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© by PSP Volume 31– No. 08A/2022 pages 8297-8302 Fresenius Environmental Bulletin

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ABSTRACT

As part of the ICARUS (Integrated Climate forcing and Air pollution Reduction in Urban Systems) H2020 EU project, sampling campaigns took place in seven European cities (Athens, Basel, Brno, Ljubljana, Madrid, Milan, Thessaloniki), aiming to characterize urban population exposure to air pollutants, altogether with over 600 participants from over 250 households. By combining spatio-temporal information on air pollution and activity data of individuals, we were able to identify individual exposure profiles and to aggregate information according to specific micro-environments and activity. Personal exposure reports were then prepared and distributed to all participants. In this paper the overall experience gained conducting sampling campaigns in all seven cities is summarised, focusing on the following aspects: sensors selection and evaluation, development of the overall study design, data harmonisation and building of supporting ICT infrastructure, as well as overall feasibility evaluation including user experience as reported by both participants and field workers.

KEYWORDS:
Air Quality, Exposure, Sensors, Activity Patterns, User-Experience

INTRODUCTION

One of the aims of the ICARUS (Integrated Climate forcing and Air pollution Reduction in Urban Systems, H2020) project described in this paper was to enhance exposure assessment. In particular, the aim was to overcome the oversimplification of classic approaches that use ambient concentrations only. For this, the actual individual exposure to chemical and environmental stressor, which depends on time-activity profiles of individuals as well as on the inhalation rate due to the intensity of each activity, were taken into account [1]. Nowadays, this is enabled by array of new (low-cost) sensing technologies that are largely used to assess exposure at individual level [2-3]. If wearable, these sensors can provide very detailed spatio-temporal information on exposure patterns in various microenvironments and for activities person is involved in [e.g. 4-5]. Moreover, utilisation of such easy to use devices enables active involvement of citizens in monitoring the quality of their living environment based on the principles of citizen science and in this way improve their wellbeing [6]. Indeed, several authors are reporting change in perceptions, behaviour and increased awareness of participants in such type of studies [7-11]. There is, however, still quite a few drawbacks in the current state of the art that have to be considered when using such devices. One of the most important disadvantages is the fact that most of the available low-cost technologies for air quality are still in testing phase and without clearly demonstrated fitness for purpose.

ICARUS sampling campaigns (winter-heating and summer-non-heating) took place in seven European cities, and aimed at characterization of urban population exposure to air pollutants, using a combination of exposure monitoring devices, questionnaires and time activity diaries. Altogether, several hundred participants were recruited in these cities, comprising individuals of all ages and various socioeconomic groups. Specific objectives of these campaigns were to: (i) collect data on external environmental exposure and exposure determinants by combining location, activity and air pollution data in different micro-environments, (ii) demonstrate feasibility of using new sensor and mobile technologies in collecting exposure data, and (iii) analyse and compare exposure data in several different European cities. Here we report on the overall experience gained during the implementation of these campaigns.

MATERIALS AND METHODS

Sampling campaigns were conducted in cities of variable sizes starting from relatively small (Basel, Brno, Ljubljana) to mid-size (Thessaloniki) and large cities (Athens, Milan and Madrid). The cities were selected to represent the mix of urban settings around Europe and to cover a wide range of environmental issues and spectrum of "green urban management".

A schematic outline of the ICARUS sampling campaign is shown in Figure 1. Each participating city targeted about 100 individuals of all ages and socio-economic groups to be involved in the camping, with a focus on including vulnerable groups of population (e.g. asthmatics, children and elderly). To this end, various recruitment methods were used, from advertisements at thematic public events, through social-media and using respective stakeholder networks previously established in individual cities. Campaigns included both static samplers deployed at home and personal monitors for seven days, including weekend, and were conducted in summer and winter periods, in order to capture seasonal variation.

Based on a detailed review of scientific literature reporting applications of personal air quality sensors and physical activity trackers, considering their overall performance, including commercial availability, were considered:

(i) the Indoor Air Quality uHoo monitor that measured CO, CO_2, VOCs, $PM_{2.5}$, O_3, NO_2, temperature, relative humidity, and air pressure with minute resolution;

(ii) a portable Arduino based IOT low-cost sensors to monitor personal exposure to particulate matter (referred to as PPM) developed within the ICARUS project and that provided PM concentration data in one-minute resolution for three particle sizes: <1 µm (PM_1), <2.5 µm ($PM_{2.5}$), and <10 µm (PM_{10});

(iii) commercially available smart activity tracker (SAT), a Vívosmart 3 from Garmin International, which provided various physical activity related information, e.g. hearth rate, steps taken, calories "burned", distance walked, and stress level with one-minute resolution;

(iv) silicon wristband that passively absorbs a wide range of organic chemicals (e.g. polycyclic aromatic hydrocarbons, pesticides, and flame retardants) from the participants' surroundings.

