followed by a follow-up post-campaign survey.

2.2 Surveys

Two additional surveys were developed just for the Ljubljana case study to ascertain the participants' motivations and expectations, user needs, feedback on the information they received and its usefulness, feedback and satisfaction on the used monitoring devices as well as the campaign itself. The surveys also included re-occurring questions about the participants' behavioural intentions and changes and perceived risk and worry of air pollution exposure. All of the above collectively reflected their lived experience in the campaign. The first "pre" survey (Appendix A) was administered at the beginning of the case study during the second house visit when collecting the sensor devices and filled out

by the researchers in an interview setting, while a link to an online version of the second "follow-up" survey (Appendix B) was sent out by email after the participants had received the results report.

The survey contained binomial (yes/no) questions, multiple-choice, five-point Likert scale answers and open-ended questions where the participants could freely express their views and ideas.

Personal demographics and socio-economic data were obtained from the general ICARUS questionnaire. Each participant was allocated a unique anonymised participation identification number, which allowed all the data (questionnaire, survey, TAD and the sensor data) to be tracked and easily collated.

2.3 Data Analysis

Responses to closed questions in the survey were summarized and analysed quantitatively. The content analysis of the responses to the open-ended questions was conducted using coding and thematic analysis. Two coders were used for quality control, and no significant inconsistencies were found.

Descriptive statistics were used to characterize participants' views. Regression, paired sample t-test and Odd ratios (OR) (equation 1) were performed and calculated to reveal the underlying predictive factors that affect behavioural change and risk perception.

Predictor \ Outcome	Yes	No
Yes	A	B
No	C	D

$$OR = \frac{(A*D)}{(B*C)} \quad (1)$$

3. RESULTS

3.1 Participant Characteristics in Sampling Campaigns

Forty-nine households participated in the winter campaign, and 49 in the summer campaign, with 45 households participating in both campaigns (Table 1). Eighty-two participants responded in the pre-campaign survey and 31 in the post-campaign survey, with only one submission rejected (failed completion of the online survey).

Table 1. Participant characteristics and descriptive statistics.

General campaign (number of households)		
winter campaign	49	
summer campaign	49	
same households	45	
Number of participants		
winter campaign	75	
summer campaign	81	

Survey respondents		
pre-campaign survey	82	
the post-campaign survey	30	(1 disqualified out of 31)
	pre	**post**
women	46 %	57 %
median age	41	43
Income		
Lower 25 %	12 %	17 %
Average (25-75 %)	54 %	53 %
Upper 25 %	29 %	27 %
unknown	4 %	3 %
Education		
Primary education (including children still at school)	18 %	10 %
Completed secondary education	12 %	7 %
Higher education	70 %	83 %
Underlying health condition	37 %	40 %
Primary recruited	63 %	77 %

3.2 Motivation and Expectations

In a survey, participants were asked a series of open-ended questions about their motivations for participating in the project and what they expected in return (Questions BQ2 and BQ3 in Appendix A). The results are summarised in Table 2. Almost half (51 %) reported a singular motivation, and 46 % multiple motivations, up to three. Most participants (77 %) described "interest in the topic" as their primary motivation. This broader topic included interest in their living environment, air quality, results and measurement values, personal exposure, improving their living environment, citizen science, the importance of clean air and the environment. Twenty-eight % of participants wanted to help science and society while 23 % had an external motivation, 16 % were motivated by curiosity, and 7 % were motivated by the possibility of participating in this kind of study. Those motivated by helping science also understood how difficult it is to find volunteers and wanted to help. For others, they did not specify but emphasised that they were asked to participate. This reply was classified under "external motivation/convinced", representing primarily those whom their family members recruited.

Table 2. Motivation to participate.

Motivation	[%] of different motivations	[%] of participants with this motivation*
Interest in the topic	51%	77 %
Help science and society	19 %	28 %

External motivation/convinced	15 %	23 %
Curiosity	10 %	16 %
Possibility to participate	5 %	7 %

*participants had multiple motivations

Like motivation, participants also had many expectations (up to 4 different expectations (BQ3), which were answered as an open-ended question). For example, they expected to personally benefit from the campaign by obtaining information about the topic; Twenty-five % wanted information about their living environment, including their home and work environments, while 12 % were looking forward to the results without specifying the type of information they were after. Also, 10 % and 6 % wanted information about their exposure and air quality levels, respectively. A minority also expected to gain information on mitigation strategies (2 %). Three % wanted to know more about other health-related parameters measured in the study, while only 1 % expected to learn more about CS. One participant mentioned how they expected the study would give them insights about their bad habits, which they then intended to change. Twenty-two % of the participants had no expectations, and 7 % wanted to wait for the results before expressing any specific expectations. Some participants (7 %) also expected that their participation would benefit science and society, such as new air pollution mitigation strategies or guidelines for reducing air pollution. They also expected that the results would educate the population about environmental risks posed by poor air quality, resulting in people becoming more environmentally friendly. Some individuals hoped that performing certain outdoor activities would produce insights for the project on outdoor air quality.

Participants were also asked to describe what surprised them after looking at the results (AQ3 in Appendix B). The topics of surprise were related to their observation of air quality and physical activity. For example, participants were surprised how much lower the CO_2 concentration is when they are not home and how high it is when they are home. Some were surprised that indoor CO_2 concentrations were higher during summer despite increased ventilation. They were also surprised about the prompt influence of opening windows on air quality, e.g. lower CO_2, yet higher NO_2 if done during heavy traffic. The average values of PM, TVOC and NO_2 concentrations per individual activity also surprised them, e.g. PM levels are high during the night when having open windows, while the highest levels of TVOC are detected during winter and NO_2 during summer. Also surprising was that PM levels in homes located in the city centre were lower than expected. Some were also surprised about their lower than expected stress levels and higher than expected heart rates determined by the SAT. Some participants were disappointed that their PPM device did not work and produce data, despite all their effort into carrying it around.

3.3 Participant Experience

The majority of participants (59 %) indicated that they were very satisfied or satisfied (27 %) with the participation, while none were unsatisfied (BQ17). All who replied (88 %) said they would like to participate again in a similar study in the future (BQ18), and all participants who replied wanted to receive a results report (BQ14). The majority (79 %) of participants were also confident that their data was handled accordingly, while 21 % were unsure or did not answer the question (BQ19). No one indicated concern over data usage.

The overall impression of the campaign was positive. The participants were asked to write what they liked or disliked about the campaign (BQ17b and c). They liked how the

campaign was designed and executed and how easy it was to become involved. The execution and research approach were described as simple, uncomplicated, interesting, executed in a popular way, and with an individual approach. The duration of the campaign was considered appropriate. The inclusion of several measured parameters was seen positively. Also, the opportunity to try out a SAT was exciting for many. On a personal level, participants liked the possibility of being part of the project, contributing to research, receiving the results, learning new things, and feeling important. Researchers received positive feedback on their work and approach, i.e., they were comprehensible, diligent, professional, adaptable, available and communicable.

Participating in the study meant that new daily habits were introduced into the participants' lives. These changes included wearing and carrying the sensors and mastering the routine of charging the devices. The campaign also created a feeling of being constrained in terms of carrying the devices. Two such examples:

"Mastering the routine of charging the PPM sensor and the Garmin"

" I felt limited in terms of carrying the devices"

The campaign created additional stress for several participants, with several regretting not providing sufficient data.

The majority (67 %) of the participants reported inconveniences and negative experiences during the campaign (BQ6). The majority (57 %) mentioned issues with the PPM sensor in their daily lives, i.e., that it was inconvenient, awkward to carry (attachment at the belt), big, noticeable, and heavy. Also, only 65 % always remembered to carry the sensor everywhere with them, but 79 % did remember to charge the batteries prior to them running out (BQ7). Some were bothered about the illumination of sensors, especially at night, and were unsure about the functionality of the PPM sensor's reset button. The humming noise was also bothering some at night. These inconveniences with the PPM also meant that some participants decided not to wear it during sports activities, such as running. Its size and impracticality prompted some participants to suggest that its design is not good. Younger participants (under 15) felt they were not sufficiently mature to care for sensors and kept forgetting to carry them. Similarly, many participants felt apologetic and felt they had to confess they forgot to charge the PPM or left it behind at home or work.

"I had issues with the PPM sensor. I forgot it several times and had to go back to collect it"

The SAT was generally considered a device one can forget about, but sometimes, the lights would turn on in the middle of the night when the participant changed a position while sleeping. This feature had been disabled before giving the device to the participants, but it was later turned back on without knowing. The device would also show daily goals (of steps or walked floors) and notify the user with vibrations, which confused the participants, as they were not informed about such features. Some participants were given inappropriately sized SAT and silicone wristbands which were either too large or too small, which prompted some participants to remove them during the night. For others, it was inconvenient to wear it 24/7, while those who already wore a wristwatch replaced it with the SAT but then missed their own watch during the campaign.

"Carrying SAT and sensors is sometimes a burden. I like to be without devices during my freetime."

"I would change the PPM sensor and the TAD. Also, a possibility for real-time air quality monitoring would enable changing a habit on a fly."

Several participants showed particular interest in the sensors. For example, some were interested in how they worked and their accuracy. Most participants were excited about wearing the SAT, and some were hoping to keep it after the study. A suggestion was made that instead of several sensors, all should be combined in a single device.

The time-activity diary was not filled out consistently (BQ7c); 4 % filled the TAD every twenty minutes, while 80 % filled it out every full hour and sixteen % entered their information once daily. Most remembered to fill it out daily while some participants also confessed to adding to the TAD approximately every second day. Those who filled it at the end of the day admitted it was difficult to remember what they were doing at a specific time each day. It was also reported that the TAD activity categories were sometimes illogical, not specific enough, and did not cover all possible activity categories, while some activities were seen as unusual. It was also suggested that the TADs be shorter, more precise and with a finer time resolution. The participants had difficulties recording activities that lasted less than an hour—for example, driving in a car for ten minutes. More instructions on how to fill the TAD were desired. It was also suggested that they write down their activities and times themselves.

"The ambiguities in the TAD should be fixed. For example, where should one write a 10-minute car drive, or if you were home for 50 minutes? "

"The TAD should be improved: Sometimes I did not know how to fill it in, e.g. how to mark a lunch break at work"

Fifty-one % were disappointed that they did not see real-time measurements (BQ12), 41 % were not disappointed, and 7 % did not know. One participant specified that seeing real-time data would bother him/her. Also, 56 % mentioned that they would like to see the result before commenting or taking action.

Fifty-seven % also communicated their results to other people, i.e., 57 % to family, 18 % to friends, 18 % to co-workers and 7 % to someone else (AQ7). No one talked to a healthcare provider or shared their results on social media. They discussed the general results, the study's usefulness, individual exposure, compared results between other participating family members, high PM and CO_2 values, unusual results, air quality and mitigation actions, professional topics, temperature and climate, physical activity and household cleaning habits. The younger participants received help and clarification from their parents, while several school-aged participants reported getting into uncomfortable situations when asked why they were carrying the sensors, i.e. an issue about standing out from their peers.

Filling out several questionnaires was mentioned as burdensome by some of the participants. The standard ICARUS questionnaires were also not adjusted for stay-at-home parents (e.g. maternity leave) or retired people. The campaign duration was seen as appropriate, although some suggested that multiple short-term campaigns would be better. Participants also wanted to see long-term time trends. It was also asked if the campaign could be national and how having more participants would be beneficial. One participant hoped the project would make a real impact and not be forgotten after the project officially ended.

"I hope the research will not end up forgotten in a drawer."

3.4 Impacts on Risk Perception

In the pre-campaign survey, 33 % of the participants reported they were worried about their exposure to air pollutants, while 39 % were not worried and 27 % were indifferent (BQ4). While in the post-campaign survey, only 23 % were worried, 48 % were not worried, and 23 % were indifferent. The participant's worry over personal air pollution exposure decreased after the study; 43 % reported a lower level of worry, 32 % reported being more worried, while 25 % had not changed their opinion. However, a t-test suggests no statistically significant difference between pre-and post-survey responses ($P = .74$, > 0.05).

We measured participants' perceived risk in air pollution exposure on a 5 point Likert scale from "very low" to "very high" (BQ5 and AQ6). Six % indicated it was very high, 18 % high, 44 % moderate, 24 % low, 5 % very low in the pre-campaign survey. The post-campaign survey's respective numbers were 0 % very high, 23 % high, 50 % moderate, 17 % low, and 3 % very low. However, the scale was not sufficiently sensitive to discover statistical differences ($P = .36$, > 0.05). The participants were also asked whether the individual results changed how they felt about their exposure to air quality (AQ5). This finding, together with their expected exposure to air pollution, is summarized in Table 3. Cumulatively speaking, participation raised the level of perceived exposure, i.e. those who considered their exposure as "low" or "lower" reduced from 29 % to 20, those who had selected "medium" values reduced from 44 % to 36 %. However, those who selected "high" or "very high" increased from 24 % to 36 %. Again, these differences could not be proven statistically (T-test: $P = .88$, > 0.05).

