A Citizen Science Approach for Enhancing Public Understanding of Air Pollution

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**Graphical abstract**
Research highlights
- A multi-component citizen science approach is designed for community engagement.
- Our approach revolves around the ideas of inclusion, collaboration and reciprocation.
- Behavioural changes can be promoted using tools like interactive air quality quiz.
- Citizen science workshops can result in establishing community-led air sensing schemes.
- Citizen scientists permit detection of events with wider spatial and temporal coverage.

Abstract
The deterioration in air quality is a challenging problem worldwide. There is a need to raise awareness among the people and support informed decision making. Over the years, citizen science activities have been implemented for environmental monitoring and raising awareness but most of such works are contributory in nature, i.e. task design, planning and analysis are performed by professional researchers and citizens act as participants. Our objective is to demonstrate that citizen science can be used as a ‘tool’ to enhance public understanding of air pollution by engaging communities and local stakeholders. We present a co-creation based citizen science approach which incorporates the ideas of inclusion, where citizens are involved in most of the steps of the scientific process; collaboration, where the citizen scientists define research problems and methodologies, and reciprocation, where citizen scientists share their observations through storytelling. We integrate the use of interactive air quality quizzes, offline questionnaires and low-cost air quality monitoring sensors. The results show that such methods can generate insightful data which can assist in understanding people’s perception and exposure levels at a fine-grained level. It was also observed that community engagement in air quality monitoring can enhance partnerships between the community and research fraternity.

Keywords: Co-creation; Low-cost Sensors; Citizen Science; Interactive Quiz; Behavioural interventions

1. Introduction
Deteriorating air quality is an important problem in both highly industrialized and less industrialized countries (WHO, 2014; Kumar et al., 2014). It is adversely affecting human health and well-being (Ghorani-Azam et al., 2016). Air pollution is a complex mix of particles and gases (Heal et al., 2011). Particulate matter is known for causing cardiovascular and respiratory problems (Brook et al. 2010; Cascio and Long 2018) among people of all age groups (He et al., 2016) and causing environmental damage (European Environment Agency, 2014). To build sustainable cities of the future, it becomes essential to reduce air pollution and raise awareness among people which still remains an open challenge (Silva et al., 2018). This could be achieved by interdisciplinary research and using analytical internet of things framework of smart sensors (Bibri 2018; Bibri and Krogstie 2017). Smart cities would have infrastructures like smart pollution monitoring and sensing systems (Silva et. al, 2012). Raising awareness and creating environmental consciousness (Rickenbacker et. al, 2019) among citizens is of utmost importance to efficiently assess the harmful impact of air pollution on human health and the sustainability of cities.

Most of the official institutions and government bodies use traditional environmental monitoring equipment. Although they are accurate and precise, the number of such monitoring units is sparse (Kumar et al., 2015). To get more fine-grained environmental information, a
citizen science approach is being followed, which involves using low-cost sensors for community engaged environmental monitoring. Such data can be considered as informal environmental sensing data (Kamel Boulos et al. 2011). In most studies involving citizens, environmental monitoring is performed using smart sensors enabled by devices utilizing information and communication technologies (Perera et al., 2014; Chen et al., 2017). Citizen science can be described as a process in which communities and individuals are involved in designing a research question and performing scientific experiments with minimum involvement of professional scientists (Eitzel et al. 2017). Another important part of the citizen science approach is having open software and open hardware. This encourages participation as it enables people to study the devices/instruments easily and make changes and also share those changes with others people as well. It also verifies the approach followed by the researchers, if general public can redo the design and run the software successfully, it verifies the authenticity of the work. Using the data from open portals, the citizens can get involved at an individual or community level and contribute to the campaigns that are carried out by other projects but shared on open data portals (Jiang et al. 2016).

