SenseMyStreet: Sensor Commissioning Toolkit for Communities

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The rise of big data and smart sensing, with the promise of more educated and informed decisions, has fuelled a shift towards more data-driven decision-making in local and national government. However, we are observing a disconnect between the people who are affected by these decisions and their access to tools and resources to collect data in order to provide the needed evidence for change. To truly democratise this process and for citizens to become active prosumers of data, new mechanisms of citizen data production are needed. In this paper we report on a two-year ethnographic and iterative co-design process with the local community. This work encompassed the design, development and deployment of SenseMyStreet (SeMS), a bespoke sensor commissioning toolkit that enables citizens and community groups to use and commission a city's scientific-grade environmental monitors, determining where they will be located on their streets and collecting data to evidence hyper-local issues. Unlike prior research, which creates alternative data sources to contest city data, our toolkit helps integrate citizen commissioned data into the city datasets used by citizens and decision-makers. Reflecting on the design process and evaluating the ways people engaged with the digital tools of the toolkit, we highlight how commissioning can be configured to promote equity in the smart city, empower citizens to take ownership of issues and facilitate the creation of community networks that utilise the data for local benefit.

CCS Concepts: • **Human-centered computing → Collaborative and social computing systems and tools**.

Additional Key Words and Phrases: civic participation; smart citizen; digital civics; commissioning; community-data interaction

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1 INTRODUCTION

The vision of a smart city, where information technology is woven into the city infrastructure to help optimise resources and improve the lives of citizens [23, 79], has been the focus of heated debate in recent years. For many years now, commercial companies – IBM, Cisco and Siemens, to name but a few – have been 'hooking up' the city with sensors and other information technologies in order to gather all the data about the city in the hopes of solving some of the old and new 'wicked' problems of society. For example, intelligent street lighting is in place in many cities to improve efficiency and reduce energy costs; CCTV and traffic counters are used to manage the flow of traffic through traffic signals; and pedestrian counters are utilised to understand the flow of people through the city. In this regard, there seems to be a push for the use of data in all aspects of life in order to optimise and organise resources [11, 18], reduce our carbon footprint [67, 76, 101] and improve sustainability [96], in addition to also facilitating novel modes of participation [93], democracy and social interaction [7, 88]. Although there are plenty of 'smart' applications available, discussion around what makes a city smart is still ongoing [29, 39, 59, 71, 87], and with the increase of urbanisation and the expansion of cities, this trend will likely continue to increase, and more businesses are developing solutions to supposedly '*compute away local problems*' [94].

Through algorithmic smart city governance, the people who inhabit these cities are often viewed as another passive source of data for measurement, control, optimisation and management at scale. This is a very narrow and top down view of the role of *citizens: people who inhabit, work and play in cities*. Berntzen et al. [14] argue that in addition to political participation – direct and indirect participation in political decision-making – the role of the citizen in the smart city is also to participate in helping solve problems and improve services in the city (also [94]). However, this requires the city to have the necessary infrastructure and processes to support communication and multiple types of participation [13]. In modern democratic societies, citizens are expected to be actively participating in all matters of civic life [23], including political discourse [51], through civic engagement activities run by the state [14] as well as citizen initiatives. Indeed, many have recognised that using technology for participation is the key to a successful model of a smart city [81, 83].

One of the ways technologies are utilised in the city is through sensors. Monitoring the urban environment through sensors is an important part of figuring out how the city operates and how people – through their everyday activities – are influencing the city as a whole. However, technological distribution and the drivers for carrying out city-scale monitoring often come from institutional actors, and such projects are mainly run by experts who make assumptions about the population and the issues important to them [93, 94]. Communities are often not involved in sensor placement, or in monitoring or evidencing urban challenges and hazards [93]. Although portable, cost-effective ICT and IoT devices have enabled a wave of smart city sensing to be carried out by citizens, this often creates additional datasets that are separate from the city data used for decision-making. It is also problematic that citizen sensing projects can often be disregarded by decision-makers because of a lack of trust in the data quality or accountability of the process. Here the perception can be that citizens are simply going around using 'toys' that lack the accuracy of monitoring tools used by the city [40] – questioning the validity and reliability of data produced by citizen-led sensing. It seems that while this is partly to do with citizens not having the resources to acquire the equipment for monitoring equivalent to that used by the city, it also relates to a lack of mechanisms that would enable citizens to access already existing resources to conduct their own investigations.

Citizens can broadly contribute data to the smart city in two ways: *passively*, by using some service or automated system (e.g. a data logger), or as the result of a 'data exhaust' that sends data off to be analysed by algorithms implemented on automated systems; or *actively*, providing data by reporting issues and problems through personal computing devices or using citizen science devices to collect data about issues. However, what it would mean for citizens to not only produce data for the smart city, but also access the data for their own ends, and even commission the kinds of data they need, was the focus of our research. Through this paper, we contribute key insights to the CSCW community through engaging with citizens as *active data users* of, as well as contributors to, the smart city. In doing so, we recognise the type of participation enabled by the smart city is determined by how citizens are able to engage with the smart city infrastructure and technological interventions, and what roles they take in the use, design, creation and ownership of these solutions.