Table 3. Perceived exposure.

Expected exposure to air pollution 5-point Likert scale before the campaign// I think my exposure to air pollution is:	[%]	According to the results, my exposure to air pollution is:	[%]
Very low	5 %	Much lower than expected	3 %
Low	24 %	Slightly lower than expected	17 %
Medium	44 %	As expected	37 %
High	18 %	Slightly higher than expected	33 %
Very high	6 %	Much higher than expected	3 %
Unknown	2 %	Unknown	7 %

A regression test found a correlation with moderate internal consistency in perceived worry and perceived risk to air pollution exposure (r 0.54, $P = 2.41\text{E-}07$ (or .000000241), < 0.05) and r 0.54, $P = .003$, < 0.05) in the post-campaign survey. Those who reported being highly concerned about air pollution were more than ten times more likely to report having a high level of perceived risk to air pollution exposure than those who worried less or the same (OR 10.63 with 95 % CI [1.48, 76.08]). This ratio increased in the post-campaign survey to OR 23.75 with 95 % CI [2.65, 212.99].

3.5 Impact on Behaviour

One of the leading research objectives was to assess how participation in a multi-sensor air quality monitoring campaign changes a participant's behaviour. We investigated this aim using specific survey questions. The participants mentioned how they started to think about their exposure and how it links with their behaviour. In the pre-campaign survey, 23 % of the participants said they had been affected by their participation and intended to change their behaviour (BQ11). However, 26 % said they needed to wait to see the results. The following answers provide insight into the logic of the participants thinking:

"Now when I started to measure, I started to think".

"I don't have an opinion. Only now I started to think about what kind of environment I live in and that I can also improve it myself".

"I would be ready to change my behaviour, but so far I haven't because I don't know the results of the research."

In the post-campaign survey, 62 % reported changing their behaviour having received the results (AQ8) and similarly, 58 % due to mere participation (AQ9). Sixty-one % of primary recruits made changes, as did 57 % of the secondary recruits. The participants implemented some of the suggested preventive measures to reduce individual exposure and proposed their own measures. These included a more active lifestyle, opening the windows more frequently and other efficient ventilation techniques, quitting smoking and reducing car travel. They also said they would opt for greener transport, change their commute route to avoid heavy traffic, use less aggressive cleaning chemicals, reduce the number of aerosol products, including products with VOCs (scented candles), safer storage of VOCs containing products, buying an air purifier and consulting with a doctor. Only 4 % were unsure how to change their habits and their living environment.

"*I follow the proposals to reduce the negative effects of pollution more consistently, especially those I was able to implement without much difficulty, for example ventilating during cooking (I have a gas stove), fast and intensive ventilation in early morning and late evening, when there is less traffic and I am at home, the use of perfumes and other sprays on the balcony (and not indoors), I removed scented candles, glues and paints from the living space to a storage space etc."*

Given that only 23 % (BQ11) of the participants intended to change their behaviour at the start of the study, and 62 % responded that they had altered their behaviour by the end (AQ8 and AQ9), it is essential to study the underlying predictive factors for this observation. However, unlike in models of planned behaviour, in this study, an intention to change does not guarantee an actual change in behaviour (OR 0.77, 95 % CI [0.13, 4.54]). The results show the opposite, i.e., those with no intention to change at the beginning were 1.3 times more likely to change (OR 1.29 with 95 % CI [0.22, 7.50]). We found that those who would otherwise not change their behaviour were four times more likely to change if they received air quality measurements in real-time (BQ13) (OR 3.8 with 95 % CI [1.81, 8.00]). Fifty-seven % reported they would likely change their behaviour if they saw real-time data (BQ13). Receiving the results triggered a wish to change in 62 % of the participants, and those were six times more likely to take action based on the results they received than by participation alone (OR 6.13 with 95 % CI [1.17, 32.10]).

Also, those more worried about their risk (BQ4, AQ4) were more likely to change their behaviour than those who were worried less or the ones who did not differentiate in the before and after surveys(OR 2.55 with 95 % CI [0.41, 15.65]) while 78 % of those who

were more worried changed their behaviour. Also, primary recruited participants were more likely to change their behaviour than their family members who were secondary recruited (OR 1.17 with 95 % CI [0.21, 6.48]). Interestingly, some participants commented that they followed the rules of the study, but if they had their own sensor, they would experiment more and find out more about how their daily activities related to air quality.

3.6 Evaluation of the Sensor Technologies

Participants were asked to evaluate the four sensor devices (BQ8, Figure 3). The IAQ sensor unit ranked the highest on the satisfaction scale from 1 to 5 (Mean 4.9), followed by the silicone wristband (4.5) and the SAT (4.5). The PPM sensor ranked lowest (2.8).

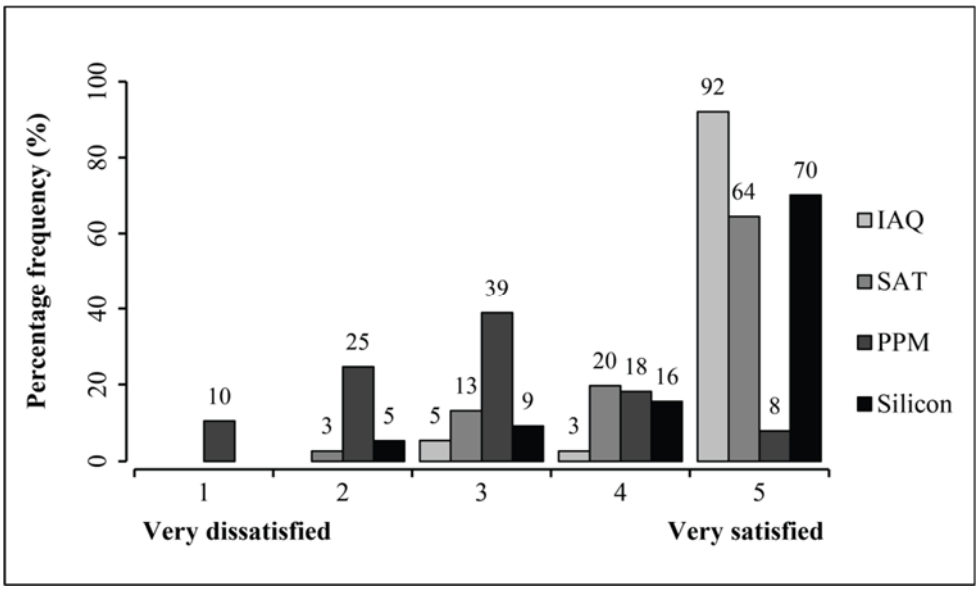

Figure 3. Satisfaction with the used monitoring devices.

Forty-eight % of participants were interested in buying either one of the devices used in the study or a similar device (BQ10). With an open ended question eighteen participants showed interest in the SAT, six for the IAQ device, and one for the PM sensor. The Rasberry Pie, Arduino, air quality, temperature and humidity sensors were other devices of interest. Two participants indicated an interest but did not specify a device. Renting of such devices was also mentioned. Eighteen % wanted to wait to see the results before commenting.

The participants were ready to pay various sums if bought. For the SAT, they would pay anywhere between 20 and 200€ (74 € mean, SD 48.7), for the IAQ between 30-400 €, and the PPM 250 €. The renting option could cost 5 € per month or twice a year for 20-50 €.

3.6.1 IAQ Sensor Device

The IAQ sensor device was considered unnoticeable, nondisturbing, unobtrusive, and something that is plugged in and forgotten. Participants found it positive that they did not have to interact with or carry the IAQ device, but it stayed in one place. One participant suggested that it should be battery-powered, which would make it portable. In addition, it was considered well (cleanly) designed, pretty and quiet. Since the IAQ device measured conditions in the house, participants reported that they would like

access to real-time data online. The majority (95 %) of participants did not have any remarks or wrote that everything was OK, reflecting that it did not create any disturbance. Only three participants noted as a negative feedback that it needed to be plugged into the electricity 24/7. No other negative feedback was recorded. It was suggested that results should be available online (which is possible for normal uHoo IAQ users) and that the device should have an indicator (LED light) of air quality. Considering that, 95 % had no negative feedback about the IAQ unit, and the only negative comments were about its electricity dependence, we could presume the device was successfully designed. The following user testimony sums up the practicality of the device:

"It (IAQ device) works unnoticed and does not require interventions"

3.6.2 SAT

The SAT was considered simple, light, small, handy, fun, nonproblematic, nondisturbing, unnoticeable, long battery life, and comfortable to wear. Its positive features were that it displayed the time, was waterproof, was easy to clean, and had a touch screen and a clear battery level indicator. Some participants were pleased to be informed about their daily goals (steps and walked stairs). The participants were also explicitly asked not to browse the SAT and change settings, yet some did. Few participants reported they were happy to be able to browse the device. Some participants were explicitly excited and considered it a bonus that it measured their activities, tracked movement, sleeping and heartbeat. The practicality of the SAT was summarised in the following participant feedback:

"Suitable for carrying everywhere"

There were negative comments (39 %) about the SAT. Some participants were confused about the daily goals, while others were uncomfortable wearing the device on their wrist, especially when there was a chance of it getting wet. Few participants had an allergic reaction (to nickel). Some of those who already had a wristwatch preferred their regular watches. Several participants were also disappointed not to see the results, although some did change the settings to see their activity data. Also, it was reported that the SAT would light up at night when the person moved, which bothered some participants. Similarly, the bright green light from the heart rate sensor, visible if the wristband was not sufficiently tight, was also bothering at night. Sixteen % reported the light bothering them. A few also reported taking off the device while sleeping. Also, the SAT would sometimes not turn on when the participant tried to see the time from the touch screen. Others reported that the device was too small. A typical bad user experience was as follows:

"It obstructed me up to a limit that I had to take it off since the light woke up our children."

The participants had few suggestions for improving the SAT. As they were confused about the daily goals, they would have liked to be better informed what those meant, or simply remove them, or change the setting so high that the participants would never receive a notification. They also wanted information on how to switch off the night light. Furthermore, they pointed out that it should work with a turn-on button instead of the night light being triggered to turn on by motion.

Design-wise, the participants wanted a more visible battery level indicator, greater flexibility/elasticity and more anatomical, and the touch screen to be more sensitive. Several mentioned that they would like to have access to real-time data on their smartphones. Some participants also suggested they would like to keep the SAT after the

campaign. Since some participants were bothered by the light, and others took theirs off to sleep, it was suggested that it be worn only during the day.

3.6.3 PPM

The PPM sensor did not receive an abundance of positive feedback, with 85 % of participants finding fault with the device. However, one positive was that it could be operated independently and charged using a USB cable, allowing those who forgot the charger to charge it, e.g., using a phone charger. Regarding its design, it was considered compact and relatively small for what it is capable of doing, and it was good to have the possibility to attach it to a belt or bag. Alternatively, it was considered bulky to carry. Being portable and having an integrated GPS in some units was also positive and meant that participants could better understand their exposure at specific locations. They were especially interested in the PPM results, as this was considered the most interesting data. While some people were bothered by the lights in the device, others were grateful that the lights were not as bothering as the SAT ones. Others were bothered by the humming noise from the inbuilt fan, while others considered it quiet.

The majority of the participants were bothered by the low battery life of the device and that it requires regular charging. Interestingly, one participant considered the device to have a long battery life, which might be due to a non-IMEI device that did not collect GPS data. Some participants also felt restricted by the need for frequent charging, which interfered with their work. Another issue was the lack of a charge level indicator, while some also had issues relating to connecting the charger to the device port and preventing it from detaching. The charging itself was also not fast, and it was not clear whether the device was charging when plugged in, as the indicative lights were deep inside the device and dimmed. Other negative feedback included its bulkiness, awkwardness, being unattractive, noticeable, clumsy, unpleasant, burdensome and difficult to carry (even with the attachment), particularly during winter months when the air intake was easily covered by winter clothing and carrying during sports or other physical work was considered impractical. Also, feedback states how the device did not have clear indicative lights, and it stopped working without warning when left unnoticed. The participants were also unsure whether the device was working or not. Unlike the other devices, the participants had to remember to take the PPM with them wherever they went and not forget it somewhere. It was also reported that they accidentally dropped theirs. On one occasion, a participant mentioned the device looks “dangerous”, and another described it as looking “conspicuous”. The reset button on the device was considered to be sticking out unnecessarily, which caused several participants to press it accidentally. The following two testimonies sum up the struggles participants had with the PPM:

“Needs charging of battery, it takes conscious planning effort to keep it along. It felled on the ground twice.”