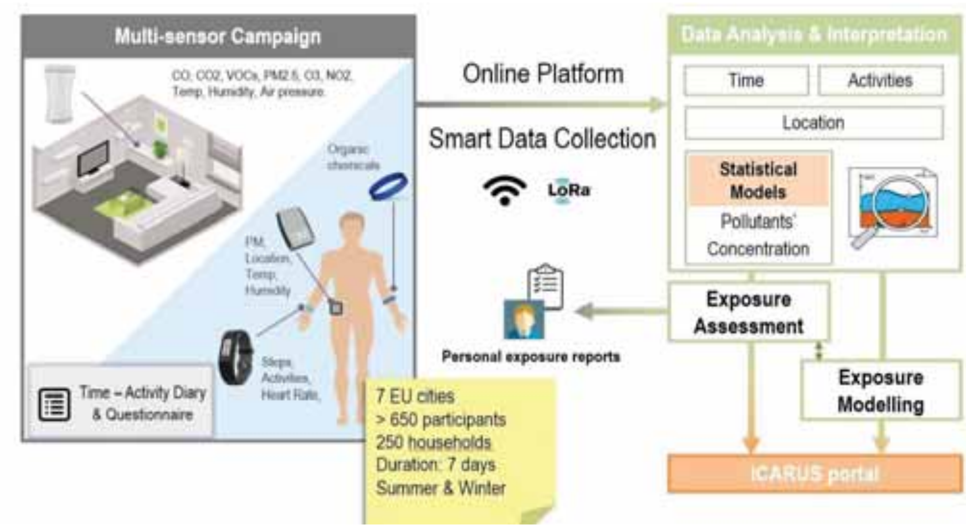

FIGURE 1
Schematic outline of the ICARUS sampling campaign

In addition to sensors, two questionnaires were distributed among participants in the beginning of the campaign. The first one gathered information for each participant on personal demographics, living habits, medical and socio-economic information, while the second one, for each household, was more focused on the type and specifics of their dwelling and technical specifications such as insulation, heating system, ventilation. Other information such as location, neighbourhood, green spaces, traffic, and noise were also considered. During the campaign, participants were also asked to record information on the type of microenvironment (home, office, work, and means of transport), activity (leisure, sleep, sports, work, cooking, cleaning) and indoors conditions (ventilation, use of candles or fireplace) by using a time-activity diary (TAD) with one-hour resolution.

Initially, participants were given an information leaflet, explaining the study's aims and objectives. All the tools were explained and demonstrated during the first visit by researchers, and the participants were given an opportunity to ask questions prior to providing consent for themselves and/or their child to participate in the study by means of a signed consent form.

None of the data collected was accessible by the participants during the campaign in order to not influence their usual daily routine and behavioural patterns. The local researchers, who were available throughout the campaigns via phone and email for trouble shooting or additional questions, were regularly checking the data that was uploaded on the purpose-designed ICARUS data portal.

Through the internet of things and taking advantage of WiFi and LoRaWAN communication protocols, data from connected devices were wirelessly uploaded and synchronized to an online data collection platform. At the end of the campaigns, data were then compiled, aggregated and visualised for individual participants in a form of a final report. The participants were consulted in designing the reports in order for them to be understood. Throughout the campaign, user experience of participants and field workers was also observed and collected.

RESULTS AND DISCUSSION

Sensors selection and evaluation: Selection of sensors was conducted considering the perspective and the needs of both researchers and participants. The following criteria were established to select the devices. Sensors that measure several air pollutants and include additional parameters such as temperature, humidity and location can help during interpretation/post-processing of signals from low-cost sensors. Portability as well as reliability of data collected was also considered, and only the sensors with performance previously evaluated and reported were considered. Another important aspect was the cost, as each campaign city had a large number of volunteers. In terms of data collection and transfer protocols, high-resolution collection, transmitting and storing of data was requested. From the participant's perspective, it was considered important for sensors to be unobtrusive to the wearer, (i.e. not attracting attention) and robust (i.e. could be used repeatedly with a low failure rate, and to have longer battery life). Moreover, sensors were expected to be user-friendly enough for a non-scientifically trained individual to use it correctly.