In this paper, we describe a two-year longitudinal study of co-designing community commissioning resources for civic participation and action in the context of a city attempting to become a smart city. We contribute to CSCW research by highlighting the important factors influencing active citizen engagement with the existing smart city infrastructure and the collaborative processes needed for communities to make effective use of the data. To achieve this, we adopted a Participatory Action Design Research (PADRE) approach to designing the research and community resources. It is a novel method that combines action research, participatory design and technology iterations through engineering sprints that help produce an artefact which responds to the context and needs of communities involved [44, 45]. In the paper, we offer the following contributions: (i) insights from an in-depth participatory design process with the community, based on ethnographic observations and engagements, identifying the need for and the process supporting community commissioning; (ii) the development and configuration of multiple digital platforms and tools that respond to the needs of the community; and (iii) learnings from the deployment and usage analysis of SenseMyStreet (SeMS), a bespoke toolkit that enables citizens to both gather useful data and commission the deployment of smart city sensors in their neighbourhoods. The intention of this paper is to provide an example of the process of designing and deploying smart city technologies 'in the wild', for use by future researchers, designers and engineers embarking on projects with similar aims.

2 RELATED WORK

Collecting data about the environment can be useful for understanding complex processes, informing decisions, and evidencing changes implemented in a city. Motivations for monitoring and evidence gathering could be, for example, creating a digital twin of a city [17], building a smart city analytics tool for more efficient service delivery [77], or understanding levels of noise or air pollution [2, 31] to inform policies around planning and infrastructure changes in the city. In addition, there are several ways that citizens can get involved in monitoring their environment. These initiatives can be connected to citizen science [47] projects (e.g. Neighbourhood Nest Watch, BioBlitz, British Bird Watch, climateprediction.net and Rosetta@home), crowdsourcing of public infrastructure issues (e.g. FixMyStreet, FiksGataMi, SeeClickFix, PublicStuff and Street Bump) or research efforts [35, 36, 62, 63, 65, 66, 82], all with various levels of participation [4, 47].

However, many smart city projects come with already-framed agendas or are driven by other actors, meaning when citizens are eventually invited to participate, they have little scope to decide on what, where and how data should be collected. Similarly, citizen science projects are sometimes presented to people as something to 'have a go' with rather than seriously influence city decisions. Hakken [46, p. 384] is critical of these kinds of approaches, stating that real constructive learning is replaced by participation in the development of scientific knowledge. Looking at this through the lens of Arnstein's ladder of participation [4, 19], most of the current ways for non-expert citizens to engage with smart city and its data are still at the *tokenism* phase, as citizens are rarely involved in decisions around which smart city tools are taken up by the city or for what purposes the data is used. One example is in Boston, USA, where city officials designed an engagement process to enable citizens to experiment with smart city tools before they were installed and decide on how they could be best used [75]. Yet even in this example, the technologies were selected by decision-makers for specific purposes and in specific trial locations. Although contributing to scientific knowledge and open resources is important for advancing human knowledge, it does not provide individual citizens with the power and choice to create scientific knowledge around issues important to them.

There can be other purposes for conducting citizen data collection than advancing science or providing data to the smart city, e.g. for self-knowledge and personalised health interventions [53], to raise public awareness around environmental issues [33, 35, 49, 61, 63, 69] or to evidence an issue in the community and push for change [6, 10, 52, 62, 63]. The latter approaches involve community-led investigations, whereby citizens are actively involved in the definition of the issue, as well as the collection or acquiring of data and its analysis. For example, Balestrini et al. [9] explored how low-cost sensing equipment can be used to empower citizens tackling specific sustainability issues they were facing. Meanwhile, Kuznetsov et al. [62] designed low-cost sensors for measuring the outdoor air quality, handing them out to non-experts in diverse communities to be positioned in the city collecting data for public awareness and activism. Finally, Hsu et al. [52] built an air quality monitoring system to help the local community gather and make sense of scientific data to empower community action. However, while these efforts represent positive steps towards meaningful engagement with citizens, the ability to influence city decisions with such data is limited, as they centre on generating data that sits outside of policy-making contexts and city datasets.

Some of these efforts have also benefited from portable and cost-effective ICT and IoT devices, which have enabled a wave of smart city sensing carried out by citizens. To achieve this, people can use their mobile phones or some type of citizen sensing toolkit or commercially available monitoring devices (e.g. Foobot, Airthings, Netamo), whether part of research efforts or citizen science projects [47]. Moreover, the availability of micro-controllers such as Arduino, Raspberry Pi and MicroBit enable those with the capacity or skills to build their own sensors to use in citizen sensing. Although people can assemble various components to achieve this[1], plug and play citizen sensing kits are also available (e.g. AirBeam[2], Smart Citizen Kit[3], AirQuality Egg[4], AirPi[5]). Their low barrier to entry means such devices are particularly useful for involving those who are not typically involved in participatory initiatives (such as children) in gathering data about the environment to spark discussions around environmental issues with the wider community [84]. Similarly, multiple platforms have been developed, such as Open Data Kit (ODK) [48], EpiCollect [1], Sensr [58], wq.io [85], CitSci.org [72], DisCoPar [100] and App Movement [41], which people can use for their own investigations. This can be achieved through a reusable mobile or web application that can be reconfigured and deployed to a specific project. The use of these tools has been successful in engaging citizens with issues and widening participation. However, there are still issues around legitimizing citizen efforts in the eyes of decision-makers [40].