“It is very big, and you need to think about it constantly so as not to forget it. Care also needs to be taken that it is not covered etc., and has a bad battery.”

The participants wanted more and easier options for carrying the device, such as a strap or a small bag, neck bag, or a Velcro attachment. Carrying it by attaching it to the pocket clip was clumsy, as it would hit doorways and one could not sit normally. It was also mentioned that it was difficult to attach to clothing, for example, and when doing so, it increased the risk of it falling. A more unambiguous indication of operation with led lights was also suggested as well as better battery life, being more practical, smaller size, lighter weight, better design, better quality, less loud, more discrete reset button, battery level indicator, visualization screen, and with better sensors. With a smaller size and a better attachment option, like a sports watch, the participants would automatically carry

the device with them, rather than them needing to remember it constantly. Another suggestion was to have a PPM sensor that could identify the pollution source (e.g. pollen).

3.6.4 Silicon Wristbands

The silicon wristband was described as unobtrusive, unnoticed, waterproof, small, easy to clean, portable, great, cute, light, practical, with a nice design looking like a bracelet. One would have wanted more colour options. The wristband did not bother and interfere with most of the participants' everyday lives, and it was even less disturbing than the SAT. The device also did not require any operation to work, but it was passively carried and was suitable to be worn everywhere. However, some pointed out that they would like to see results before commenting.

Twenty-one % of the participants were disturbed by or felt uncomfortable wearing the wristband because it was either too small, too big or otherwise annoying. When the wristband was too big, it was loosely moving on the participant's wrist and even came off when undressing. Unnecessary stress was created when care was taken not to cover the wristband with clothes, as this would interfere with the band's ability to sample air pollutants passively. This fact was especially the case during the winter. They were hoping it could be adjustable to overcome the size issues. Some also did not find it visually appealing. One participant took the wristband off at night.

4. DISCUSSION

4.1 Participant Profiles

The campaign recruitment yielded diverse cohorts, including children and the elderly, various income levels, and balanced gender profiles contributing to more inclusive and equitable research. Nonetheless, as is typical for citizen science projects, this case study also had a substantial proportion of participants having completed higher education (Soleri et al., 2016). Since the initial recruitment took place six months before the campaign, several recruits decided not to participate either because they were no longer available or had become sceptical about using personal sensors. During the phone calls, participants asked many technical questions regarding the sensor's specifications, including dimensions and measuring techniques.

Sixty-three % were primary recruited, while the rest were secondary recruits, e.g., family members. 77 % of the respondents to the post-campaign survey were primary recruited, which might explain why such a small number of responses was received with a single-family member providing feedback. The ethics standards in Slovenia prevent children under 15 y old to participate in exposure studies without parental consent. In this study, nine children under 15 y old (6 – 9 yrs) participated. Out of the four preliminary criteria for selection: (1) owning a Bluetooth capable smartphone and (2) English language comprehension became less important once the project evolved. Excluding two factors at the recruitment phase might have boosted participation.

4.2 Motivation and Expectations

The reported motivations of the participants are in agreement with other CS initiatives (Robinson, Kocman, et al., 2021), i.e. altruistic wish to contribute to science and society,

curiosity or the egoistic learning opportunities the campaign enables them, e.g. to learn about the subject area. In addition, the participants listed various interests, e.g., living environment, air quality, results in general, the overall theme, measurement values, improving the environment, personal exposure, citizen science and the importance of clean air. Forty-six % of the participants were multi-motivational. The participants pursued different goals, which explain the different motivations (Clary & Snyder, 1999). Collecting data on their immediate environment and receiving results about their living environment seems to be more motivating than campaigns that aim to collect air quality monitoring data at the city level. This observation already became apparent in our earlier studies (Robinson et al., 2018). This phenomenon can be explained by their involvement , increasing their understanding and prompting a more appropriate response (Keune et al., 2016).

Due to the ICARUS specific objectives for the campaign to recruit households, 37 % were family members recruited by the primary recruited people in the first winter campaign, and hence their motivation to participate might differ. Twenty-three % of participants, i.e. spouses and the children of primary recruits, reported having participated for external reasons, e.g. someone convincing them. Eighty-two participants originate from 49 households, meaning there was a large number of secondary recruits. The motivation can change and evolve (Cox et al., 2018), explaining why 57 % of secondary recruits also changed their behaviour.

The expectations reflect the information that the researchers had given to the participants about the study. The themes in the answers included their exposure to air quality, both as individuals and as families and knowing more about their living environment. Several participants expressed that they had no expectations or were expecting to know more after receiving the results.

The measured exposure presented to the participants in a results report was to some extent higher than they expected. Even if at the beginning, 6 % anticipated that the exposure is very high, while 0 % thought so after receiving the report, with the results reassuring. This finding explains why we see a decrease (not proven statistically) in worry about air pollution exposure. The participants also learned something new about their living environment, which can be seen from the observations and surprises they made about their results. The participants processed and comprehended the received information from the results reports.

4.3 Participant Experience

The overall experience of the campaign was positive. Participants were satisfied with how the study was organized and gave positive feedback about the researchers involved. The campaign, however, also introduced inconveniences in the participants' lives. Even if the sensor care and charging were easy to integrate into existing routines, e.g. when charging their smartphones, many did not remember to charge the devices. The prototype PPM device was inconvenient to carry around, and additional stress was created when the participants were unsure if the device was working, especially since it lacked clear indicative lights. During campaign preparation, wrist-wearables were assigned to participants based on their sex and body weight with bigger sizes for men and medium and small sizes for women and children. Despite all the preparations, many felt they had an uncomfortably small or large sensor on their wrist and decided not to wear them all the time. In the future, more adjustment options should be developed and care taken to find the best fit. A solution would be to ask participants to measure their wrists or to use the ratio of weight/height compared to wrist size before the start of the campaign. Another approach could be to measure the strap length of their current wristwatch if

they wear one, or they could take a photograph of their wrist with a 1€ coin for reference. On the other hand, the researchers had only a limited amount of wrist wearables at disposal at one given time.

Filling out the time-activity diary was seen as burdensome. This issue is common in studies collecting such data (Chatzitheochari et al., 2018). The time-activity diaries introduce a human error in the study. Not everyone remembered or decided to fill them out as frequently as asked, and when filled out afterwards, it was difficult to remember what individual activities they did in certain hours. The TADs also did not have clearly defined activities and finer-grade time slots, which would reflect a more realistic profile of their activities. It was not always clear whether the participants should mark that they were in transit or at home, for example, if the journey took only 15 minutes, as the time-activity diary had only one-hour slots. It was also, for example, difficult for participants to choose a category for a lunch break at work.

Filing out the TAD by hand was also inconvenient. One solution would be to digitalize the TAD with a phone app, e.g. as in the study by Glasgow et al. (2016), or even further, through machine learning-based recognition of activities based on a smart activity tracker and air pollution data (Novak, Kocman, et al., 2021). Many participants were disappointed that they did not see real-time data, something that was reflected throughout the survey answers. Offering real-time data is according to Zappi et al. (2012), a key to high satisfaction user rates and would support more sophisticated and relevant usage patterns.

Over half of the participants felt it important to discuss, share and reflect on their experience and results, mainly their family. Discussing and raising awareness within the groups can help facilitate the uptake of behavioural changes (Massung et al., 2013) and the ripple effect of discussing with and encouraging family members to learn about air pollution (Wong-Parodi et al., 2018). On the one hand, it is good to involve the whole age spectrum in the campaign, but on the other, as noted by our participants, some are too young to care for the sensors and kept forgetting to carry them.

Unfortunately, some data was lost during the campaigns due to connection issues, poor design, battery faults or a missing timestamp or GPS data. It is vital that the technology does not fail, as it is very disappointing and de-motivating for participants to discover that their device did not collect data. Fortunately, the multi-motivational nature of their participation and their altruistic wish to help science counterbalances their more egoistic reasons, e.g., to learn about their environment, which could not be fulfilled due to the missing data. Any malfunctioning of the data flow should prompt an automatic alarm, rather than rely on scientists to manually check and notice that the device is not sending data.

4.4 Risk Perception

The campaign reduced participants worry about air pollution exposure. Being less worried might be due to the effects of heuristics or the familiarity principle. The first survey was given before they had any experience, so they worried more than after participating. It might also be because they perceived control over it and had received knowledge about their level of exposure and how to influence their exposure to AQ. Such observations certainly agree with the risk perception literature (Keune et al., 2016).

Many participants perceived that their exposure was higher than they expected. Their participation might have given them a more realistic view of the probability of their exposure. Namely, Wollf et al. (2019) enlighten us to how the risk of mundane events, like air quality in our case, is commonly underestimated, which is called probability neglect. The threat from air pollution might not be directly experienced in areas of low-

air pollution, and hence difficult to evaluate and relate. It is easier to express concern about an issue that poses an immediate effect on their everyday lives. However, the literature has not yet provided any consensus on whether people can perceive air pollution correctly since people's perceptions are subjective and can vary over time and are influenced by individual characteristics and efforts on raising public awareness (Dong et al., 2019). Also, a prerequisite for risk perception is the awareness of risk (Slovic, 1987). The involvement of the participants enabled them to understand the risks and associated uncertainty better, which is known to reduce public concern (Keune et al., 2016) while learning more about negative health effects can influence participants intention to change (Evans et al., 1988). The participants wished to see the results, learn about their immediate environment, and make decisions based on the data is consistent with the theory of inclusive risk governance, in which they seek to understand the risk from a personal perspective (Asselt & Renn, 2011).

We observed that the more the participant worried about exposure, the higher is their perceived exposure, the odds being even stronger after the study. This might be partly explained by awareness bias, in which the participant is more aware of the risk (Moffatt et al., 2000). We speculate that the participant's worry had reduced, as their fear had reduced due to familiarity with the topic of AQ, while their understanding and awareness might have helped them re-evaluate their risk. The risk from air pollution seemed to be more acceptable when the participants worried less.

4.5 Behavioural Change

Individual empowerment through participation in multi-sensor personal air quality exposure studies plays a role in the behavioural change of the participants. Increasing knowledge alone does not necessarily lead to a change in behaviour (Schultz, 2011), but involvement in a study has potential to empower people to control and reduce their exposure (Gabriel et al., 2020). The experimental learning, which participation enables, provides more than knowledge gain. Participants knowledge of the subject matter usually increases even if the participants are passively making observations (Jordan et al., 2011). However, intention to change does not guarantee behavioural change; in our case, more people who did not originally intend to change changed. Something else made them change other than their conscious intention to change. Interestingly, The pattern we have observed does not seem to follow the traditional models of planned behaviour (Ajzen, 1991).

Even though the new low-cost devices enable real-time data visualization, exposure studies commonly report results to the participants after the study has already been concluded. In the ICARUS project, this was particularly the case, as one of the study objectives was to use the data for agent-based modelling (Chapizanis et al., 2021), whereby seeing the data during the campaign was seen as bias towards the outcomes. One of our objectives was to study whether participation without seeing the results empowers participants to change their behaviour while also examining their preferences to receive real-time data.

Several participants reported their intention to change, while many requested to see the results before taking action. Whether or not the campaign made them change their behaviour is difficult to ascertain, but it made them think about their exposure and its link to their behaviour. The participants mainly reported changes that have a high impact in reducing their overall exposure to air pollution, e.g. more frequent ventilation by opening windows or choosing a greener way to commute. They are also relatively easy to implement and with few structural obstacles such as convenience.

In order to achieve behavioural changes towards lifestyles that reduce individual exposure, mere participation might be enough to motivate people to change. In our case study, 58 % reported doing so. Bonney et al. (2009) assert that volunteers participation represent a behavioural change since they have changed their behaviour by participating in a scientific study. Our observations of behavioural change due to participation align with that of Cooper et al. (2015), Crall et al. (2013), Toomey & Domroese (2013) and Wright et al. (2015). Toomey & Domroese (2013) provide a feedback loop model explanation where participation fosters the belief of a "greener perception of self", thus leading to more positive attitudes reinforcing pro-environmental motivations.

The participants were also eager to see the real-time results and were disappointed when they were not allowed access. Participants indicated that if they could see the AQ data in real-time, they would be more likely to change their behaviour. This response raises a question of trade-offs whether "hiding" results in air pollution exposure studies using low-cost sensor technologies is necessary if the participants are motivated for change by simply participating. Further studies are needed to investigate if making the AQ data available to the participants during the campaign in real-time increases their motivation to change their behaviour. The importance of providing access to data, even preliminary data, as soon as possible was already recognised by Druschke & Seltzer (2012).