In the past few years, many projects have used citizen science activities to improve citizens’ understanding of air pollution and raise awareness. For example, Chen et al. (2017) proposed an open framework for participatory PM$_{2.5}$ (particulate matter ≤2.5µm in diameter) sensing in Taiwan. The core idea behind the work was to have open hardware and open software tools. It allowed citizen engagement at a grass-roots level. The data quality was verified using anomaly detection tools (Chen et al. 2018) and the PM$_{2.5}$ data was made available to the general public. Later, Jiang et al. (2018) used online surveys to investigate and understand the perception of citizen science communities and experts about environmental issues and sensing data. The main idea behind this work was to integrate official environment monitoring data with data sensed informally by citizen communities and show that formally and informally sensed data actually complement each other. Earlier, Bell et al. (2015) analysed the data obtained through citizen weather stations set up by citizens in the UK. Although a large amount of data was sensed using citizen weather stations, it was observed that instrument biases affected the data as well. In another example, citizen science noise monitoring was conducted by D’Hondt et al. (2013). The work claimed that the accuracy achieved through noise monitoring carried out by citizens was equal to standard noise monitoring. Other works have also been conducted which used citizen engagement and participation to tackle environmental issues: climate change (Hurlbert and Liang 2012), air quality analysis (Paulos et al., 2008; Kim et al., 2013), forecast (Mahajan et al., 2018) and noise pollution analysis (Maisonuneve et al., 2010). Table 1 presents a summary of relevant literature on the application of the citizen science approach for air quality monitoring and exposure estimation. A majority of these works focus on using low-cost sensors to understand human behaviour and perception (Commodore et al., 2017; English et al., 2017; Hubbell et al., 2018; Pritchard & Gabrys, 2016; Willett et al., 2010). A few others have focused on crowdsourcing techniques (Castell et al., 2015; Jerrett et al., 2017; Leonardi et al., 2014; Zappi et al., 2012). Low-cost sensors have been used widely (Heimann et al. 2015; Lewis et al. 2016; Ottosen and Kumar 2019) for monitoring air quality at neighborhood scale as well as city scales. Such an approach generally involves a large-scale deployment of low-cost sensors to gather air quality data for a particular location. The data is then used for understanding the trends in air quality at a finer resolution. However, it has been observed that it is important to test low-cost sensors with reference monitors before using them for field-
studies (Jiao et al. 2016). In another work (English et al., 2017), the authors have described a collaborative air quality monitoring network which employs a community-based air quality monitoring process. However, the individuals and communities are just treated as participants and their involvement is limited to data collection in most of these studies (Schäfer & Kieslinger, 2016; Wiederhold et al., 2013). Here, we adopt an integrated citizen approach which ensures meaningful community interaction and participation. The citizens are no longer just treated as the participants but more like collaborators and are involved in all the steps; from problem formulation and experimentation to results dissemination. This provides new channels for environmental sensing and monitoring. With the questionnaires, we can get an idea about how people perceive a certain problem. However, our approach of equipping the people with low-cost sensors gives them a first-hand experience to define the research problem and design the experiments that they feel could shine more light on existing problems.

We examine the possibility of integrating conventional techniques such as using a questionnaire and interactive quiz with activities such as using low-cost sensors for exposure monitoring to enhance public understanding of air pollution. We identify and discuss the challenges associated with community engagement, low-cost sensor use, data gathering and knowledge extraction. We also recognise the opportunities for developing a citizen science community facilitating co-creation which could potentially raise public awareness about air pollution and allow individuals and communities to reduce personal exposure to air pollution.

2. **Methodology**

Our approach encompasses three basic ideas: (i) Inclusion, which can be defined as a way to encourage participation at the individual as well as community level to foster strong relationships between practitioners and the citizens (Hecker et al. 2018). The key idea is to have an approach which fosters openness and diversity in representation making the scientific process more participatory by including multiple stakeholders. The aim is to involve local communities as well as encourage underrepresented groups to define and investigate the important issues they are facing. The implications of diverse community participation in citizen science activities can be far-reaching. This can lead to a global network of citizen scientists sharing their ideas and data; thus creating a large network of ecosystem monitoring. We use mechanisms such as seminars and citizen science workshops (Section 2.3) to involve people from different genders and age groups and equip them to engage with the subject area and conduct research. (ii) Collaboration, a key aspect of our approach that involves interaction between the researchers, communities and policymakers. The main idea is to provide an environment where communities and scientists can collaborate towards a common goal that further leads to community capacity building. Ideas and resources are shared to support initiatives to address critical problems like air pollution and build inclusive and dynamic communities. (iii) Reciprocation, an important aspect of our approach that involves active debating over key outputs and results dissemination. Engaging citizens in effective communication with professional scientist is one of the key issues for citizen science research. Instead of having series of formal sessions, we followed a storytelling method that promoted interaction between participants and the researchers. The storytelling sessions provided citizens a platform to clearly present their overall experience by contextualizing the story i.e. identifying the aim, understanding the need and identifying the obstacles and finding solutions.
lead the debates and the researchers act as observers and facilitators. This gives a sense of empowerment to the citizens who feel that their opinions and views are heard and valued.

All the three ideas of inclusion, collaboration and reciprocation are inter-related and are important for the effectiveness of our approach. With an inclusive environment, we encourage participation and diversity making sure that even marginalized groups are also included. A collaborative environment fosters the relationship between researchers, citizens and policymakers that provides a platform to share ideas and resources to tackle pressing issues. The results obtained through the collaborative approach are then discussed and debated on to understand the effectiveness of the adopted methods and future course of action.