As digital technologies increasingly pervade our cities and societies, there is need to move beyond tokenistic involvement of citizens towards supporting more meaningful forms of participation (vis-à-vis Arnstein's ladder [4, 19]). The breadth of studies in CSCW and HCI community have shown that bottom-up and issue-led approaches can have a greater impact on the lives of involved citizens than those implemented through organisational strategies. Examples can be found in

[1] https://wonderfulengineering.com/10-best-raspberry-pi-sensor-kits/
[2] http://aircasting.org
[3] https://smartcitizen.me
[4] https://airqualityegg.com
[5] http://airpi.es

community commissioning, [8, 41, 89, 91] democratic discourse [28, 55, 57, 95], situated voting [12, 43, 50, 92, 98] and community infographics [24, 60, 68]. Meanwhile, researchers are investigating ways that data can be used by citizens to improve their personal and community lives. While recent works in CSCW have investigated ways of understanding and helping communities voice the issues [56] and developed tools to support citizens accessing and working with existing Open Data to evidence issues impacting local neighbourhood [78], these approaches do little to overcome the challenges and inequalities in data deserts [80]. Similarly, when citizen generated data is included in decision-making, for example in a planning process [66], it is taken as an additional dataset that is not fully integrated as part of the standard practice.

Although these works and other digital civics [74, 99] approaches have good examples of helping to identify the needs of the community through bringing common concerns to the surface [70] and extending the social capital [25] to enable community driven change, their limitations are often a creation of separate contrasting evidence bases (i.e., datasets) contained within a specific group or community, rather than integration of citizen generated data with the existing city data for decision-making. Furthermore, the tools often used by citizens to collect data do not integrate with the existing smart city infrastructure, nor is the city infrastructures used for decision-making seen as community assets that can be accessed by citizens. As data becomes the de facto driver for decision- and policy-making, it is vital that we provide citizens with equitable access to the tools and processes needed to collect and effectively use the data from our smart infrastructures. Instead of having small victories from bottom-up approaches in isolated communities, we need to explore ways to legitimise these types of approaches, scale them and make active citizen participation and advocacy through data a norm in the smart city.

3 STUDY CONTEXT

In 2017, over two thirds of households in the UK commuted by car [73] and with vehicle registrations growth of 630 thousand per year[6], the issues of congestion and air quality become more prevalent in urban areas. This is creating significant issues for the environment and for public health; for example, outdoor pollution is now linked to around 40,000 deaths each year in the UK[7]. To address this, UK government announced a national plan setting out safe legal limits for roadside nitrogen dioxide (NO_2) levels [8]. Newcastle, the focus city of this study, was amongst the cities that were breaching these limits. Although parts of the city have been under constant monitoring since 1995, air quality remains a significant issue, and with car ownership still on the rise, this shows no signs of abating. The city has made several attempts to increase public awareness about air pollution, in combination with measures to discourage car use and incentivise alternative modes of travel. However, proposals instigated by the city in 2019 were met with resistance and controversy [9].

Innovations in sensing technologies have meant cities like Newcastle can get a more accurate picture of air quality in the city. Allied with the growth in citizen science efforts, it has also spurred city residents into taking an active role in conversations about air pollution and the collection of air quality data. A 2016 report published by health professionals[10] captures this, by inviting citizens to *'be aware of the air quality where you live and harness technology to stay informed and monitor air pollution effectively'*. Although there have been active efforts around air quality monitoring through national urban observatories (UOs)[11], from which Newcastle UO is part of, it was largely driven by

[6]https://www.gov.uk/government/statistics/vehicle-licensing-statistics-2018
[7]https://www.rcplondon.ac.uk/projects/outputs/every-breath-we-take-lifelong-impact-air-pollution
[8]https://www.gov.uk/government/publications/air-quality-plan-for-nitrogen-dioxide-no2-in-uk-2017
[9]https://www.breathe-cleanair.com/
[10]https://www.rcplondon.ac.uk/projects/outputs/every-breath-we-take-lifelong-impact-air-pollution
[11]https://www.ukcric.com/

research, governance and opportunistic deployments. The data collected was made available to everyone; however, this did not give everyone the opportunity to monitor air pollution ‘effectively’, especially on a hyper-local neighbourhood scale. However, having the UO already established served as an excellent opportunity to investigate ways we could open such resources up for citizen and community use, and explore mechanisms that help incorporate the wishes and desires of citizens into the picture of how a city operates.

4 RESEARCH APPROACH

The motivations outlined in Section 2 within the context of local issues - a result of increasing urbanisation, affecting public health and urban mobility (Section 3) - along with the ready availability of digital resources for investigating such issues presented an opportunity for research. Such research could shed light on how data production could be democratised and used to better engage communities affected by these issues. The study took a Participatory Action Design Research (PADRE) [44, 45] approach to understanding the needs of communities. Through engagement activities and user-centred co-design processes, we developed digital tools and processes for supporting people-led investigations, data collection and advocacy efforts at the same time integrating with the existing smart city infrastructures used by decision-makers.

The research in this paper encompassed three stages detailed in the following sections: (1) *Building Relationships* with local residents in the city to map out citizen data needs and find people interested in participating in the co-design process; (2) *Designing Community Resources*, with a group of residents, that help citizens produce data about hyper-local issues; and (3) *Developing, Operating and Evaluating the SeMS Toolkit* tools and processes and its use by the community. A timeline on Figure 1 shows the chronological order of the research, from its inception to evaluation. Although timeline on Figure 1 shows *Stage 3: Developing, Operating and Evaluating the SeMS Toolkit* this process linearly following from the design, this was rather an ongoing process spanning across the whole study, with constant feedback loops and reflections as is the nature of iterative design.