By including several participants from the same household, we enabled communities of shared experience. They were able to talk about their experience and together introduce new behaviours, i.e. social norms. Social norms influence behaviour according to various behavioural theories (Lai, 2017). Involving family units in the study, we have also created a ripple effect. Also, those parents whose children did not participate could influence their behaviour by being role models and allowing their children to play an active role in the community. The involvement of children and younger individuals in the study could affect the cultural capital beyond the project's lifetime. Children could also evolve a lasting interest in science (Eriksen, 2015; Youssim et al., 2015) and specifically in Science, technology, engineering, and mathematics (STEM) fields when allowed hands-on experience (Kocman et al., 2020).

Together with the results report, the participants received a list of suggested actions to reduce their exposure to air pollutants. Providing such a list without the experience of participation would be less likely to prompt behavioural change. Even if motivated, according to Schultz (2011) information alone would not be sufficient to change their behaviour.

Contributory CS projects are expected to have a low potential for behavioural change and primarily feed scientific aims (Shirk et al., 2012). Although the ICARUS project can be classified as a passive contributory project, it did spike behavioural change. This effect could be explained with the participants directly benefitting from the results compared to CS projects with indirect benefits. When made collaboratively with participants, the potential of behavioural change in multi-sensor personal air quality exposure study could be even higher. For example, it would be interesting to give freedom for participants to study and experiment with air quality to make their conclusions and empower them intrinsically to make changes in their lifestyles, e.g. (Froeling et al., 2021). Namely, several participants wanted to see real-time data and experiment more, although they obeyed the rules during this study. There is a clear interest in more open and inclusive citizen science approaches.

4.6 Sensors

Three out of four sensor devices received mostly positive feedback. The prototype PPM sensor was considered inconvenient, even though it measured the most scientifically interesting parameter (PM). The fact that it received a low satisfaction rating (2.8 out of 5) confirms our earlier observations (Robinson et al., 2018) on how prototypes of low-cost sensors are not suitable for participatory campaigns aiming at collecting air quality data. It is important to gain early feedback from real end users rather than scientists alone, and user experience studies can help to understand the human aspects of the device use and prioritize device design aspects which need solving prior the device is ready to be deployed in large scale.

The priorities to improve such devices include reducing their size, better battery life, better attachment options, clearer LED indicators and adding a visualization option, e.g. on a phone app. To summarize, the features the participants found preferable would mean that the device would not obstruct or interfere with their everyday lives; its operation needs to be self-explanatory and leave no doubt about its active status. A plug-and-play type device would leave little space for making a mistake in the observation process. For portable devices carried on the wrist, the participant must be given a device of the appropriate size or adjustable. Some materials irritate the skin (e.g. nickel), while other inconveniences resulted in the participants deciding not to carry the sensors 24/7. The SAT had several downsides, which distracted the participants. Other equivalent smart activity trackers could be used in similar studies, and some of the annoyance could be avoided if the device was worn only during the day. While designing the study, researchers should weigh the benefits of the additional data recorded during the night with the annoyance this causes to the participants.

Almost half the participants expressed an interest in buying such devices, especially the smart activity trackers. However, the prices that the participants would be willing to pay were lower than the actual retail price of the devices.

4.7 Study Limitations

When dealing with human subjects, various biases can affect the results. No two research subjects (humans) are identical, and each will respond differently. In the case of “worry”, the participants could have, for example, interpreted the question differently and associated it with the current air quality, which was different from the air quality before and after the moment when they made their evaluation.

Actual air pollution exposure levels were not in the scope of this study, although it is necessary to discuss technical issues other than those reported by the participants. Namely, environmental sensors used in exposure studies are not as sensitive as research-grade sensors. Their fitness for purpose: sensitivity, specificity and stability, are still under rigorous scientific testing (Castell et al., 2017; Morawska et al., 2018; Omidvarborna et al., 2021). Finding a balance between the quality of data and the simultaneous deployment of several low-cost sensors amongst participants is a challenging task.

Delays in the campaign occurred on several occasions. First, there was a substantial time delay between initial recruitment and the campaign starting, during which some of the anticipated sensor devices changed. We believe that except for a few participants who had moved, this initial delay had little effect on participation rates. Second, the delay in the participants receiving the results after the campaign might have affected how participants answered the second survey, as they might have forgotten some details. Also, the length of winter and summer campaigns were not always seven days. This time

difference was due to scheduling issues involving individual house visits (e.g. participants were on holidays), which were impossible to match or schedule over the weekend. Not all the sensors worked, and only those with a mobile network connection (and not only logging data to SD card) were prioritized to be used. There were also a relatively small number of field workers compared to the number of households. Although these factors did affect both the winter- and summer campaigns to span over several weeks to cover all participants and to provide them with working sensors, we believe that this did not substantially affect the participants' experience.

When studying perceived risk, we had used the wording “worried”. Wolff et al. (2019) argue that even if it is a commonly used phrasing in risk perception studies, it is not a synonym for perceived risk but rather “worry” refers to anxiety and is characterized to view threatening situations. Despite this, “worry” is a better predictor of behaviour than risk perceptions, which in our case is more desirable.

5. CONCLUSIONS

This descriptive qualitative study of the ICARUS multi-sensor personal air quality exposure campaign provides valuable information on the design of multi-sensor campaigns in exposure studies by articulating the user experience. Ubiquitous sensor technologies are a growing practice, and user research studies can further improve instrument design (more user friendly) and data interpretation beyond numerical approaches by providing valuable insights.

Exposure scientists implementing low-costs sensor technologies should re-think the trade-offs of not displaying the results during the campaigns. The participants are likely to change their behaviour by mere participation — in our study, 58 % reported behavioural changes. However, showing participants the results in real-time would boost their motivation for change four-fold and create direct valuable feedback of the participants’ measurements. The lack of visualization is disappointing and hinders participants from taking action earlier based on informed decisions.

Although the participants anticipated receiving the results and did learn new about their living environment and how individual choices affects their exposure, doubt remains about the relevance of the results given the significant time that had passed (12 months) before receiving them. Namely, how well they could match what they were doing during peak events observed in the data—adding another argument to communicating the results as soon as possible.

Participation gave a more realistic image of their exposure, which is, as a mundane event, otherwise easily ignored. Participants would like to derive personalized meaning from the data, i.e. to learn about their environment. Their understanding of risk is also reflected by how their exposure can affect their circumstances. Even though not sensitive enough to detect statistically, the decrease in worry and increased perception of personal exposure is in line with the risk perception literature. Qualitative research methods allowed us a deeper understanding of participants’ views, actions and lived experiences and enabled us to articulate them.

The inconveniences caused by participation could be eased if the used devices were made more user-friendly. This issue was especially the case for the PPM sensor, which is not suitable for whole scale participatory campaigns in its prototype version. Instead of participants carrying and caring for several different sensor devices, they should be combined in one autonomous device, which does not require setting up and daily care from the participant, which can be passively carried or set in a fixed location and “forgotten”. The used uHoo IAQ is a good example to fit these criteria. The data flow

needs to function, and a clear indication of battery level and operation of the device needs to be addressed.

We urge the researchers of similar campaigns using low-cost sensors to validate the sensor's usability in technical terms and to implement interdisciplinarity to study the participant's user experience and nurture and feed the motivational drivers that lead to their participation in the first place. In this way, the evolving field of low-cost sensors used in exposure studies can be improved to benefit the researchers and guarantee a better participation journey to the participants of these studies and ensure their motivation in long-term studies if their expectations are also met. Finally, this study is also an important example of the disadvantages and advantages of sampling design, user feedback on AQ sensors and could be helpful in future multi-sensor studies for AQ monitoring.

Author contributions

Johanna Amalia Robinson: Conceptualization, Methodology, Validation, Formal analysis, Investigation, Resources, Data Curation, Writing - Original Draft, Writing - Review & Editing, Visualization Rok Novak: Investigation, Resources, Writing - Review & Editing, Visualization Tjaša Kanduč: Investigation, Resources, Writing - Review & Editing Dimosthenis A. Sarigiannis: Project administration, Funding acquisition David Kocman: Conceptualization, Validation, Investigation, Resources, Writing - Review & Editing, Supervision

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Institutional Review Board Statement

The study was conducted according to the guidelines of the Declaration of Helsinki, and ethical approval for the ICARUS project in Slovenia was obtained from the National Medical Ethics Committee of the Republic of Slovenia (approval nr. 0120-388/2018/6 on 22 August 2018.

Informed Consent Statement

Written informed consent has been obtained from all subjects involved in the study to publish this paper.

Availability of data

The datasets used and/or analysed during the current study are available from the corresponding author on reasonable request.

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3.4 Scientific Article: "User-Centred Design of a Final Results Report for Participants in Multi-Sensor Personal Air Pollution Exposure Monitoring Campaigns"

This section is a scientific article authored by Johanna Amalia Robinson, Rok Novak, Tjaša Kanduč, Thomas Maggos, Demetra Pardali, Asimina Stamatelopoulou, Dikaia Saraga, Danielle Vienneau, Benjamin Flückiger, Ondřej Mikeš, Céline Degrendele, Ondřej Sáňka, Saul García Dos Santos-Alves, Jaideep Visave, Alberto Gotti, Marco Giovanni Persico, Dimitris Chapizanis, Ioannis Petridis, Spyros Karakitsios, Dimosthenis A. Sarigiannis, and David Kocman. The article was published in the International Journal of Environmental Research and Public Health. The article is a result of EU-funded project ICARUS and describes the human-centred approach used in creating the final results report for participants in multi-sensor personal air pollution exposure monitoring campaigns. The article suggests a UCD model and demonstrates the iterative approach and the resulting report comprising planning, researching, designing, evaluating, adapting, and validating. It describes the benefits of co-design, which resulted in a well-accepted and understood final report. The article confirms hypotheses five and six. The candidate conceptualised the idea for the manuscript and the framework, designed pre- and post-campaign surveys, collected user feedback with the other authors, co-designed the focus group, analysed the results, prepared illustrations for the manuscript and wrote the manuscript.

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MDPI

Article

User-Centred Design of a Final Results Report for Participants in Multi-Sensor Personal Air Pollution Exposure Monitoring Campaigns

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Abstract: Using low-cost portable air quality (AQ) monitoring devices is a growing trend in personal exposure studies, enabling a higher spatio-temporal resolution and identifying acute exposure to high concentrations. Comprehension of the results by participants is not guaranteed in exposure studies. However, information on personal exposure is multiplex, which calls for participant involvement in information design to maximise communication output and comprehension. This study describes and proposes a model of a user-centred design (UCD) approach for preparing a final report for participants involved in a multi-sensor personal exposure monitoring study performed in seven cities within the EU Horizon 2020 ICARUS project. Using a combination of human-centred design (HCD), human–information interaction (HII) and design thinking approaches, we iteratively included participants in the framing and design of the final report. User needs were mapped using a survey (n = 82), and feedback on the draft report was obtained from a focus group (n = 5). User requirements were assessed and validated using a post-campaign survey (n = 31). The UCD research was conducted amongst participants in Ljubljana, Slovenia, and the results report was distributed among the participating cities across Europe. The feedback made it clear that the final report was well-received and helped participants better understand the influence of individual behaviours on personal exposure to air pollution.

Keywords: user-centred design; air pollution exposure campaign; report to participants; communication; focus group; design thinking

1. Introduction

The rise of low-cost personal air monitoring devices has democratised environmental health decision making, enabling scientists to involve the public in air quality (AQ) monitoring programmes. The small size of these devices, their low cost, high temporal resolution for data capture and internet connectivity for remote access facilitate their use in large-scale studies of multiple stressors [1,2]. It is known that personal exposure to air pollution depends on individual trajectories and activities [3], and exposure studies have demonstrated the need for data with a high spatio-temporal resolution in order to obtain a rigorous personal exposure assessment [4,5]. Exposure to air pollution is a serious threat to human health, as even low-level exposure to pollutants is linked to acute systemic inflammation and cardiovascular mortality and morbidity [6–8].

Reporting the final results of personal exposure campaigns to the study participants has not always been the practice [9,10], and even if they are, there is no guarantee that the report is comprehensible to the non-specialist. We should also not take for granted the participants' desire to see final data [10,11]. Rather, it is every individual's right to know or not to know [12–14].

The rise of low-cost personal air monitoring devices brings both opportunities and challenges in communicating results. In addition to the challenges brought by the quality of the data [15,16], it is challenging to communicate the significance of specific parameters that do not have established health guidelines or when health effects are uncertain [17,18]. However, risk communication principles can help to frame the messages [19].