Figure 1 presents an overview of our co-creation citizen science approach for air pollution awareness and empowering citizens with knowledge for pollution mitigation. We integrated a number of components: (i) an interactive online air pollution quiz which gives the user an estimation of pollution exposure, (ii) an offline questionnaire to get participant’s views and suggestions about the quiz content and design, and (iii) citizen science workshops facilitating air pollution monitoring using low-cost sensors. Co-creation citizen science can help in achieving a wide range of social and scientific outcomes. The citizen science workshops are aimed at citizen engagement and discussion. The questionnaire and interactive quiz help in understanding people’s opinions and suggestions about the technology aspect of citizen science that can be later incorporated for improving the existing design and technological frameworks. The interactive quiz and offline questionnaire were designed for the Guildford Living Lab as a part of EU project iSCAPE (Improving the Smart Control of Air Pollution in Europe) (https://www.iscapeproject.eu/) by the University of Surrey’s team in cooperation with Future Cities Catapult (FCC; London, UK) and Institute for Advanced Architecture of Catalonia (IAAC; Barcelona, Spain).

2.1 Interactive Air Pollution Quiz

An interactive air quality quiz was designed to engage people in a fun way but at the same time passing relevant research and significant information about air pollution in a simplified manner. The air quality quiz, which could be played online (https://quiz.iscape.smartcitizen.me/) as well as using a joystick-based console (Figure S1), allowed the user to assess their qualitative level of air pollution exposure, through answering a number of simple questions as shown in Table 2. To choose the correct tool for engagement and information, we conducted a series of brainstorming sessions and exchanges between the team of pollution, social, data, and citizen science scientists, where several aspects were considered. The basic idea was to have a portable interactive platform to spread awareness about combating air pollution with characteristics such as: playful, informative, interactive, portable and possible to display indoors and outdoors. The interactive display was the most comprehensive solution, including all the above, while guaranteeing the high level of feasibility, together with a degree of replicability and sustainability. The air quality quiz questions were designed in a way so that it can engage people irrespective of their digital literacy or technical knowledge about air pollution (Table 2). The questions were primarily based on both the generic understanding of air pollution and the outcome of our research focusing on local study area, covering topics such as exposure at intersection (Goel and Kumar, 2015), exposure mitigation via green infrastructure along roadsides (Abhijith and Kumar, 2019; Abhijith et al., 2017), exposure to air pollutants during commuting (Rivas et al., 2017; Kumar
et al., 2018) and pedestrian exposure to airborne particles and effect of roadside vegetation (Al-Dabbous and Kumar, 2014; Abhijith and Kumar, 2019). They were simplified to the level where people could easily read and understand. Participants were asked eight questions and based on the answers their exposure was estimated. The questions were designed in such a way that it would give an idea about how people deal with air pollution in everyday life and based on their choices how much are they exposed to pollution. The questions and answer choices are elaborated in Table 2. Depending on their choices, the interactive display provided tips on how to reduce exposure to air pollution (Tables S1 and S2). The interactive quiz system console was initially placed at Guildford Borough Council offices in August 2018 for about three months and was widely used by people. Later, it was placed at the University of Surrey, UK, campus. It was also regularly used during the citizen science workshops (Section 2.3) and other Guildford Living Lab activities such as community events and co-creation workshops. Thus, its widespread use allowed us to capture a wide range of communities.

2.1.1 Technical description of the quiz development and operation

The quiz was designed as a web application using the React Web framework which is a JavaScript library for developing interactive user interface (Gackenheimer 2015). All the content is fully decoupled from the app and stored as a separate JSON file allowing multiple versions or translations of the quiz to be easily built and loaded. The application is hosted in Github (Camprodon and Smári 2019) and served using Github pages, allowing a fast and efficient workflow between developers and researchers providing new content. Participant’s interactions are stored using Google Analytics by making use of the custom event tracking feature. We designed a wooden stand that provides users with a playful interface, inspired by traditional arcade machines, to interact with the quiz. We took advantage of the Gamepad API now supported by all modern web browsers to interface with an off the shelf Arcade USB Joystick Kit. The stand also includes a Raspberry Pi running the quiz web app removing the need for an external computer or an internet connection. In this case, participant interaction data is stored locally as a CSV file by a small Node web server.

2.2 Offline questionnaire for user feedback about the quiz

A short offline questionnaire was designed, based on slight adaptations from Kessel et al. (2018) to understand participant’s views and opinions after playing with an interactive quiz (Table S3). The questionnaire inquired about participants’ opinions regarding general aspects like interface and navigation of the interactive quiz. The anonymity of the participants was maintained and the questions were general and intuitive. The participants were asked in this questionnaire about how they rated the quiz design in terms of the overall interface, ease of using it, content, colours and font size. The response range was from 1 to 6: 1 meant they found it good and 6 meant they did not find it useful. In addition, the participants were also asked to write their suggestions, ideas, and any criticism concerning the quiz, what they liked the most and what bothered them.