5 STAGE 1: BUILDING RELATIONSHIPS

The first stage of the research was to build relationships with community members who were concerned about these issues in Newcastle and understand the ways that they were using data for civic advocacy. This was also key for understanding public perceptions of the data being collected by the city and recruiting members of the community to take up the SeMS toolkit later in the research. We gauged the initial interest of the community through an exploratory workshop, held in April 2017. The aim of this was to listen to the concerns and motivations of local residents, explore their data and technology needs for supporting their civic advocacy and action and earn their trust to participate in a design process. The workshop was advertised publicly through posters, direct contacts and through social media accounts widely followed by city residents.

Shortly after this work, we were approached by several attendees based in a neighbourhood of the city who were keen to explore different routes to action on air pollution. They supported the infrastructure changes that the city was proposing but wanted to see these changes go even further. Owing to a lack of data about local air pollution, as the city’s sensor coverage did not reach their neighbourhood, one of these were monitoring air pollution using a diffusion tubes[12]. They were keen to scale up this data collection and analysis, as for them, this data was the strongest way to demonstrate the extent of air quality issues in their neighbourhood and advocate for change. We saw this as an opportunity for a partnership, where motivated local residents could participate in the design of a toolkit that would enable them to collect data through handheld sensing equipment

[12] https://laqm.defra.gov.uk/diffusion-tubes/diffusion-tubes.html

Fig. 1. Timeline of the study with three types of events shown: activities and events related to the SeMS toolkit, activities and actions of the group involved in the co-design process, and the events and changes in the community

and commission their own static sensors to be installed in their neighbourhood. Later on, this became the SeMS toolkit.

Table 1. People involved in the SeMS toolkit co-design process

Participant	Roles
P1	local charity trustee, retired council worker (city planner) from a different council
P2	professional working in ICT
P3	parent, manager working in academia
P4	parent, general practitioner working at the NHS
P5	parent, lawyer
P6	parent, professional working at the NHS
P7	parent, public relations officer
P8	consultant

From this initial approach, a total of eight residents based in this neighbourhood volunteered to participate in the co-design of the SeMS toolkit (Table 1). All of these were active or retired professionals with prior experience of participating in city consultations and felt comfortable using ICTs to collect data for political advocacy. All these participants were already involved in official and unofficial or *insider* and *outsider* activities [5] around the issues and thus were able to draw on their connections within the wider community. While we recognise that this group does not reflect the diversity of the city as a whole, we felt it was significant that they were able to leverage their political capital to support the project and provide vital in-roads to engaging with the wider community.

6 STAGE 2: DESIGNING COMMUNITY RESOURCES

Once these residents had agreed to participate in the design of the toolkit (Table 1), the second stage of the research centred on gathering requirements for setting up this toolkit. This involved a five-month long engagement and iterative co-design process involving community meetings, mapping and citizen sensing activities, focus groups and ethnographic work. We set out these activities below.

6.1 Surfacing and Mapping Community Concerns

An initial design workshop provided indicative evidence of community interest and also a group of residents keen on getting involved with the co-design process. Furthermore, there were available funds from the UO to acquire environmental monitoring equipment; however, up to this point, there was no commissioning toolkit in place to manage this shared resource, nor was there a clear view of the places and the sort of environmental indicators people were interested in measuring. Together with the research team from the UO, we came up with a set of potential monitors that could be acquired or repurposed, provided there was interest from the people. These included scientific-grade air quality, noise and traffic monitors that could be located on lampposts by UO engineers and hand-held environmental monitors that people could use themselves on commutes.

To explore these avenues and get an idea of what people were particularly interested in measuring, a meeting was set up with the group of residents (Table 1). At the meeting, the group provided some background to their area and talked about the areas of concern and their *'desire for data to help residents make better decisions and advocate for change'*. These discussions also carried onto the group's Facebook page and were summed up by P2:

> *Firstly, there doesn't seem to be any information about the air quality in [the area] that is readily available to members of the public. I think it would be good to establish a baseline on the level of pollution within [the area], particularly along the main roads.* (P2)

Having no data available from that particular area, the residents had to rely on their perceptions and local knowledge when deciding what the most important places were that needed investigating through environmental sensing. Through discussion, people had to agree on where to focus their efforts and use the limited resources to gather environmental data about the area. As five of the participants were parents whose children went to the local schools, the focus was on areas where young people may be exposed to the harmful effects of roadside traffic pollution. This focus was a recurring theme with almost all community groups engaged throughout the project. In this sense, advocates were trying to voice the concern of those who may not have been able to do so themselves (e.g. young children, the elderly, and people with reduced mobility) but were often the ones affected by the issue the most. Although this type of engagement activity worked well in a focus group setting, it needed everyone to come together in a physical space and needed support from the researcher to facilitate the mapping. Reflecting on the engagements, it seemed that in order to scale this process and enable broader participation from the community, there was a need to reach beyond those in attendance of community group meets and support alternative modes of participation mediated by online interactions.