ICARUS campaigns in numbers: Recruitment rate varied between the cities and seasons (Table 1), and so were the number of the involved households (16-55) and the duration of individual campaigns (20-45 days). Across all the cities, over 600 participants from over 250 households participated. In terms of gender, participation was well balanced in all the cities. Similarly, both children and elderly were involved, representing over one quarter of participants in some of the campaigns. Typically, turnout was slightly lower during the second season. The most common reasons stated to abandon the study were limited number of devices, lack of time and unsatisfactory user experience. Throughout the campaign, the interaction between researchers and volunteers was very intense. As an example, in Brno during the first campaign, almost 1,200 e-mails were exchanged, more than 140 telephone conversations took place and over 400 text messages were sent.

Data harmonisation, ICT infrastructure and generation of individual reports: A multi-platform data collection tool – the ICARUS platform [12] - stored, managed and analysed all data coming from different devices, providing an interpretation of the data using advanced statistical methods, sophisticated data mining techniques, computing power as well as a careful sharing of data sources while also maintaining privacy protections for personal data. A user-friendly interface allowed exploration and extraction of data by researchers. Each campaign (city and season) had participants and households assigned to it, which in turn had all the devices assigned to them. This facilitated a clear overview of the data and allowed the identification of the relevant data points quicker and more accurately. The tool offered several options for retrieving the data to a local device, including downloading the entire campaign or just a small section of data from one single device. These data then served for generation of individualized reports that were provided to each participant, with detailed descriptions of the inputs, and visualizations, which offered the participants a clearer representation of the data. Data from each device were visualized in several plots, depending on the context. For example, T, RH and AQ data were visualized with time series line plots with ribbons presenting "optimal" values, while the three most relevant indoor gaseous air quality parameters - CO_2, NO_2 and TVOC - were visualized with heatmaps with each cell representing an hourly average, and coloured relatively to all the other measurements in that time frame. Due to accuracy issues with this device, a decision was made to not show absolute values as this could lead to misleading message for the participant. A representation of relative differences via heatmap offered insight into their individual actions and how they affect the concentrations of each pollutant, e.g., opening a window near a busy road would reduce CO_2 concentrations and increase NO_2. The PM concentrations and heart rate were visualized with time-series point plots, one plot for each PM size and heart rate values. Activities collected from the TADs were also visualized in these same plots by colouring each point according to the specific activity (Figure 2). This offered the participant an option to research possible visible correlations between their activities and PM concentrations, while also taking account of their heart rate which would increase the intake of PM [13]. An average daily concentration of PM was also calculated and provided in plots for summer and winter together. Participants could then see how their PM concentrations change from day to day during the week, and also observe the difference between both seasons. The report compilation was done automatically by using the markdown library with R in R studio (r-project.org) which allowed each report to be individualized while still making the process automatic and in turn significantly speeded up the process.

Feasibility evaluation including user experience of participants and field workers: Overall, majority of the participants were very satisfied about the way the study was organised and implemented. During the campaign, some of them shared pictures demonstrating their participation on social media. They assessed the duration of the campaign as appropriate and, with rare exceptions, were prepared to participate in the second season as well. Of the sensors, they were most impressed by the Garmin smartwatch, especially the children were very enthusiastic about the cooperation due to the possibility of using it. Practically all participants expressed a desire to receive individual reports, which they mostly assessed as appropriate and understandable upon receiving it. On the other hand, quite a few volunteers complained about the size and ergonomics of the PPM sensor, which they also often forgot at home or forgot to charge. There was also some misunderstanding about the purpose and functionality of the silicone wristband. Furthermore, most participants found the completion of TAD time consuming or did not fully understand it. Thus, some people did not complete it, while others suggested a diary that would allow indication of more detailed time steps. Some specific questions in the questionnaires were considered redundant. Moreover, few participants complained over the fact that they were not able to see the real-time data during the study.

The field workers were very pleased with the detailed instructions and training provided at the beginning regarding implementation and management of the campaigns. Thus, they could easily answer all the questions raised by participants, including those related to the GDPR (General Data Protection Regulation). Similar to the volunteers, they were less enthusiastic about the technical problems with individual sensors leading to data gaps, especially PPM (e.g. inactive sensors in the platform, loose connections, empty or no log files), which in turn increased the need for communication with the volunteers.

TABLE 1
General statistics on participation in the campaign in individual ICARUS city during winter (W) and summer (S) campaign

City	Athens (W)	Athens (S)	Basel (W)	Basel (S)	Brno (W)	Brno (S)	Ljubljana (W)	Ljubljana (S)	Madrid (W)	Madrid (S)	Milan (W)	Milan (S)	Thessaloniki (W)	Thessaloniki (S)
No. of Participants	100	90	46	48	86	45	75	78	112	98	89	65	85	50
Female	47	44	23	25	42	24	36	36	46	48	50	34	47	28
Male	53	46	22	23	28	21	39	42	54	50	39	22	38	22
Age														
Children (<18)	25	21	0	0	16	0	10	13	6	7	21	9	27	14
Adults (18-65)	68	63	43	46	70	45	62	61	66	69	62	53	57	36
Elderly (>65)	7	6	3	2	0	0	3	4	28	22	6	3	1	0
No. of Households	34	31	36	36	36	24	49	46	55	50	38	30	25	16
Campaign Duration (days)	45	45	32	28	24	32	25	34	31	27	21	20	25	-