Public understanding of science and environmental health literacy is partially acquired through formal schooling, but life-long learning of science topics is also inspired by free-choice learning due to personal interest, need or curiosity [20]. Participatory projects offer a playground for the public to pursue individual learning opportunities and feed their curiosity [21]. Mundane events, such as exposure to low concentrations of air pollution, can, according to Wolff et al. [22], be easily ignored or underestimated. This phenomenon is called probability neglect, which is a bias on people's perception of risk vs. its probability. For this reason, there is a need to involve the public in disputes over inclusive risk governance communication on issues that affect their everyday lives [23]. Involvement will create heightened conceptual awareness, which can help participants make informed decisions [24], and creating communication material that prompts emotional response can shape participants' perceptions [25].

According to Hubbell [26] and Keune [27], challenges in data interpretation highlight the need for a more inclusive two-way (risk) communication between the scientists running AQ exposure campaigns and the public. In order to improve the comprehension of reports and overcome the uncertainties related to communicating AQ information, a human-centred design (HCD) approach can further help to meet user needs and expectations [28,29].

Scientists should not be the only ones deciding what information is provided since the way in which participants interpret information and build contextual awareness, as well as their priorities, skills and needs, can differ from the scientists [25,30]. Co-designing the communication output with the participants can lead to improved environmental health literacy, increasing the message's effectiveness and ultimately influencing behavioural change [31–34]. Public participation in scientific research can also enhance a participant's awareness and knowledge of the subject [35–38].

Using a case study example, in this paper we aimed to develop a user-centred design (UCD) model for information design as a reference for environmental health scientists to effectively communicate results to participants involved in citizen science. Furthermore,

we aimed to meet the participants' needs and increase the participants' environmental health literacy by involving them in three iterative cycles of the design process through surveys and focus group discussion, where their feedback was used to frame and evaluate the content of a final individual results report.

2. Methods

In this section, we discuss the study settings, participants, data collection framework and analysis.

2.1. Study Setting, the ICARUS Campaign

The UCD study described in this manuscript is based on data collected during the EU Horizon 2020 ICARUS project multi-sensor personal air pollution exposure monitoring campaigns. The overarching goals of the ICARUS campaigns were to collect data on external environmental exposure of individuals and exposure determinants by combining location, activity and air pollution data in different microenvironments. The resulting individual exposure was then to be communicated back to the participants at the end of the campaigns. The participants were purposely not shown the data during the campaign because the ICARUS project aimed to apply agent-based modelling [39], and seeing real-time data could affect a participant's behaviour. The project included winter (heating) and summer (non-heating) sampling campaigns, where participants from seven European cities (Athens, Basel, Brno, Ljubljana, Madrid, Milan, Thessaloniki) carried three personal monitoring devices: a portable sensor for particulate matter (PPM), a smart activity tracker (Garmin Vivosmart 3) and a silicone wristband as a passive sampling for organic pollutants. In addition, participants had one static indoor air quality (IAQ) unit (uHoo) for collecting the following indoor air quality parameters: carbon monoxide (CO), carbon dioxide (CO_2), volatile organic compounds (VOCs), particulate matter ($PM_{2.5}$), ozone (O_3), nitrogen dioxide (NO_2), temperature, humidity and air pressure. Participants also recorded their activities, e.g., cooking, cleaning, smoking, in Time Activity Diaries (TADs) for potential sources of air pollution [40] with one hour accuracy. In addition to the silicone wristbands, which provide an integrated information on exposure over the seven days of sampling, all the devices collected data with a high frequency of minute resolution or less. This high frequency enabled deployment in everyday life conditions, although it is known that variation in speed and sensor placement with respect to direction of movement can affect the results [41]. More details on the campaigns can be found in [42,43].

2.1.1. Participants

The ICARUS recruitment strategy included asking primary recruits to inquire if other people living in the same household would also like to participate. The UCD research was conducted amongst all participants in Ljubljana, Slovenia, and who were involved in the pre- and post-campaign surveys and were part of the focus group. The recruitment strategy used in the campaigns enabled a more comprehensive array of participants' profiles, thereby extending the profile of those interested in participating [44]. This meant that vulnerable and hard-to-reach population groups were also represented, e.g., children, elderly, pregnant, low-income families, low educated and those with pre-existing health conditions. The average age of all participants in ICARUS as a whole was 38, with 15% < 18 years, 73% being highly educated and 49% from middle-income families. Table 1 summarises the participant characteristics and distinguishes between Ljubljana participants and the overall participant pool in the seven participating cities (additional information can be found in Supplementary Materials File S1 in Tables S1–S10).

Table 1. Participant characteristics.

	Participants in Ljubljana		Participants in All Cities	
Characteristics	**Total**	**Percentage**	**Total**	**Percentage**
Age				
<18	8	11%	77	15%
18–64	60	82%	398	79%
>65	5	7%	32	6%
Pregnant	1	1%	6	1%
Gender				
Male	39	53%	242	47%
Female	47	47%	269	53%
Other	0	0%	0	0%
Underlying health condition	26	36%	194	36%
Education level of adult participants				
Primary education/Not completed secondary education	4	6%	16	4%
Completed secondary education	9	14%	101	23%
Higher education	52	80%	313	73%
Income level of adult participants				
Lower 25%	7	11%	86	20%
Average (25–75%)	37	57%	183	43%
Upper 25%	16	25%	107	25%
Unknown	5	8%	54	13%

2.1.2. Research Team

The ICARUS research team undertaking the campaigns and designing the final results report consisted of international experts from various backgrounds. The case study researchers were mainly from natural sciences, e.g., chemistry, physics, environmental sciences, environmental epidemiology, exposure science, environmental and chemical risk management and geography. Several had practical expertise in social sciences and science communication. Moreover, the team behind the final results report also included database management experts, who wrote the codes to generate the reports [45]. The team's diversity enabled different perspectives to be taken into account and sufficient collaboration over design, including, for example, communication of user needs and feedback and implementing trade-offs while considering technical limitations and meeting the objective of the report.

2.2. User-Centred Design

Individual exposure is multiplex as the concentrations of some air pollutants may vary over small spatial and temporal scales; thus, communicating air pollution exposure to non-experts requires a holistic approach. We combined methods and ideologies from a human-centred design (HCD) landscape to form a user-centred design (UCD) model to design the communication information material. For simplicity, we referred to our proposed approach as UCD despite it having aspects from other related approaches. Our UCD followed the activities of HCD with aspects of human–information interaction (HII) [24], six design thinking principles [46] and practical recommendations from other case studies, e.g., Golumbic et al. [47]. Unlike an HCD framework, which focuses on improving interactive products, services and systems, the human–information interaction approach focuses on the (communication of) information itself [24]. In addition, design thinking ideology is a user-centric approach to problem solving of complex and multifaceted issues [46].

The user-centred design was implemented as a life-cycle model (Figure 1) and incorporated in the project schedule with participant feedback as part of an iterative process to improve the report's content. The participant involvement was implemented in steps two,

four and six in order to define their needs, to adjust the report according to their feedback and to validate the final product.

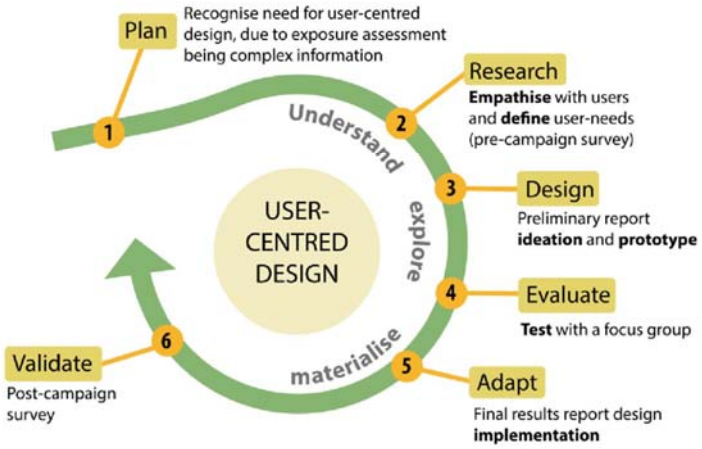

Figure 1. A life-cycle model of the UCD results report in the ICARUS multi-sensor personal exposure campaign.

The six applied principles of design thinking include the following: empathise, define, ideate, prototype, test and implement [46] (bolded in Figure 1). The steps in implementing the UCD model included:

Step (1) Defining the context of use and recognising the need for UCD, taking into account the complexity of individual exposure data;
Step (2) Identifying and understanding user needs and preferences by obtaining feedback early on in the process through a pre-campaign survey (see Supplementary Materials File S1);
Step (3) Discussing visualisation ideas and creating a prototype report (Supplementary Materials File S2);
Step (4) Creating a focus group ($n = 5$ individuals), testing the preliminary design and facilitating fine-tuning according to group feedback (Supplementary Materials File S2–S4);
Step (5) Adapting visualisations according to the focus group results while taking into account technical requirements (Supplementary Materials File S5);
Step (6) Validating and assessing whether user requirements were met with an online post-campaign survey. (Supplementary Materials File S1)

A simplified version without details of the case study is provided in the graphical abstract for researchers to adapt.

2.2.1. Plan: Recognizing the Need

In the ICARUS campaign, data were collected at high spatial-temporal scale, e.g., minute accuracy, and from various sources, e.g., indoor and outdoor together with GPS coordinates, creating a multiplex dataset. For maximising the communication output, the information must meet individual needs, which is achieved by upfront analysis of participants' information needs and goals [48]. A design that complies with user needs instead of assumed requirements was decided upon and developed using principles from the HCD landscape. This also meant involving end-users in an iterative evaluation process involving prototypes and producing feedback until the design met the end-user requirements. Systems that are designed without end-user input might fail to provide comprehensive information.

According to HII concepts, the results report needs to communicate and enable the participants to understand the concept (e.g., background), situation (e.g., individual expo-

sure) and relationships and interactions (e.g., the type and level of physical activity and air pollution levels) [24]. When the participants interconnect pieces of information, they will become aware of the different behaviours or actions that may be affecting their exposure. Similarly, in inclusive risk governance, a person will seek to understand the risk from their perspective [23]. That is why the results report should be designed to address the above elements. Displaying simple data, e.g., raw values, does not enable an inexperienced participant to comprehend the situation, whereas providing information with more intelligent output, e.g., post-processed information, can add context and help in understanding more complex relationships [24,49,50]. According to Albers [24], a complex communication situation should include the proper amount of information to maximise the communication output. In addition, jargon should be avoided in communicating scientific results to the public to ensure comprehension and readability for a wider audience [51], which is why the comprehension of the text in the report had to be tested amongst the participants.

We decided to study user needs regarding data visualization through a pre-campaign survey, fine-tuned within a focus group and validated with a post-campaign survey. Data visualisation refers to the representation and presentation of data to facilitate understanding [52]. From existing guides, it is known that using conventional tables or lists to display complex datasets can make it difficult to detect patterns, and other data visualisation types such as charts are preferred [25]. The visualisation solution should be trustworthy, accessible and elegant [52]. According to Allen [25], conceiving, creating, interpreting and responding to visualisations is a dynamic, complex space, and he suggests that visualisation practices influence a participant's engagement. Similarly, Wong-Parodi et al. [53] emphasise that the most effective visualisations are those coupled with messages calling for action to reduce individual risk. The above speaks for the importance of including a list of recommended actions in the final results report, upon which individuals can act.

Previous research [54,55] has indicated that oversimplification of air pollution in the form of air pollution index values might not be the most interesting for the participant since it does not provide a sufficient level of fine-grained information and might not always be representative. Alternatively, the use of low-cost personal air-quality measuring devices provided an opportunity to delineate and visualise personal exposure levels within short time intervals, highlighting peak acute exposure levels that occurred throughout the week. In addition, the collected GPS and Time Activity diary (TAD) data could help identify exposure pathways at specific times and locations and help formulate more accurate individual exposure profiles.

2.2.2. Research: Pre-Campaign Survey and User Needs

Defining communication value is a difficult task [24]. We approached this challenge by mapping the user needs with a pre-campaign survey (n = 82) conducted face-to face, in an interview-like setting and recorded on a paper form, at the participant's house. The survey mapped the user needs and preferences about visualisation and their motivations, risk perception and behavioural intentions. Part of the dataset was derived from surveys analysed by Robinson et al. [43].

At the start of the campaign, participants were asked to provide suggestions on the kind of information and visualisation they wished to receive in the final report (Tables S13–S14 in Supplementary Materials File S1). It was felt important to provide the participants with the opportunity to explain their suggestions for visualisation ideas to discover features or innovative ways of displaying the data. In addition, we asked how much they would be interested in a set of pre-described ideas of data display (Tables S15–S17, Figure S1).

Trust is a significant factor in communicating scientific results to the public. It includes both trustworthiness towards the data, e.g., its uncertainty, and in the ones communicating it [25,52]. In the light of the new European General Data Protection Regulation (EU GDPR 2016/679) [56], we wanted to assess participants' trust concerning personal data management (Tables S28 and S29 in Supplementary Materials File S1).