6.2 Planning Community Investigation

The first set of meetings and engagements over a month and a half with the community group helped identify places in the neighbourhood and the issues that people wanted to explore in those places. The next step for the community group was to come up with a strategy. After the initial meetings and conversations with the community group, they came up with a proposal called *'Air Pollution in Heaton - The desire for data to help residents make decisions'*, which consisted of: (1) Background; (2) Areas of concern; (3) A desire for data; Action plan; (4) Areas for fixed monitors; and (5) Areas for hand-held monitoring.

People were driven by the fact that there was no data available from the area to make an informed statement about the air quality. The first aim for people was to establish a baseline on the level of pollution in the area. This document also set out a clear action plan for doing so through collecting the data, but also for using the data for advocacy and activities for local benefit. The following is a statement from the air pollution bid submitted by the residents:

> *The hope is that the data collected from these monitors will fill in the current gaps in air quality data for the area and provide a good baseline for decisions of further research around measures designed to improve air quality.*

At this point, there was no fixed process in place that would set the criteria of how resources would be allocated to the people, nor any mechanism of transparency. The back and forth conversations between us and the community group that guided the creation of the proposal were not documented and stayed within the close group. In addition to the issue of transparency, there was also no opportunity for others to learn from these processes. Although the exercise of creating an action plan (i.e. proposal) was good for setting the agenda for the community-led investigation, the knowledge shared and obtained in the process stayed within the specific community group. This knowledge, however, could potentially be leveraged by another community group, and lessons learned from it would help improve the process of commissioning. Reflecting on the process of the community developing a data collection plan, there seemed to be a need to design a mechanism that encouraged wider participation of the community through active discussions and feedback loops.

6.3 Initial Community Investigation

In addition to enabling people to commission environmental monitors from the UO and get them deployed in their community, the people also wanted to be more actively involved in the investigation. This meant that there was a need for equipment that people themselves could use on their commutes to work or when taking their children to school. By doing so, people could not only get a personal perspective and idea of individual exposure, which links to health impacts, but also cover more ground in the neighbourhood and provide a good basis for decisions regarding further investigation around air quality in the area. Although these sensors would provide a snapshot of data, they would still provide a basis for discussions and decision-making for the residents. In a way, this part of the process was less linked with advocacy and raising awareness and more about self-knowledge and taking ownership of the investigation surrounding community issues. The main concerns pointed out by the members of the groups were linked to the increased volumes of traffic having an impact on people's safety and air quality. Through the UO project at Newcastle University, a high precision, hand-held particulate monitor[13] was then purchased and loaned out to the community group to start investigating the air quality in the area. At this point, all the communication with the advocacy group was carried out through face-to-face meetings or email correspondence, which also included the scheduling of the sensor handover and return to the UO. This meant that there was always a reliance on the researcher to make connections with community groups and coordinate the sensor loans, which brought to attention another design challenge and requirement for the technology. This stage of the investigation was highly dependent on the contributions of people. After they got the sensor and a brief introduction about how to use it, they needed to figure out the monitoring schedule (Section 6.2), time allocation and logistics around exchanging the monitor within the group to meet the monitoring schedule. People were given an overview of data collection methods, sampling, variability of different indicators, influencing factors and robustness of the data, but the actual monitoring plan was intentionally left for them to set out. For people doing the monitoring this served as an important step in taking ownership of the issue. An additional reason for promoting community-led investigation was the emphasis on people's experiences of living and moving around the area, which provided local tacit knowledge not obtained by the research team. These experiences were also important for understanding the issues and different perspectives around them. In order to share these perspectives, there was a need for a mechanism that would be able to capture them, in addition to the sensor readings from the hand-held sensor. These experiences and knowledge also prompted people to start thinking about how to present data to the wider community. A comment left on the group's Facebook page by P1 promoted a discussion on this for the group's meetings:

> *We need to start on some explanation to go alongside the plots explaining what's being measured and what the results mean before putting it on our site. We'll need to explain particle pollution and safe limits too, but we can talk about that on Thursday.* (P1)

This study was conducted through a user-centred co-design process, where the designed technologies were direct responses to the requirements that surfaced from engaging with the people. Several requirements for the design of the technology surfaced from the initial engagement with the community group around local issues. However, because of the participatory nature of the research, the main focus was not only on acquiring and providing people artefacts (i.e. the environmental monitors) that would give them capabilities to carry out community-led investigations, but on the whole design process and the *coupled technologies*, which were considered as a way of creating knowledge, expanding community networks and helping to build the capacity of the community.

[13] https://www.palas.de/en/product/fidasfrog

Fig. 2. Illustration of the four steps of the toolkit's process

This approach and the strategies linked to it echoes those of scholars working on civic engagement [5] and participatory design [15, 97].

7 STAGE 3: DEVELOPING, OPERATING AND EVALUATING THE SEMS TOOLKIT

From the beginning of the research, the focus and emphasis was on supporting initiatives where citizens are involved in problem definition, data collection and analysis, thus taking a *extreme citizen science* [47] approach and helping people to achieve more control [4]. The findings from the initial ethnography – conversations with the community members, observations and the design workshop – and the process of designing the community resources (Section 6) all fed into the first prototype of the SeMS toolkit. When designing it, the aim was not to develop stacks of more digital technologies because there was already an abundance of smart city technologies available, but also to look at how existing technologies could be reconfigured to be put to use by citizens for community problem-solving activities. Through the development and use of participatory GIS [54, 86] and mapping, leveraging environmental sensing equipment and models of community commissioning [42] and HCI for geospatial technologies, the first prototype of the sensor commissioning toolkit was built. Table 2 lists the implementation of the digital technologies that make up the first prototype of SeMS with links to the process of the toolkit. While the toolkit continues to be used by communities and is constantly evolving, for this analysis, the focus will be on the first prototype.