2.3 Citizen engagement through iSCAPE citizen science workshop

Figure 2 presents the flowchart of the two citizen science workshops that were organised (in November and December 2018) to facilitate community engagement. These citizen science workshops were used as a tool to build the iSCAPE’s Guildford Living Lab community (https://livinglabs.iscapeproject.eu/guildford/). The citizen science workshops
were organized with the aim of active engagement of people from different backgrounds and age groups interested in sensing air quality using low-cost sensors. As a part of our two citizen science workshops, we distributed ten smart sensor kits to people to do their own experiments. The participants were explained in detail about how the sensors work, how they could use them to get the best possible results and best way to interpret the data. It was observed that most of the participants had a basic idea about air pollution. A brief session was organized during the first workshop in which participants were explained about what PM$_{2.5}$ is and how it varies based on different scenarios (location, day time and night time, weekdays and weekends). The idea was to provide guidance to people so that they could collect, analyse and interpret their data. The participants were provided with the iSCAPE citizen science pack which included the guidance and recommendation pack for successful data collection. The users were made aware that these measurements should not be made for regulatory compliance purposes, given that these were low-cost sensors and data collected was over the short-term. A total of 25 people were recruited using word of mouth marketing and workshop promotion, who participated and debated over key issues related to air pollution and personal exposure during the first citizen science workshop. For the first citizen science workshop, 11 of the 25 total participants provided details about their demographic data. Of these 11 participants, two were in the 18-35 age range, five were in the 36-50 age range, one was in the 51-65 age range, and three were in the 66-75 age range. Out of 11 participants, 8 were men and three women. Five participants were self-employed or employed, 2 were students and 3 were retired, while 1 was a homemaker. Three participants had a Bachelor degree and other 5 held a Master degree, while 3 had other academic degrees. All the participants were locally from Guildford (Surrey, UK) and were enthusiastic about using the sensor kits to monitor personal exposure. Ten low-cost sensors were distributed among the participants during the first citizen science workshop. The citizen science workshop participants came from different backgrounds. Some of them were retired environmental research professionals, some of them were from different communities around Guildford. It was found out that almost all of the participants had a background idea about air pollution and environmental monitoring. We distributed the sensors based on background knowledge of the participants about the sensors and air pollution. They were explained during the workshops about the steps they have to follow for a successful data collection. For some cases where the participants lived in the same neighbourhood, a sensor was given to one of the participants. Our approach was based on environmental monitoring using low-cost sensors and do-it-yourself (DIY) digital platforms (https://smartcitizen.me/). Smart citizen kits were distributed to the participants who used those kits to perform self-designed experiments addressing the broader questions like finding pollution hotspots in their area, quantifying the exposure near traffic lights, personal exposure monitoring indoors, etc. The smart citizen kit 2.0 (Figure S2) with a particle sensor and battery with two mounting brackets, microSD card and a USB cable were used. For the second citizen science workshop, around 30 people participated that included ten people from the first workshop who received the sensors. Citizen scientists who used the smart citizen kits discussed the experiments they conducted, followed by a debate over the results during the second citizen science workshop.

2.4 Data collection and analysis
The data were collected via three main streams, in the form of an interactive quiz (Section 2.1), offline survey (Section 2.2) and low-cost air quality sensors (Section 2.3). The interactive quiz could be played online as well as using a console. The results from online interactive quiz were saved in the online database whereas the results from the console were saved in the Raspberry Pi. Participants who attended iSCAPE citizen science workshops used the sensors for two weeks and conducted their own experiments. Regular reminders and offline communication were done to stimulate responses and the sensors were returned by the participants after the two weeks test period. For data analysis, data visualisation and descriptive statistics, we used statistical analysis tools. The preliminary analysis was done using Microsoft Excel and later it was performed using R Statistical Software (R Development Core Team, 2016). Because of the large amount of data, questions were grouped together which facilitated the interpretation and analysis. The visualisation of the data gathered via the smart citizen kit during the citizen science workshops was realised by a collaboration between FCC and IAAC and was performed using Python programming language (FCC Visualization, 2019).