The paper forms were digitalized, and the findings were analysed in Excel, where open-ended questions were coded and suggestions listed and general statistics and frequencies were analysed for the Likert type questions.

2.2.3. Design: Preliminary Report

The ideas for the preliminary report were drafted based on initial user needs and collaborative efforts of the project consortium. Some visualisation ideas and decisions were discussed over email, online conference meetings and in face-to-face project meetings. We also included a hands-on workshop about data harmonisation, data visualisation and data quality. Ideas from different participating cities were discussed, and it was decided to organise a focus group to evaluate the preferences and comprehension of different visualisation options amongst the participants.

Low-cost sensors come with a particular uncertainty, and missing data from malfunction or other causes is an issue that scientists need to consider to not disappoint the participants [54,57]. Adding information about technical uncertainty is considered a positive practice when communicating the results [58]. The challenges were identified, and steps for data harmonisation, cleaning and fusion with an R script and models to identify outliers and fill data gaps were established [45].

A preliminary report was drafted and generated in Ljubljana. Pre-existing guidelines and good practices were considered, and trade-offs were discussed while accommodating the initially mapped user needs and visualisation suggestions from the other participating cities. Deciding on a design was a difficult task, as there is no one-fits-all solution. In addition, different participants might have a different level of numeracy, and sometimes simplification of the message is necessary to make sensor data more comprehensible [26].

2.2.4. Evaluation: Focus Group

A focus group is an in-depth group interview with discussion and enables a collection of views about a specific subject of concern. It is used to assess needs, preferences and attitudes of participants, and the results can help in decision making. An optimal number of participants in a focus group is between five and eight [27,59]. This allows gathering insights from all participants while maintaining control over the discussions. In larger groups, this becomes difficult and limits opportunities for those who would speak less.

Invitation to the focus group was sent to 12 participants. Following Keune's [27] and ISO HCD 2010 recommendations, participants for the focus group were selected to be representative and those who also showed interest to be actively involved. Only adult participants were invited. The focus group was organised at the onset of the SARS CoV-2 pandemic in Slovenia, causing some to decline to attend an in-person event. However, a final number of five in-person attendees is, according to Virzi [60], sufficient to identify the majority of usability issues. Some participants suggested providing feedback electronically instead, and we received 19 answers to the same questions discussed during the focus group through an online questionnaire.

A one and a half hour long focus group meeting was organised (Table 2) to ascertain whether participants correctly perceived the draft visualisations of the results report and provide additional user feedback. The displayed graphs and other visualisations used in the focus group were detailed and realistic, e.g., anonymous data from actual participants were used. Three members of the scientific project group were present at the focus group, with one acting as the facilitator. The focus group was organised after the sensor campaign and before finalising the participants' results reports. The focus group discussion was recorded, transcribed and translated into English. The main findings were implemented straight away to improve the draft report, while details of the focus group and its findings were summarized for this manuscript. Additional information about the organised focus group can be found from the Supplementary Materials, including the translated transcripts with a list of actions based on the participants' feedback (Supplementary Materials File S3) and

the materials used during the focus group, i.e., PowerPoint presentation (Supplementary Materials File S4) and the preliminary report (Supplementary Materials File S2).

Table 2. Focus group structure.

Section	Theme	Goal	Planned	Timeline in the Recording
1	Welcome and short survey	Flashback paper survey on what participants remember about the campaign	5 min	00:00–04:10
2	Introductory PowerPoint presentation	A presentation about the project and campaign, measurement uncertainties	10 min	04:10–10:15
3	Discussion Part 1	Mapping motivations and expectations on what participants would like to learn	10 min	10:15–11:57
4	Discussion Part 2	User needs: data aggregation in most useful way according to participants ideas	10–15 min	11:57–13:40
5	Evaluation	Comprehension of suggested visualizations (paper survey)	20 min	13:40–32:29
6	Discussion Part 3	Visualization: first suggestions and their comprehension and suggestions for improvements	20 min	32:29–1:07:44
7	Discussion Part 4	Impact on behavioural change and user needs during and after the campaign	10 min	1:07:44–1:18:39
8	Conclusions and socialising	Preliminary observations from the data. Final remarks and farewell	10 min	1:18:39–1:34:41

2.2.5. Adapt: Final Results Report

The design of the results report was refined and improved in response to user-centred evaluation and feedback from the focus group. Any conflicts were resolved considering reasonability, technical limitations and incorrect interpretations of figures (an example report can be found in Supplementary Material File S5). An R script was written to generate the final uniform reports to all participants for all participating cities [45]. The final results report was translated to the different languages by the local case study researchers and sent to the participants by email as a PDF document in April 2020.

2.2.6. Validate: Post-Campaign Survey

The Ljubljana participants received an online post-campaign survey invitation together with the final results report email. The post-campaign survey meant that the participants were able to assess the usability and comprehensibility of the report and provide further feedback to improve similar reports in the future. Participants were then asked how the results had influenced their behaviour and risk perception. Thirty-one participants answered the survey.

3. Results

This section describes the results of the UCD steps two to six, where participant views were used to frame and evaluate the content of a final individual results report.

3.1. Research: Pre-Campaign Survey and User Needs

The pre-campaign survey revealed that the participants wanted both visualisations that provide an opportunity to interpret their exposure and the influence of behavioural choices and also a prescription of activities on how to reduce one's exposure.

A total of 15% of the participants wanted to have all the possible data about their exposure, in either raw format, charts or numerical values (Table S14 in Supplementary Materials File S1). They also wanted a comparison with limit values (12%), comparison with other participants in the same city (11%) and spatial (12%) and time trends (10%). Five percent mentioned that they would like to have text results. Moreover, participants wished to receive data evaluation, conclusions, recommendations to mitigate exposure and information on possible adverse health effects. Nine percent of participants also specified that they wanted to receive the results electronically, e.g., a PDF file, while Microsoft's Excel was suggested for raw data. Eighteen percent of participants were happy to receive just an executive summary. While some hoped to have the raw data, others preferred summary data or simple visualisation. Some pointed out that they would like to see any unusual observations.

The participants were especially interested to know about their personal exposure and the air quality in their surroundings. Some also mentioned CO_2 levels indoors, and several hoped that the results would show how clean the air is in the local area, while others hoped the results would reveal something upon which they could act. The participants also showed interest in air quality and health parameters. The participants were also interested in the accuracy and reliability of the monitoring devices and what happens in the case of "bad" data.

The following are specific quotes from the participants:

LJU_P033: *"Similar to doctors reports, value ranges and limit values, data tables, textual and charts with explanations."*

LJU_P093: *"Pollution levels and physical activity displayed with time trends with short time intervals (1s), in electronic form, in data tables."*

The participants repeatedly mentioned that they wished to see the results before taking any action and would prefer to see the data in real-time. All the participants wanted to receive the results report and hence pursue their right to know.

From the preliminary interest list (Tables S15–S17 in Supplementary Materials File S1), on a scale from one to five, the participants expressed interest in Where your maximum/minimum air pollution exposure occurs (Mean 4.72) followed by During which activity you are most/least exposed to air pollution (4.76), Suggestions to reduce your air pollution exposure (4.55), Individual pollution concentrations (4.47), Which transportation mode contributes the most/least to your air pollution exposure (4.39), Map of your weekly whereabouts with indicative colour codes (4.37) and Is my weekly dose of air pollution less or more than others who participated? (4.36).

Each participant held a prior perception of the level of credibility of the scientific institutions that conducted the case studies and communicated the results. None of the participants thought their data would be handled inappropriately, with 79% being confident that the researchers handled their data appropriately, while 21% did not know or did not answer the question (Tables S28 and S29 in Supplementary Materials File S1).

3.2. Design: Preliminary Report

Ideas for visualisations for the final results report were prompted from all participating cities, and some distributed preliminary results to the participants soon after the end of the campaign. For example, in Brno, short reports, following a basic report structure providing available data from the commercially used sensor devices, were created. They included an introduction to the measured parameters and abbreviations, followed by tables with mean values from the whole campaign and participants' decile within the Brno campaign. Each page clearly stated that the data were not certified, accredited or validated and served only as a visual output from commercially available devices. Data from PPM devices were provided upon request. Some of the earliest visualisations in Athens included summary statistics and box plots for individual indoor pollutants. Data were cleaned by removing NA values, duplicate values and other issues. Average daily and weekly concentrations of PM from the summer and winter campaigns were also used, and different fractionations of

PM (PM_1, $PM_{2.5}$ and PM_{10}) were displayed per participant for each microenvironment and activity, e.g., cooking, cleaning, smoking (derived from TADs). In Basel, for example, the preliminary report included a map of PM_{10} data created upon request with GPS data for times when participants were not at home. Follow-up calls and emails from participants in Basel and other cities demonstrated effective communication and further interest in the topic. Individuals in different cities discussed their indoor air quality values during the final visit in households when devices were collected. Some participants also suggested checking specific PPM levels for time periods where they assumed they had been highly exposed (e.g., during campfire). In Milan, winter vs. summer visualisation of the average concentrations of PM_{10} was used.

It was agreed to use a uniform format for the final report for all cities. The report's structure was planned to include a general introduction, an overview of the air quality in households, a personal situation exposure assessment, and generalised recommendations. Creating a report with data displayed straightforwardly without giving absolute values was agreed upon, and displaying daily averages were preferred. Comparison with limit values was a subject of discussion since it could provide valuable information to the participant, although it could confuse participants due to the uncertainties in the measured data and the different time scales of the limit values. Uncertainties and the use of relative vs. absolute values were discussed. In Ljubljana, previous validation studies showed that absolute values from the IAQ sensor should not be used, while absolute values from the particulate matter monitor could [61]. The problem with the validity of absolute data from the IAQ turned the decision to provide heatmaps rather than measured values. Information about inhalation rates and intake dose assessment was not considered a priority for the report, and regarding exposure, it was decided to provide information by specific location (e.g., home vs. commute vs. work) rather than by physical activity.

3.3. Evaluation: Focus Group

During the focus group discussions, the participants had issues deciphering some of the suggested visualisations due to missing labels and different axis labels, which made comparing different charts complicated. Supplementary Materials File S3 (chapter 4. List of suggestions from the participants and actions taken based on them) contains a more detailed description of visualisations that were difficult to comprehend and taken to improve them.

3.4. Adapt: Final Results Report

An example report can be found in Supplementary Materials File S5. The adaptation of the results report included compromises between participants' requirements and technical limitations. The PM, for example, was considered an important parameter and was presented in different charts. In the most basic form, using daily averages together with WHO guidelines were displayed. A more fine-grade visualisation was not feasible due to space limitations and because WHO guidelines for $PM_{2.5}$ and PM_{10} only include daily values. In addition, charts with additional context were prepared and included specific activities or locations of the participants and heartbeat data with a more fine-grade hourly data. Winter and summer campaigns were plotted separately.

An example of adjustments to the visualisation based on the focus group discussions is displayed in Figure 2, while the whole final report can be found in Supplementary Materials File S5.

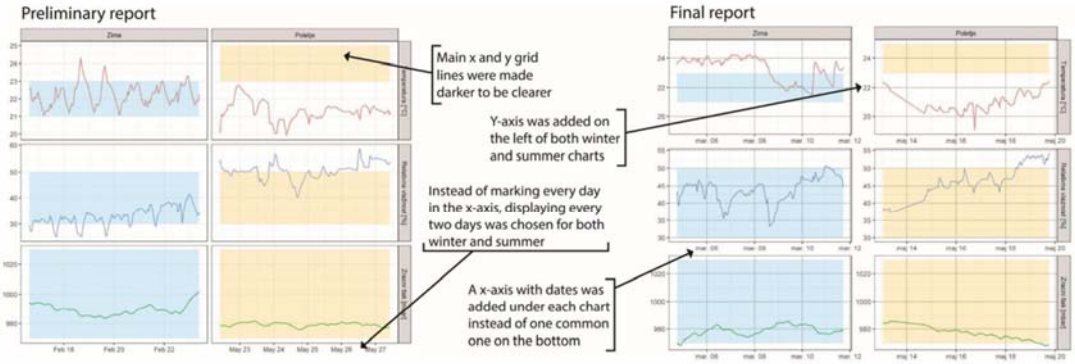

Figure 2. Example of adjustments to the visualisation based on the focus group discussions. Final figure caption: "Meteorological conditions in one household during the winter (**left**) and summer (**right**) campaigns. The top plot displays temperature, followed by relative humidity and air pressure. Optimal ranges for all three parameters are also displayed and coloured in yellow (summer) and blue (winter)".