7.1 The Process

This section will provide an overview of the process for the sensor commissioning toolkit that was derived from the co-design activities (Section 6), in addition to explaining how certain design decisions were made at each step of the process. Figure 2 shows the overall makeup of the first prototype, which consisted of four steps, each of which had its associated processes and technologies. Each step is broken down into smaller activities to provide better details of the whole process of *issue identification*, *citizen data collection* and *sensor commissioning*.

7.1.1 Identify The Issues: Negotiating with the community. Like the initial engagements (Section 6), the first step of the toolkit was to aid people in identifying the issues that they were concerned with and wanted to explore in their neighbourhood. This may have been something an individual was concerned in particular or something that a group of residents might advocate for; nevertheless, these issues were almost always connected to places in the community and something that could potentially nourish the creation of a community network. The back and forth communication between the group and researcher, and the planning and organising of the sensor handover, was replaced with automated systems that people could access online. Process of identifying issues was done by signing up on SeMS website, flagging issues on map, identifying neighbourhood areas for monitoring and applying for a loan of a hand-held monitor to conduct preliminary monitoring.

Table 2. Overview of the SeMS toolkit's technologies and data produced related to process

Process	Technologies		Data Produced
	Infrastructure	**Purpose**	
Identify The Issues	Bespoke web platform	Onboarding, issue mapping	Location based issues
	Google Forms, Scripting, Calendar	Automated sensor loan system	Sensor loan schedule
	Hand-held monitors	Citizen sensing equipment	Sensor recordings
	Bespoke mobile application	Geo-tagged citizen reflections, GPS coordinates	Audio and text recordings of reflections, coordinates
	Google Drive, Python scripts	Automated data uploads, data parsing	GPS coordinates merged with hand-held sensor recordings
	Carto [14]	Data Visualisation	Maps of citizen sensing
Plan And Propose	Bespoke proposals platform	Collaboration on proposals	Proposal documents for fixed monitoring
Get The Facts	UO deployment schedules	Deploying commissioned monitors	Deployment location
Data For Everyone	City data portal	Publishing of city data	Commissioned sensor data

Enabling the community to use an online map to identify issues expanded the participation to people that may not have been present at the community meetings and also to people who may not even have been aware of these issues in the neighbourhood. They could then engage with the other residents and start a discussion around the issues of concern and plan further investigations with the community. To extend the exploration of the flagged issues, the toolkit enabled people to investigate them further through conducting environmental monitoring with hand-held monitors. People could identify areas of concern and then apply online to borrow hand-held monitors from the UO. A set of hand-held monitors was acquired based on the types of issues people flagged through the SeMS web platform. The first prototype of the toolkit had three different types of hand-held monitors: particulate monitors, noise monitors and traffic counters. What distinguishes SeMS from most other citizen-sensing initiatives is that the types of monitors used in the toolkit were scientific-grade monitors, which are considered to be high precision and often cost ten times more than the usual low-cost equipment. Once resources became available, people received or picked up a hand-held monitor from the UO, which they could use for a maximum period of one month to monitor their commutes. Additionally, a bespoke mobile application was developed for people to track their journeys and to enable them to record audio and text based reflections while doing the monitoring. Sensor data accompanied by individual perspectives was then uploaded and shared with the community to help them further understand the issues.

7.1.2 Plan And Propose: Negotiating with the UO and other stakeholders. Using hand-held monitors provided people with an opportunity to collect data from places and about issues that were not possible before. People could use that data to look at whether the issues they flagged were also showing up in the data to see if their worries around the severity of the issue in those locations were confirmed or not. The snapshot of data not only provided an overview of personal exposure on everyday commutes, but also laid a good base for planning and proposing areas that needed more focus and additional monitoring using fixed monitors. People could use this data as a discussion point for deciding where they would need to continue monitoring in order to get a better picture of the issue. The Plan and Propose step was similar to the *Planning Community Investigation* activity people engaged with in the design of the toolkit described in Section 6, but now it could reach beyond them in attendance of the meeting. For that, a bespoke online proposals platform was developed and deployed which enabled community members to create and collaborate on a proposal and plan the deployments. Additionally, the platform enabled communication and collaboration with the professionals and engineers (from the UO) doing the deployments.

7.1.3 Get The Facts. After the community had consolidated their discussions into a proposal and it was approved by everyone who participated, they moved to the next stage of scheduling the deployment with the UO. This step of the toolkit did not introduce any additional technologies to the process but instead relied on the information and scheduling obtained from the proposals created by the community group. Once deployment was agreed, engineers at UO scheduled it in with the overall deployment plan. From this point forward, the responsibility for data collection was handed over from the community to the researchers and engineers at UO, which meant that they had to guarantee successful deployment and deliver the best possible quality of data. Initially, the maximum deployment time was one month, but because the monitors needed some time to settle, the deployment time was extended up to two months. However, the community could reapply for another deployment in the future once the resources were available again.