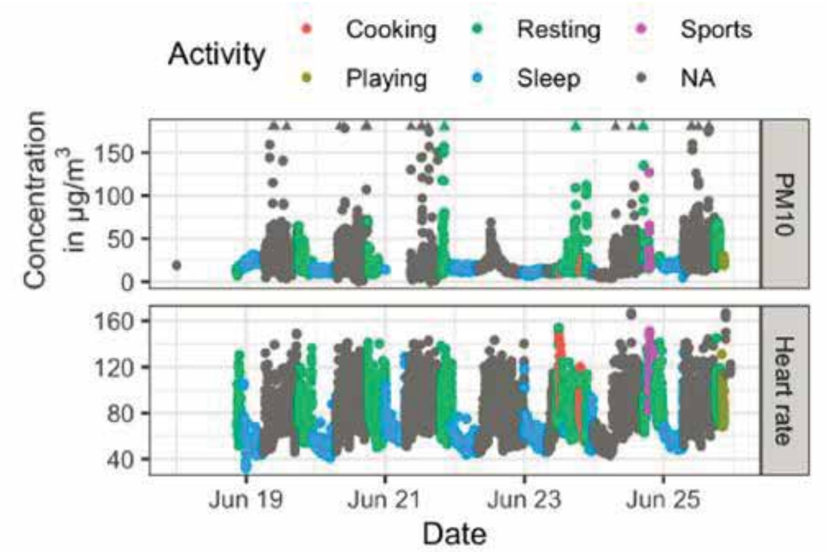

FIGURE 2
Example of figures on individual exposure to PM2.5 provided within the report to the participant's assessment results.

CONCLUSION

To our best knowledge, the ICARUS campaign is the most comprehensive study of its kind, carried out in such a large number of diverse cities and with such a large number of participants. Based on the experience gained during the implementation of the campaigns, the following should be emphasized:

- Recruiting households increases the age profile of the participant pool, enabling the inclusion of children and elderly.
- The selected tools should be easy to use and not cause disturbance in participant's daily lives.
- Prior preparations of field workers, including providing them with detailed technical instructions as well as scripts to refer to when visiting participants ensures smooth campaigns and ensures they know how to answer all questions and solve issues on the fly.
- The flexibility to organize the volunteer campaigns together with the collaborative approach to share the devices among the cities, reduce the risk and promotes the information exchange among participants. Extending the campaign period enables a larger number of participants than simultaneously deployed campaigns.
- Data gathered in this way enable new community level knowledge generation and up-scaling of the results through a diverse set of modelling tools, including Agent based modelling [14] which offers an upgrade on static approaches to modelling on an urban scale.
- Low-cost portable or wearable sensors allowed the collection of highly granular spatio-temporal data, though it was accompanied with several issues that are characteristic to low-cost devices, such as frequent data gaps, unreliable data streams, inaccurate measurements at low concentrations, etc.
- Data fusion and harmonization from low-cost devices proved to be challenging due to data gaps, inconsistent time stamps, heterogeneous data logging protocols, in addition to human errors from manually recording activities and operating with the devices. A novel approach of data fusion to facilitate data visualization and representation was employed [15] which achieved a uniform consistency of report generation while also significantly reducing time used for report preparation and allowing each report to be individually tailored to each participant, to a certain degree.
- While preparing the reports for the participants, the following has to be considered: (i) uncertainties related to data coming from low-cost sensing devices have to be clearly defined and explained; (ii) it has to be assumed that the reader is a layman in terms of air pollution and its impact on health, and therefore (iii) reports must be brief enough and concise, as too much information can create distraction; iv) consulting participants during report design (exchange between participants and researchers) ensures report comprehension.

ACKNOWLEDGEMENTS

This work has received funding from the European Union's Horizon 2020 Programme for research, technological development and demonstration under grant agreement No 690105 (Integrated Climate forcing and Air pollution Reduction in Urban Systems (ICARUS). This work reflects only the authors' views and the European Commission is not responsible for any use that may be made of the information it contains. This work was funded by the research programme P1-0143 of the Slovenian Research Agency (ARRS) and the ARRS Young researcher's programme. We would like to thank the following for their help in carrying out the campaigns: J. Vinkler, R. Prokeš, D. Kontić.

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Received: **25.03.2022**
Accepted: **17.04.2022**

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