3. Results and Discussion

3.1 Results of interactive air quality quiz

In total, we received 140 responses which were extracted from the Raspberry Pi of the interactive quiz console. These responses did not include any incomplete quiz data. Based on the participant’s responses, their exposure was estimated at the end of the quiz followed by some tips to reduce their overall exposure (Tables S1 and S2). Figure 3a shows the response of participants in the form of 0 or 1 for all the questions. 0 and 1 correspond to different choices which have been elaborated in Table 2. Figure 3b shows the exposure estimate. The exposure estimate is based on the choices made by the participants for different questions. Each question is based on the general understanding of air pollution as well as the choices which people make in their day to day life. Once all the answers are collected, the exposure level can be estimated. The exposure was put in a range from 0 to 6; 0 being the lowest and 6 being the highest. The quiz had 8 questions in total as shown in Table 2. First six questions were based on the user’s surroundings and the choices user makes in their day to day life and the last two questions were of generic nature to test user’s knowledge about air quality source in Guildford and PM$_{2.5}$. Therefore, we only took the first six questions and the response for those questions to calculate the exposure level. Every question presented a user with two options and based on the response the user was given a score, 1 if the answer meant the user was more exposed to pollution and 0 if the user was less exposed to pollution. For example, in the first question, the user was asked “Where do you live?”. If the user selected “I live next to a busy road”, +1 was added to the exposure and if the user selected “I live on a quiet street with little traffic”, +0 was added to the exposure score. Similarly, scores were calculated for remaining five questions and at the end of the quiz an exposure range from 0 to 6 was calculated. These were based on slight adaptations from Kessel et al. (2018). The results suggested that around 27% of the participants had exposure over level 4, which is on the higher side. This gives an idea of how people are susceptible to air pollution even when they are just following their daily routine.

Another set of data was obtained when the quiz was played online using a laptop, desktop or mobile phones by online users. In total, 43 responses were recorded. Behaviour analysis of the participants was performed, suggesting that most of the users played the online quiz during weekdays (Figure 4a). Interestingly, it was also observed that among all users, 35% were new
users and the remaining 65% were returning users. It meant that there were users who played the quiz multiple times.

The participants also gave their thoughts and suggestions about the interactive quiz via the offline questionnaire during citizen science workshops. In order to maintain the anonymity of the participants and differentiate them, we have used the following terminologies in the subsequent text: PQ#number (participants who used joystick based console to play the interactive quiz), PO#number (offline questionnaire participant), and CS#number (citizen scientist). Some of the quotes by the participants explained the public perception of air pollution and how they rated the interactive quiz. When asked about how beneficial the quiz was, especially for the context of quiz questions, one of the participant’s responded: “The question about the curbside was interesting as it made me consider the mini-scale decisions I make. Clarity and ease of the interactive quiz was great (PQ #1).” They were also asked to give an overall review of the interactive quiz. PQ#2 said, “More detailed questions meant more detailed advice.” PQ#3 said: “The level of detail is good.” PQ#4 mentioned, “I like the information about air pollution and how I can reduce the exposure.” The participants, in general, appeared to be informed about the factors that lead to high pollution exposure. The interesting finding was that, although people were aware that some of their daily routine choices could increase their pollution exposure, the real talking point among the participants during the citizen science workshops was the extent of exposure variation as suggested by the quiz. This gave a clear picture of people’s perception of air pollution and how their choices can be influenced in a positive way by using interactive tools like the air pollution quiz.

3.2 Results of the offline questionnaire for user feedback about the quiz

Figure 5 shows the plots for the data analysis of offline questionnaire. The idea behind designing the offline questionnaire was to evaluate what participants thought about the interactive quiz console and if they had suggestion/criticism about it. We asked the participants some basic information about their age and gender. It was interesting to see that people from many age groups showed interest in the interactive quiz console. We had participants from age of 20 to 79 (Figure 5a). The participants were asked about the intuitiveness and simplicity of the quiz and majority of the answers were positive (Figure 5b). To get a better understanding of the participant’s experience, we also asked them about features of the quiz such as the overall context, size of buttons, colours, etc. The response range was from 1 to 6; 1 being the best score and 6 being the lowest score. The results are shown in Figures 5c and 5d. Majority of the participants thought highly of the quiz characteristic and features.

The offline questionnaire asked the participants to give their assessment of the interactive air quality quiz and a general idea of their awareness with a specific emphasis on air pollution. Majority of the participants indicated that they found the quiz useful and their perception about the quiz was further explored with the help of open-ended questions. When asked if the participants felt something could be improved. PO#1 mentioned, “I guess the design could be more creative. But it is very clear, which I loved.” PO#2 said, “I found the operation simple and intuitive. It’s easy to operate.” According to PO#3, “The design seems to be good and efficient. The present way of guiding is good.” A similar pattern was observed in the responses of the majority of the participants who felt that the interactive quiz design was effective and easy to play with.

3.3 Results of citizen science workshops
The iSCAPE citizen science workshops were used as a way to start a citizen science community-led air quality monitoring scheme. The broader objective was to measure PM$_{1}$, PM$_{2.5}$ and PM$_{10}$ using a low-cost air pollution sensor and to understand how pollution exposure varies in indoor and outdoor environments, especially PM$_{2.5}$ concentration because PM$_{2.5}$ poses as one of the biggest threats to human health (Heal et al., 2012). Each of the ten of our citizen science kit users (referred hereafter as citizen scientists) were asked to present their findings during the second citizen science workshop. All of them presented some interesting results (Table S4). In the next sections, we discuss a few distinct results that provided insightful observations with a clear take-home message.