QA/QC steps to remove outliers with extremely high concentrations (over 240 $\mu g/m^3$) were performed in R for PM data following predetermined criteria of consecutively occurring measurements, as reporting these types of erroneous results could have been worrying for the participants. Conversely, removing outliers might have unintentionally underestimated someone's exposure to severely high concentrations, e.g., time spent in a nightclub where smoking was permitted. In most cities, only a small number of the participant's (up to 12%) data had significant outliers, i.e., over 10% of all measurements of PM_{10} were more than 240 $\mu g/m^3$, and only the participants can know what they did when the peak values occurred. The codes were checked and revised for flaws such as double reports, mixed summer/winter seasons, wrong participant numbers, typos and the deletion of some lines. The individual reports were still manually checked for any mistakes before sending them to the participants. The results from the silicon wristbands were not distributed in the final results report as the laboratory analyses of passively sampled organic chemicals were still ongoing.

The structure of the report (visually displayed in Figure 3) followed the planned initial structure, and the text, e.g., in the introduction, was fine-tuned collaboratively with researchers from participating cities. The final report (Supplementary Materials File S5) was 11 pages long and included charts (histograms, line columns), tables and heatmap visualisations with colour-coded additional information of activities and guideline values or optimal ranges where applicable.

3.5. Validate: Post-Campaign Survey

The post-campaign survey validated the usability and comprehensibility of the report amongst 31 participants.

An emotion of surprise was present in the group who evaluated the final results report (Tables S18–S20 in Supplementary Materials File S1). Almost half (48%) were surprised by their data, especially about different from expected concentration values of air pollutants.

The majority (79%) indicated that the report was useful, easy to understand (79%) and contained the right amount of information (Tables S21–S25 in Supplementary Materials File S1). One-third (35%) of the participants also gave suggestions on how the report could be improved (Tables S26 and S27 in Supplementary Materials File S1). Some suggested simpler infographics for laypeople, while others would have liked more detailed ones. Suggestions for improving the charts included a better colour scale for activities and more charts displaying activity data. They also suggested the results should be displayed

spatially, a comparison with other participants, an online introductory video, a public web page and an invitation to all participants to a dissemination event.

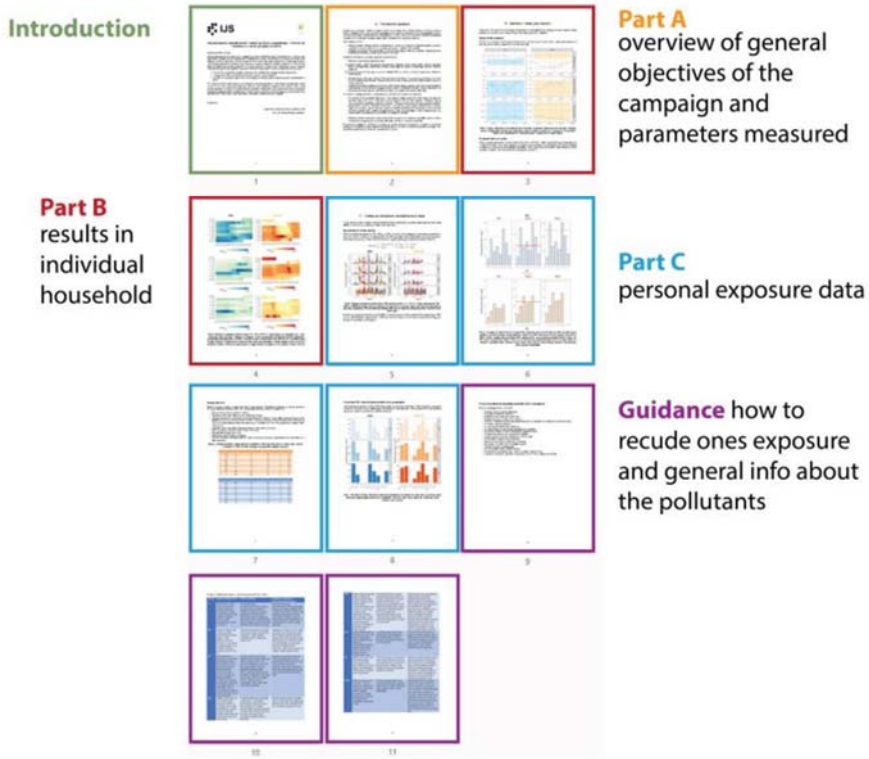

Figure 3. Structure of the final results report.

The participating children received help from their parents to interpret the research results. In some households, the results and participation had created further discussions beyond family units. The results report was well-received both in Ljubljana and in the other participating cities. Post-campaign communication continued in all cities, and some participants reached out to the research groups to ask for additional visualisations, e.g., trajectories along their cycling trip. In some cities, e.g., in Brno, a public presentation of the results was organised, where all participants were invited.

Due to the nature of low-cost sensors, some sensors failed to record any data while others malfunctioned, resulting in data gaps. The result was that some participants' reports had missing data resulting in blank charts, which left participants feeling disappointed, especially given all their effort. Equally, many understood the nature of low-cost sensors as a possibility at the beginning of the campaign. Some participants, both in Ljubljana and in the other case study cities, contacted the local researchers to ask about the missing values. Others wanted to know, for example, if they were above or higher than the study average or to explain to the researchers the reason for the observed peak values in their data.

Mitigation guidance was presented at the end of the report. Over half (58%) of the participants reported having made behavioural changes, and 36% thought their air pollution exposure was higher than expected.

4. Discussion

Deciding on a universal design for a final results report is a challenging task. Individual characteristics influence how participants interact with health information, making it difficult to meet everyone's needs [62]. Information exists within a continuum, and individuals interpret and reflect on the information based on their own experiences, feelings, assumptions and beliefs [24,25]. This was also emphasised from the participants' side during the focus group discussion: "It was also interesting to see how some of us understood, while others did not. You could see how all of us look at things differently."

The involvement of the participants in the three report design stages enabled us to fine-tune the details and make sure the final report was fit-for-purpose and comprehensible to the majority of participants. Another reason for using a common approach in the reporting on the European scale was to create a harmonised analysis of the data itself. Involving participants in the design provided meaningful input to the content and provided a user perspective. Adding another cycle before distributing the final report would most likely further increase the comprehensibility. An additional step would be to target different sub-groups specifically, e.g., children, elderly, health-suppressed individuals, participants with low socioeconomic status (SES) or the highly educated, by using personas to divide the subgroups and adjust and enhance the communicated message accordingly. In addition, to improve the report using UCD, including a science communication expert to assist in designing the communicated results would be beneficial [63]. This inclusion of an expert would also contribute towards higher environmental health literacy [64].

The focus group enabled us to explore the report's content in depth through group discussions, e.g., comprehension of suggested visualisation and possible misunderstandings, feedback for improvements, and refining user needs at the end of the project. The discussion also reflected their environmental health literacy. A focus group method enabled us to obtain a common impression and in-depth information in a short time. The involvement of the participants enabled us to frame and formulate risk information about their exposure to be communicated in a way that a participant could comprehend.

The participants' needs, feedback, and suggestions reflect the users' capabilities, characteristics, and experience, agreeing with ISO recommendations. The detailed user studies were conducted in Ljubljana, but given that the report's reception in other participating cities was positive, the design was well suited to the community that participated all across Europe. Hence, similar design aspects could be implemented elsewhere.

Effective and efficient communication methods based on data from low-cost sensor devices is an ongoing debate. The study advances the current practice in environmental health communications where results of an exposure study are communicated retrospectively to the participants by providing insights and evaluations of user needs through an UCD process. Careful planning, time and effort is needed to perform a UCD study to meet the user needs while adapting to the challenges and limitations of the technology and information design. We illustrated increased understanding of user needs and demonstrated an approach to support and validate it.

Being trustworthy is also a factor. The majority of the participants expressed confidence that we would handle data appropriately, while the rest were unsure or did not answer the question. None explicitly expressed "worry".

The report was considered lengthy at 11 pages and was one of the issues discussed while preparing the report. However, the participants confirmed that the amount of information was "just right", which is appreciated, especially at a time when people are experiencing information overload [65]. Despite this, some participants preferred timelier reporting.

The final results reports were provided almost a year after the campaign had finished. While this can be unfavourable, they would have been less relevant for the participants if delivered earlier and without going through a UCD process. If data were shown in real-time, or the report was sent earlier, we could have increased the communication value, as communication needs to be relevant and on time [24,66]. Thus, this would increase their

intention to change behaviour [43]. A step forward would be to create an online version of the results report, allowing participants to change variables to suit their contextual needs, facilitate comprehension and nurture curiosity. The number (n = 31) of the post-campaign surveys reflects how some interest was lost compared to the pre-campaign survey (n = 82). In most cases (i.e., in 28 households), only one person from the household answered the post-campaign survey instead of the whole family, which can explain this difference.

Using hourly and daily averages instead of higher time resolution visualisation, we could not provide detailed information about each activity, location and time. The final interpretation of the results was left to the participants, who had information about their specific activities if they still remembered. Automating the information content related to individuals spatial location and activity mode using data mining techniques, which classifies relative location and activity using supplementary information available, could further improve the interpretation of the results and remove the burden of filling out time activity diaries and remembering details [67].

Involvement in the process leads to greater understanding, and consequently, appropriate action [27], e.g., as many as 58% reported behavioural change in the Ljubljana case study. Sensitive individuals, especially those with underlying health conditions, received an opportunity to examine possible triggers if peak values were present during their study period. It is considered good practice to communicate uncertainties, e.g., sensor performance or outliers that over- or underestimate a participant's exposure.

Collecting data on their immediate environment and receiving results about their living environment must be more motivating than campaigns that aim to collect air quality monitoring data on the city level. Robinson et al. [54] concluded that participants in an air quality study are more motivated to learn about their immediate environment and hence more likely to change their behaviour when provided with more targeted results about their living environment. Instead of the mass communication of aggregated results, the individuals received only their results, although some would have liked to see their situation compared to the other participants.

The WHO 24 h mean guideline values for some of the used AQ parameters were updated after the project had ended, e.g., $PM_{2.5}$ was lowered to 15 from 25 $\mu g/m^3$ and PM_{10} from 50 to 45 $\mu g/m^3$ [68]. Future studies could study the risk perception of exposure to air pollutants in the light of measured AQ values and the new WHO guideline values.

5. Conclusions

This work describes and proposes a model of user-centred design (UCD) of a final results report and demonstrates a deliberate, collaborative science communication effort. The participants of the multi-sensor ICARUS campaign in Ljubljana, Slovenia, were included in the design of a final results report during three stages of the design process. The report was individualised, self-descriptive and intuitive, fit for purpose, met user expectations and provided an opportunity to learn something new.

The UCD model is a result of lack of existing UCD models for results reporting in environmental health studies. The developed UCD model is a combination of principles and practices from the HCD landscape, design thinking and HII, the latter focusing on communicating complex information where the user makes decisions about a complex situation. The UCD approach was incorporated into the project schedule and involved collecting information on user needs and gained feedback about preliminary design solutions from an end-user perspective to improve the final design and evaluate and validate whether user requirements were met. The information presented was subjected to a series of trade-offs, to be understandable by the general public, yet not overly simplified, which would underestimate the complexity of the information, and hence to take into account the underlying situation, people's needs and the way they come to understand the information provided. Using a UCD approach, we co-created usable content, enabling participants to comprehend the complex topic of personal exposure that they could use to make informed decisions, both being essential aspects of environmental health literacy.

By asking participants to provide input, we were able to better meet the participants' needs, which probably influenced the high acceptance of the information. By involving the participants in co-designing the communication output, we increased the inclusiveness of the project from traditionally contributory type ones. We recommend others to use the UCD approach to democratise science and to involve the participants in co-creating complex information.

The report provided both options to examine the results in light of established air quality standards and display individual levels of exposure for the study period. By providing several visualisations, we addressed multiple goals and the motivational drivers of the participants before their involvement. Carrying sensors in places where official air quality monitoring does not extend, e.g., at homes and in private cars, enabled the participants to understand personal exposure. The communication was effective, since it prompted a change in behaviour in the majority of the participants. This finding shows that lived experiences and co-created communicated material increases environmental health literacy by increasing the interest, awareness and understanding of the particular topic leading to taking action [32,69]. It also conforms with other literature on behavioural change [53,70], which also emphasises that information about a risk to air pollution exposure on its own is not as powerful. By providing each individual with a set of sensor devices, we enabled them to experience the air quality first-hand. Projects involving participants in collecting data should use the opportunities modern technology provide to grant the participants access to real-time (instantaneous) data in addition to online visualisation and self-exploration of data.