7.1.4 Data For Everyone. Once the monitors were successfully deployed, people were notified and could access the data from their commissioned monitors using UO's city data portal. To avoid creating another data silo, the data collected from the commissioned sensors was made accessible in real time on the UO city data portal – similar to other monitors deployed in the city. The monitors were recording up to nine different environmental indicators, saving a reading every minute. Hence, in a month, one monitor would have recorded *9*43,800=394,200* readings from a commissioned place in the neighbourhood. People could then use the portal to view the latest readings, graph 24 hours or 7 days of readings, and use the data download functionality or API to get data on any period of the deployment.

7.2 Collected Data

This section reports on the usage data of SeMS (Table 2) and the observed interactions with it across different platforms and tools linked to the toolkit. Participants included in this reporting are everyone who took part in the design of the toolkit (Table 1) and also people who engaged with any of the toolkit's digital platforms later on when it was operational for the period of this evaluation (Figure 1). An overview of the submitted issues are given with their geographical division in relation to the Index of Multiple Deprivation (IMD)[15]. Additionally, this analysis provides an overview of activities for different groups and individuals who took part in the study and engaged with the digital systems.

The SeMS toolkit enables the collection of engagement metrics from three different bespoke user-facing platforms: the SeMS web platform, the automated sensor loan scheduling system, and the SeMS Proposals platform. Each system uses its own infrastructure (Table 2) to collect statistics about the engagement:

- The SeMS web platform allows reporting on the number of people signed up and reported issues and provides locations and information about inserted issues;
- The automated sensor loan scheduling system allows reporting on the number of people that applied for conducting hand-held sensing and their advocacy group association; and
- The SeMS Proposals platform allows reporting on the number of proposals created and the groups involved;

[15] https://www.gov.uk/government/statistics/english-indices-of-deprivation-2019

The SeMS toolkit was officially launched in the summer of 2017. Over two years leading up to this evaluation, 65 people had signed up through the SeMS web platform and 45 issues had been submitted using the mapping tool on the site. From there, six groups (G1-G6) and seven individuals (I1-I7) signed-up (Table 4) to borrow hand-held monitors, using the sign-up form linked to the automated sensor loan scheduling system. Following that, four proposals were submitted through the SeMS Proposals platform for commissioning fixed monitors to be installed by the UO, and four deployments have been carried out. Additional data used for this analysis originated from ethnographic work, including field notes from private meetings, community events organised by the group and public meetings around particular issues of concern. Although each platform was independent and often required users to sign up separately, ethnographic work conducted by the main author enabled links to be made between each participant's activities across different platforms and an overview of each participant's level of engagement to be compiled. However, the data collected to report on the study is not definitive as the toolkit is still operational, is constantly evolving, and is being used by communities to gather data for exploring and evidencing issues in their neighbourhoods.

7.3 Analysis

Table 3 shows that the majority of issues were linked to air quality, which was also one of the main drivers of this study. Issues with traffic were also mainly related to the air quality issue; however, one of the traffic monitoring submissions was to do with counting the number of people using the new cycle lane. The issue form also enabled people to flag issues about matters the toolkit could not measure at that point. The *Other* issues submitted where about measuring water level and quality in the river and vibrations from the building works in a residential area. This could help expand the toolkit in the future and acquire new sensing equipment to respond to citizen's concerns.

Table 3. Distribution of submitted issues on the SeMS web platform

Issue Type	**Count**	**Example**
Air Pollution	36	*There is a nursery for infants and air quality may be poor at peak times due to queuing traffic which idles / high traffic volume.*
Noise Pollution	3	*Late night noise from student houses / HMO - residents cannot get enough sleep.*
Traffic	3	*(Local) Road is a busy road off the coast road leading to (anon) Lane Ends. This area has seen a huge increase in traffic in the last 5 years. Sainsbury's expanding, new houses being built are creating more traffic.*
Other	3	*Flooding may be caused by a combination of tidal and river effects. There are warning signs in the basement of (anon) Street of what to do in the case of high water level, but no monitoring of the water level. It would be great for this data to be available through the UO so it can be used by people living and working in the area.*

Furthermore, having the mapping component on the SeMS web platform and the availability of Geo API enabled analysis of the issues through geography. Figure 3 illustrates all the submitted issues compared against the IMD, which is the official measure of relative deprivation for small areas in England and Wales, as outlined by the Office of National Statistics (ONS). These statistics are published at the level of Lower Super Output Areas (LSOAs) that contain an average of 1,500 residents within any given boundary. The IMD uses seven domains to produce this overall measure: income, employment, education, skills and training, health and disability, crime, barriers to housing and services, and living environment. Using this metric, it is possible to look at the socioeconomic characteristics of the areas and draw a comparison between different neighbourhoods within England and Wales. When looking at the flagged issues compared against the IMD, it can be seen that the majority of the issues flagged are in the 10% - 40% of the least deprived areas according to the metric. This may be an indication that the people who engaged with the toolkit were living in those areas.