### 3.3.1 Indoor PM$_{2.5}$ concentration is driven by indoor activities and sparse ventilation

Citizen scientist #1 was interested to understand personal exposure in her flat during various activities over the day. The participant placed the sensor in her flat (Figure S3) near the window and electric stove (Figure S4). The data were continuously collected between 13 and 23 November 2018. The flat was located in a busy street near the Guildford city centre and was also 0.5km from the railway station.

An interesting association was found between cooking time and PM$_{2.5}$. The participant observed that most of the mornings when cooking activities were performed, PM$_{2.5}$ levels rose sharply (Figure 6a). One reason could be lack of ventilation as the windows were closed during most of the time. A similar pattern between rise and decline in PM$_{2.5}$ concentration was observed during the morning hours (Figure 6b). There was a sudden peak that was observed and subsequently, the levels went back to normal in few hours. During some days, cooking was done during late night, which can justify the high concentration after midnight (Figure 6a). This participant assessed how personal exposure varies in an indoor environment and based on the results, it was learnt that daily activities like cooking and cleaning can significantly affect the indoor PM$_{2.5}$ concentration.

### 3.3.2 Traffic jams on major highways worsen air quality in nearby residential areas

Citizen scientist #2 was interested in observing how traffic jams affect the air quality around houses close to a major roadway. The sensor was put in the front porch in a protective vented shelter 1.5m above the ground surface and around 8m away horizontally from the road at Great Oaks Park (Figure S5) in Guildford, UK. The road near the location formed a T-junction with another road. Regarding the traffic condition, it has urban traffic from the A3 slip road at London road, travelling towards New Inn Lame and then Merrow, with local usage including lorry drivers. The data was collected from 19 November 2018 till 3 December 2018. For most of the days, the data was collected from morning till evening and the sensor was charged during the night time. The weather during the data collection period was mostly misty, cold and damp with intermittent rain showers.

An interesting incident on 22 November 2018 can be observed from Figure 7. The participant noted that there is a sudden increase in particulate matter levels as compared to other days. It was found out that there was an accident on the major highway nearby. There was a huge traffic jam that resulted in high particulate concentration levels. The inflection point can be clearly observed in Figure 7b. This citizen scientist highlighted how accidents and associated traffic
jams affect the air quality in the surrounding neighbourhood and the time it takes for the air quality to get back to normal.

3.3.3 Having my home-office in the second floor is better than on the first floor

Citizen scientist #3 usually works from home and was interested in knowing where to set up the office in the house. The citizen scientist considered three scenarios for monitoring: (i) sensor was put in the room facing the road on the first floor from 13 November 2018 to 14 November 2018, (ii) sensor was put in the room facing the road on the ground floor from 15 November 2018 to 20 November 2018, and (iii) sensor was put in the porch in front of the house from 21 November 2018 morning till midnight. During the data collection period, maintenance works were happening in a nearby area, resulting in traffic being diverted towards the road next to the house. Figure 8a shows the variation in the PM$_{2.5}$ levels. It was observed that the exposure level is more for the room downstairs as compared to the room upstairs (Figure 8b). Also, the highest concentration levels were recorded when the sensor was located on the porch outside the house on 21 November 2018, owing to the close proximity to the road (Figure 8b). Citizen scientist #3 highlighted that it is better to set-up office on the first floor compared with the ground floor. It was also highlighted that such a setup was only suitable for that particular house and would not apply to other dissimilar places because of the nature of citizen scientist’s house location, traffic conditions and other environmental factors.

3.3.4 Burned food in my kitchen took hours to reach PM levels to normal

Citizen scientist #4 was interested in understanding the indoor air quality in the kitchen. A food burning incident occurred in the kitchen and the citizen scientist focused on its analysis. The sensor was located inside the house near the kitchen. The data was collected from 13 November 2018 to 25 November 2018. Most of the time, PM$_{2.5}$ level was low (Figure 9a) but a sharp increase to almost 1200 µg/m$^3$ in a couple of hours was noted by the participant during the evening of 18 November 2018 (Figure 9b). The citizen scientist found that during this evening, there was an accident in the kitchen and the food got burnt. This clearly supported the sudden change in the PM$_{2.5}$ levels. After further inspection of the data during this event, the participant found that it took almost 12 hours for the concentration level to go back to normal since the burning incident, clearly highlighting that PM$_{2.5}$ concentrations can disproportionately increase during such incidents to expose families, including most vulnerable such as young children (Sharma and Kumar 2018) and elderly people (Segalin et al., 2017), to harmful level of pollution. The citizen scientist highlighted the need for sufficient ventilation in kitchens, especially the importance of opening the windows, during food burning events, where PM$_{2.5}$ concentrations can take hours to return to normal levels without sufficient ventilation.