Supplementary Materials: The following are available online at https://www.mdpi.com/article/10.3390/ijerph182312544/s1, Supplementary Materials File S1: Data analysis, Supplementary Materials File S2: Printed materials, Supplementary Materials File S3: Transcript of the voice recording and summary of changes, Supplementary Materials File S4: Focus group PPT, Supplementary Materials File S5: Example report.

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Chapter 4

Conclusions

The presented thesis aimed to evaluate the user experience (UX) of novel air quality sensing technologies for citizen engagement in environmental health studies. It is argued that the definition of fitness for purpose, as it is currently used in the literature, should go beyond the technical capabilities and consider social aspects. With ethnographic user research, the presented work articulates the perspectives and gives a voice to the participants of two environmental health studies while providing insights into their participation experiences, needs, expectations, motivations and behavioural changes. The findings will help to understand to what extent the low-cost sensor devices can be used in environmental health studies and suggest adaptations to current work practices in light of co-design. The main conclusions from four manuscripts (see Chapter 3) are further summarised below, following the hypotheses of the dissertation.

In light of hypothesis one, "Prototype low-cost sensor devices are not sufficiently adapted to user needs", both theoretical study and empirical findings emphasised the importance of understanding the participants' motivations to recruit and retain them in the future. As illustrated through two prototype low-cost sensor devices designed for two different studies, this thesis shows how it will reduce user motivation and satisfaction if a design does not meet user needs. This work demonstrates that the low-cost prototype tools used in these case studies were not easy to use when given to participants. They caused frustration and did not enable them to meet their needs and expectations. While it is known that resource limitations in CS projects often require adopting sub-optimal tools, which, however, may come with hidden costs stemming from poor usability and underwhelming functionality, thus reducing volunteers' motivation, the main conclusion in this regard is that the end-users need to be included in the design loop to understand their needs in the earliest stages. It is not enough that scientists alone test and design the tools used in CS projects. Alternatively, not involving the citizens in the feedback loop might make the projects rather contributory ones in Haklay's classification. In contrast, the general evolution of CS projects goes towards more collaborative projects. Using plug-and-play type devices would, however, enable the participants to better ideate and execute research questions with or without the help from researchers, rather than merely contribute by carrying the devices.

The ICARUS case study confirmed the second hypothesis, "Commercial low-cost sensing devices are more readily accepted amongst participants than prototype ones", as both types of devices were used. It was clear from the CITI-SENSE case study that the prototype technology was not yet ready for unobstructed use in CS projects, which was later confirmed again in the ICARUS case study. This finding reflects the lack of dedicated UX design activities integrated into the project structures since usability

cannot be achieved without a user-centred process. The theory supports re-using tools that are known to work, and to avoid reinventing the wheel in every project. The theoretical study gave further insights which functional features of CS tools fulfil and nurture participants' motivations and expectations. Moreover, the results confirm that the tools need to be user friendly, self-intuitive, unobstructive and cause as little interference to the participants' everyday life. Plug-and-play devices are desired which do not require any interference from the participants.

Regarding the third hypothesis, "A positive user experience will positively influence user motivation and satisfaction", it is possible to approach it from both directions. The lack of efficiency in data flow proved to be demotivating. If data display did not meet their expectations, i.e. in the case of APIN, which did not change regardless of whether the participant was in a forest or along a busy street. Some even decided to stop using the device after too much struggle. On the other hand, the experience of participation per se was seen as positive and motivated and inspired the majority of participants to reduce their personal exposure to air pollutants. In addition, the case studies also revealed an important aspect of the multi-motivational nature of participants, i.e. how a combination of altruistic and egoistic motivations is beneficial. Namely, even if the technology fails, the participants would still have fulfilled their desire to help science and society, although failing to collect data makes them apologetic.

The above overlaps with the fourth hypothesis, "Participation in environmental health studies as a sensor device user causes participants to adopt pro-environmental behaviour." In addition, reporting results in real-time would further promote pro-environmental behavioural changes, while not seeing data (as in the ICARUS case study) inhibited participants to implement changes based on their immediate air pollution exposure. The positive environmental change could be seen in more ways. First through individual behavioural change, and secondly through social network championing, changing collective or individual practices. More than half of the participants talked with someone about their results, and hence, generated environmental impact through social network championing. This was more obvious in ICARUS case study, where the recruitment strategy also included family members of first recruits.

The fifth hypothesis, "Participation in environmental health studies increases the participant's knowledge and interest in the subject", was studied both from the point of view of their motivations, risk perceptions and behavioural changes. The presented participatory projects offered a playground for the public to pursue individual learning opportunities through hands-on experiences and feed their curiosity, e.g., experimenting with how their daily activities are related to air quality (e.g. opening a window) while also providing more realistic exposure estimates. Participation alone prompted the participant's intention to change their behaviour even before they had access to the data. Their participation made them "think". Among others, participants' motivations were to learn more about their living environment or help science. The participants' participation enabled them to explore their living environment as the data collection took place in their everyday environment. The results show that also a seemingly crowdsourced project can still meet all the ten criteria of good practices of a citizen science project, which we also demonstrated in the ICARUS project. Despite ICARUS project being characterised by a lower level of participant involvement than CITI-SENSE project, they aligned with the ten principles of citizen science. They enabled the public to participate in and learn from the project. The fifth hypothesis is in line with the first ECSA principle of "generating new knowledge or understanding".

With the sixth hypothesis, "Including participants in the design process of results report leads to increased use and understanding of the report," an iterative user centred design cycle was introduced. The final feedback received made it clear that the final

report was well-received and helped participants better understand the influence of individual behaviours on personal exposure to air pollution, while during the design of the report, the participants pointed out which aspects were difficult to comprehend. In addition, the displayed information needs to be understood and made sense of by the participants, i.e., participants want to derive personalised information from the data, enabling them to evaluate their risk. To achieve meaningful data visualisation, users need to be involved in the design of the products to find a suitable fit that serves the community of users.

The methodological contribution of this dissertation highlights the importance of additional user research and evaluation in environmental health studies that utilise low-cost sensor devices since the UX and UCD methods help improve studies and the technologies used. Both empirical and theoretical evidence from this thesis advocates the design of CS tools that meet the needs of its end users. This thesis additionally demonstrated and validated meeting the user needs with the user-centred design of a final results report for participants in a multi-sensor personal air pollution exposure monitoring campaign. This dissertation presents important empirical evidence of the pitfalls in design and other challenges that limit participant engagement throughout the project life cycle.

Moreover, the presented case studies and monitoring technologies have limitations to broader societal applications. For example, the LEO was a prototype not capable of capturing fine-grain air pollution important for human health. Also, the ICARUS case study was focused on personal exposure, especially in the home environment. While the participants also carried a PM sensor, capable of a more detailed description of air pollution in the outdoor environment, the participants received the results later, rather than in real-time, which can demotivate participants to take action in local policymaking. Also, in addition to the devices' accuracy issues, the type of data produced by personal sensor devices might not be appropriate for evidence-based policymaking, as it is too individualised. Only the person carrying the sensor knows the specific circumstances that elevated their pollution levels. However, if such data is used to support validation of exposure assessment in modelling, it could indirectly support decision making.

One of the limitations is related to the fact that the case studies were part of the larger projects, and hence the pre-design of the case studies had happened at a higher level. However, adding user research aspects to a case study with in-depth feedback loops, e.g. additional surveys and interviews, enabled the user experience analysis of novel air quality sensing technologies for citizen engagement.

People with lower literacy or self-efficacy would have most likely had even more technical issues operating the devices, which suggests that the development of such devices should need an even more user-centric approach. Such approach could on the one hand, facilitate the uptake across diverse profiles and socio-cultural backgrounds.

A relatively small sample size did not allow proper (statistical) evaluation of differences in outcomes between different groups; neither was it a focus of this thesis. However, with the help of unique participant IDs, the individual before-after answers could be matched. The small size of the presented projects enabled in-depth interviews and open-ended questions instead of less insightful large datasets, which might have had more statistical power. Moreover, the aim of this thesis was not large scale campaigns, which on the one hand could have led to a larger impact in terms of reaching more people who could change their behaviour, but rather to study whether and what kind of changes we can observe with the participation and used technology.

In addition, the level of time investment and commitment, e.g. the sensor caring and wearing and the assets required to participate, e.g. owning an Android smartphone or having constant Wi-Fi connection at home on their own already, can pose restraints on

who would or could participate. On the other hand, the data collection nor meetings with scientists generally didn't require additional (travel) costs from participants, as the data collection happened alongside their daily lives and meetings (with the exception of a focus-group discussion) took place either at participants' homes or at their work-places and in that sense did not introduce inequity to participate.

Inclusion is also about understanding and learning from the target audience. In this sense, by including the end-users in the design loop, we have increased the inclusiveness, as scientists should not be the only ones determining the features of the tools.

4.1 Implications for Practice

This research serves as information for scientists developing the sensors and those applying them in environmental health studies, including citizen science projects and epidemiological studies and advocates attitude change towards UCD. The results suggest that participant perspectives, e.g., user research and human-centred design in related citizen science, health- and exposure studies, should be incorporated. Implementing user research will also require collaboration across disciplines such as the social sciences and usability experts to capture and articulate participants' perspectives not typically studied by environmental (health) scientists and CS practitioners.

Projects that aim at data collection and participant empowerment should allocate resources early on and enable participants to contribute to product development. The level of public participation in scientific research should be matched with intended scientific, educational, social and environmental goals. Projects should also aim to achieve a level of usability of their products, making CS tools easy to use, fit-for-purpose and future-proof allowing participants to reach their goals and feel empowered. Designing better CS tools also saves valuable resources, such as the time and money lost in making a poorly designed device. By involving the user in the development phase, many features that could create issues in the sampling campaign can be avoided. Hence, scientists are encouraged to share their design experiences even from past projects. The broader scientific community can avoid making the same mistakes, i.e., re-inventing the wheel and can learning from best practices.

Environmental health campaigns involving the general public should be aligned with the ECSA ten principles of citizen science. They cover various concepts and good practices reflecting all stakeholders' mutual benefits from the projects. The level at which projects align with the ten principles is open for interpretation. It is also evident that activities can be seen to align with these principles loosely. However, a higher level of alignment could be achieved through more active participation in various activities and roles. This increased participation would enrich data collection, keep participants as equal partners who have a say in how the project evolves, identify and help overcome obstacles crucial for a positive participation experience, and keep them informed throughout and beyond the project's lifetime. It would also provide opportunities to those who wish to participate at a higher level.

It is also important that exposure studies re-evaluate the value of communication and take advantage of the new technology to display relevant and timely near real-time data since participants are eager to receive the results and take action based on an informed decision. Participants have varying information needs and understanding, requiring user studies to achieve tailored and effective environmental health communications. This might be even more crucial amongst commonly unrepresented groups in CS projects. Future studies should integrate inclusiveness in their recruitment strategies to further investigate the needs of different groups.

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This thesis supports the fact that scientists have a moral obligation to participants to acknowledge and compensate them for their participation and the burden of participating. The best way to do this is to meet their needs and expectations and enable them to have a positive experience. In this case, the research should move beyond field trials of testing and demonstrating the performance, as the full potential lies in the public's long-term adaptation of such systems, highlighting the need to make the systems user-friendly and study participants' experience.

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Biography

The author of this thesis, Johanna Amalia Robinson, was born in 1986 in Finland. She obtained her first undergraduate degree as a Bachelor of Engineering in Environmental Technology at the Lahti University of Applied Sciences, Faculty of Technology, in 2009. In the same year, she moved to Slovenia and, in 2010, started a dual undergraduate program in Educational Biology and Geography at the University of Maribor, Faculty of Mathematics and Natural Sciences and Faculty of Arts. In 2015, she obtained her Master's degree from the Jožef Stefan International Postgraduate School titled *Empowerment initiative in air quality*. The same year she enrolled in a PhD program and continued in the IPS Ecotechnology study program while holding a young researcher position at the Department of Environmental Sciences at the Jožef Stefan Institute under the supervision of Dr. David Kocman. During her studies at the IPS, she was involved in various citizen science projects on air quality using low-cost sensor technologies and gained comprehensive knowledge and experience in participatory approaches in environmental health studies. After observing the challenges these projects were facing with the technology, her research has focused on advocating user-centred design and studying user experience and participants' motivation using low-cost technologies and their influence on the vitality of projects. During her studies, she has had the chance to collaborate with several institutions abroad, and spend several months at the Norwegian Institute for Air Research (NILU), Kjeller, Norway, and Centre for Research in Environmental Epidemiology (CREAL, these days IS Global), Barcelona, Spain, strengthening her collaborative skills and knowledge in air quality-related citizen science. She has presented her work at various international and national conferences and workshops and is part of the European Citizen Science Association's working group on empowerment, inclusiveness and equity.