4. Discussion

While there are numerous citizen science studies which examined citizen science approaches to address air pollution problem, most of them follow the idea of designing the research problem and recruiting the volunteers to participate only in the data gathering process (Castell et al. 2015; Jiang et al. 2016). Conversely, our approach was based on three principles of inclusion, collaboration and reciprocation. We followed a multi-component approach to understand public perception and raise awareness about air pollution. To evaluate our approach, we analysed the degree of participation and found out that we had participants from different background and age groups, some with extensive knowledge of air pollution and some
with basic understanding. They were not only just involved in small participatory tasks but we let the citizen scientists decide which problem-related to air pollution they wanted to address and the experiments they wanted to perform. When asked about the inclusiveness of the citizen science workshops, one CS said: “Citizen science is a great way to involve local people and acts as a bridge between the academia and the community.” As feedback about the collaborative nature of the workshops, another CS said “An important start to understanding ‘Pollution’.” The other anonymous CS mentioned about the clear reciprocation throughout the workshops and quoted: “An important program to bring awareness to a major problem and an insight to the scientific exposure evaluation method.”

We also used narrative as another evaluation method for this study that would encourage communication and sharing of ideas between experts and non-experts. We followed a storytelling approach in which the participants explained their experience as a story and elaborated the critical points they experienced during the experiments. A number of participants performed their experiments and came up with very interesting results: Someone found that it took hours to clear their food burning smoke in their kitchen (emphasising ventilation as important); someone found the second floor is better than ground floor (hence the second floor is a better place for office when working from home), someone found that traffic jam due to accident on the nearby road affected air pollution around their house (reflecting clearance of jam). The above case studies by citizen scientists highlighted that personal exposure to pollutants changes based on our day to day activities and our surroundings. These studies represented varying degrees of PM concentration which were highly dependent on the context in a particular scenario. A little awareness about the air quality and some changes in the day to day routine habits can actually help in personal pollution exposure reduction. All the components of this study were mainly focused on how to engage the community members in the best possible way by motivating them to participate, share their problems and get a first-hand experience of conducting citizen science research. The results not only helped in gaining an insight into people’s perception about air quality but also raising awareness that could possibly lead to better decision making and sustainable development.

5. Summary and Conclusions

We investigated the perceptions of people about air quality using a citizen science approach. Our approach integrated the use of an interactive online quiz, offline survey and low-cost air quality monitoring sensors. The participants were treated as citizen scientists and were allowed to design their study around a research question. The interactive quiz indicated how much people know about air pollution and how people make choices in their day to day lives which affect their personal exposure to air pollution.

The following conclusions were drawn:

- The study helped us demonstrate that a citizen science approach can be considered as a viable approach to raise awareness and improving individual knowledge about air pollution and eventually reduce their personal exposure.
- Citizen science activities can benefit from community-led air quality monitoring, which could provide reliable exposure information, when combined with surveys and other assessment methods such as interactive quiz, and could help address important questions like road-side exposure assessment and indoor exposure.
Raising awareness at the grassroots level and engaging the community to participate in air quality monitoring can generate partnerships in which citizens and researchers can effectively work towards a common goal.

Open responses received from the participants’ showed that our methodology promoted critical discussions and can lead to community actions to tackle air pollution.

Our study demonstrated a multi-pronged citizen science approach with insightful findings. The participants demonstrated an improvement in their knowledge of and awareness about air pollution. Besides, a bridge was built between professional scientists and the local community. Future work is warranted to understand how useful is the data collected by citizen scientists for professional scientists to exploit further value from such engagement activities and if and to what extent the experience carried out by citizens can actually lead to behavioural change in their daily routines.

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Figure 1. Schematic diagram of an integrated co-creation citizen science approach for air quality awareness.
Figure 2. Flowchart showing different stages of two citizen science workshops.

Citizen Science Workshop 1
- Introduction to air pollution monitoring using low-cost sensors
- Distribution of 10 smart sensor kits

Experimentation and Analysis
- Experimentation by citizen scientists (2 Weeks)
- Data Analysis period (1 Week)

Citizen Science Workshop 2
- Dissemination of findings and storytelling
- Debate over key issues and future strategies

Figure 3. Data analysis of quiz including: (a) participants response for different questions; and (b) exposure estimation within a range of 0 to 6; 0 being the lowest and 6 being the highest exposure level.
Figure 4. (a) User count based on weekdays; and (b) percentage of new visitors and returning visitors who used the online air quality quiz.
Figure 5. Results of offline questionnaire showing: (a) age and gender of participants; (b) response to question if the quiz was intuitive and navigation was easy (all the participants felt that the navigation of the quiz was easy); (c) satisfaction score for quiz button size and context of text; and (d) satisfaction score about colours, font size and content per page.
Figure 6. (a) Diurnal variation of PM$_{2.5}$ during indoor air pollution monitoring by the citizen scientist #1; and (b) concentration variation of PM$_{2.5}$ during the morning cooking period. High concentrations were observed during similar time periods for days when cooking was done.
Figure 7. (a) PM$_{2.5}$ variations when the sensor is located close to the road by the citizen scientist #2; and (b) inflection point observed during a traffic incident and rise in PM$_{2.5}$ concentration during roadside traffic incident.
Figure 8. (a) Concentration heat map of PM$_{2.5}$ concentration when the sensor is placed on the first floor, ground floor, and in the porch outside the house by the citizen scientist #3; and (b) Daily average PM$_{2.5}$ variations at different locations in the house.
Figure 9. (a) Concentration heat map of PM$_{2.5}$ for the indoor environment by the citizen scientist #4; and (b) sharp increase in the PM$_{2.5}$ concentration because of burning food incident and time required for the concentration levels to get back to normal.
### List of Tables

Table 1. Summary of relevant research studies undertaken on air pollution monitoring and exposure estimation using citizen science.

| Author (Year)          | Study Focus                                                                                                                                                                                                 |
|------------------------|-------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------|
| Hubbell et al. (2018)  | Focused on social science and the use of air quality sensors for understanding people’s perception, attitude and behaviour. The authors also discussed how a collaboration of citizen scientist and professionals can enhance understanding of sensor technology use which can potentially raise air quality awareness. |
| Commodore et al. (2017)| Study about how community-based participatory research was driven by the desire to be more aware of air quality in the community and a desire to learn about health issues due to pollution exposure. |
| English et al. (2017)  | Highlights of the significance of community engagement in every aspect of air quality monitoring when creating a community-wide monitoring scheme.                                                               |
| Jerrett et al. (2017)  | Performed studies which showed that low-cost sensors could potentially reduce exposure measurement error and could act as a valid data source for citizen science studies.                                           |
| Pritchard and Gabrys (2016) | Analysis of how citizen sensing can be used not only to develop new technologies but to develop new partnerships, communities which can lead to a joint effort towards addressing issues like air pollution.                        |
| Castell et al. (2015)  | Presented the Citi-Sense MOB approach which facilitated public participation in environmental governance using mobile technologies.                                                                          |
| Leonardi et al. (2014) | Presented a mobile crowdsensing system for air quality. The aim was to monitor air pollution and also to get the participant’s reflection on their pollution exposure.                                                |
| Zappi et al. (2012)    | Proposed the CitiSense project which evaluated how people responded to getting feedback about the air quality in their surroundings. The participants were provided with an online mapping tool to visualize air quality pattern. Interviews were performed to understand if the air quality data influenced their behaviour in any way. |
| Willett et al. (2010)  | Interviewed community members, researchers and regulators who were engaged in air pollution measurements using personal air quality sensors. The authors used the responses to derive design principles and frameworks for data collection and knowledge extraction. |
| Questions                                                                 | Answers with options                                                                                       |
|--------------------------------------------------------------------------|-----------------------------------------------------------------------------------------------------------|
| Q1: Where do you live?                                                   | 0 - I live next to a busy road                                                                           |
|                                                                          | 1 - I live on a quiet street with little traffic                                                           |
| Q2: What kind of road do you walk down most often?                       | 0 - On pavements close to traffic                                                                          |
|                                                                          | 1 - On pavements behind hedges                                                                           |
| Q3: Where do you stand while waiting to cross a traffic light?            | 0 - Next to the curb, so I can start crossing right when it’s green                                       |
|                                                                          | 1 - A few metres back from the curb                                                                      |
| Q4: When are you most likely to go cycling?                              | 0 - Rush hour (roughly between 7-10am and 4-7pm)                                                          |
|                                                                          | 1 - Off-peak                                                                                            |
| Q5: When stopped in heavy traffic, do you prefer to have your car windows open or closed? | 0 - Closed                                                                                             |
|                                                                          | 1 - Open                                                                                                |
| Q6: When stopping briefly in your car, what do you do?                   | 0 - I tend to leave the car running as I’m only stopping for a short time                                 |
|                                                                          | 1 - I always switch the motor off when stationary, even if it’s only briefly                             |
| Q7: Which of the following is a bigger cause of air pollution in Guildford? | 0 - Airport                                                                                             |
|                                                                          | 1 - Traffic                                                                                                |
| Q8: How visible do you think this PM$_{2.5}$ is in the air we breathe?   | 0 - It’s a large dust particle and can be found only in visible air pollution                            |
|                                                                          | 1 - Some types of PM are smaller than a human hair and are invisible to the naked eye                |