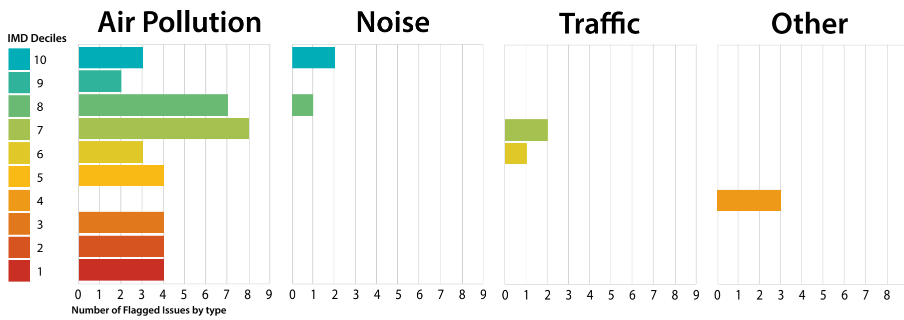

Fig. 3. Number of Flagged Issues compared against Indices of Multiple Deprivation (IMD) statistics: *decile 1* represents the most deprived 10 per cent of areas and *decile 10* represents the least deprived 10 per cent of areas nationally

Table 4. The SenseMyStreet toolkit usage: ✓ means 'yes', × means 'no' and ◯ indicate that the engagement is ongoing (no data yet) and 'None' indicates no data available

	Existing Community Group	**Flagged Issues**	**Hand-Held Monitoring**	**Formulated Publics**	**Submitted Proposal**	**Planned Action**	**Used Data**	**Channel(s)**
G1	×	✓	✓	✓	✓	✓	✓	Newsletter, Facebook, Blog, Twitter
I1	×	✓	✓	✓	✓	✓	✓	Blog, Twitter
G2	✓	✓	✓	✓	✓	×	×	Facebook, Website
I2	×	×	✓	×	×	×	×	None
G3	✓	✓	✓	✓	×	×	×	Facebook
G4	✓	×	✓	×	×	×	×	Website
I6	×	×	✓	×	×	×	×	None
I4	×	×	×	×	×	×	×	None
G5	✓	✓	✓	✓	✓	✓	◯	Facebook, Website
I3	×	✓	✓	✓	✓	×	◯	None
G6	✓	✓	✓	✓	◯	◯	◯	Facebook
I5	×	✓	✓	◯	◯	◯	◯	None
I7	×	✓	✓	◯	◯	◯	◯	None

Based on ethnographic work and the toolkit usage data (Section 7.2), an analysis of the overall engagement with the digital platforms supporting the process of commissioning was conducted. In order to understand the factors influencing active citizen engagement with the commissioning toolkit and physical infrastructure, a comparison of activities for each community group or individual has been analysed. Table 4 shows the level of engagement and usage of the different technologies across the toolkit. The key aspects considered are: existing community *group*, perceived *issues* flagged on the SeMS web platform, engagement in hand-held *monitoring*, formulation of a *public* [32] around the issue, submission of a *proposal* for sensor commissioning, an action *plan* for data use, and usage of *data* by the community. Additionally, each individual's or group's communication *channel(s)* with the community are provided as a comparison.

The analysis indicated that the existence of a community group is not essential for starting engagement with the toolkit. In many cases, groups and publics formed alongside participating in the activities related to the SeMS toolkit. However, it was paramount to identify the issues within the community to focus on at specific locations in the neighbourhood. Participants who did not identify the issues or did not have a specific agenda in mind did not manage to get further from hand-held monitoring. There was one special case where an individual's advocacy efforts might have had negative consequences on their quality of life, which meant that the issue was dropped by the individual. However, it could be picked up again if enough people are interested in the issue and want to do something about it. This indicates that there is a need for a public to emerge at some point in order to ensure the successful use of the toolkit and the data it generates. The findings also indicate that participant(s) who set a prerequisite action plan following data generation managed to make use of the data. This was prominent in both cases – when people used hand-held monitors to collect measurements or using data generated through commissioned monitors. There were instances where participants engaged with the toolkit up to the point of getting fixed monitors commissioned from the UO, seeing that as the end result of the engagement. Although the data generated may be useful in the future as part of the city dataset, e.g. when infrastructure changes are implemented in the area, without any promotion or intended use by citizens, it does not serve the purpose with regard to the effective use of data by the community itself for civic participation, advocacy and action.

8 DISCUSSION

In this paper we explore how citizens can take more active roles as prosumers of data in the smart city. Through the iterative co-design process of setting up the SenseMyStreet toolkit and evaluating its use, we illustrated how commissioning infrastructures are effective in providing mechanisms for democratising access to smart city technology and promoting active citizen data production. We discuss how commissioning can be seen as infrastructuring that opens up the digital and physical infrastructure of the city to citizens, enables the integration of citizen data into the smart city decision-making processes and through careful configuring can help form community networks for taking local action. The documented design and implementation of the SeMS toolkit provides an example for researchers and practitioners working in this space, and could help to inform the design of projects that have similar aims.

8.1 Increasing Social Equity Through Commissioning

Although the promise of smart cities is to fight injustices and provide prosperity to everyone, the physical infrastructure powering the smart city is still inaccessible for citizens. Despite data from it often being made available, citizens to not have any control over how these smart city assets (e.g. sensors) are spatially distributed and for what reasons. This puts communities in a disadvantageous position of not being able to address issues important to them. The way scholars in design and HCI and have aimed to address this is by focusing their efforts to design technology for immediate use by communities or a response to a particular inquiry, but also for future unseen uses [16, 26, 30, 38]. This is what is referred to as *infrastructuring*, which essentially means using design practices to support capacity building in the community.

Designing commissioning platforms situates itself somewhere in between, where the aim is to develop a generic infrastructure that could be appropriated by people in their pursuit of issues, e.g. systems such as App Movement, where people come together to leverage technological infrastructure to commission bespoke location-based mobile applications [41]. Although it is packaged as a finished platform or toolkit (i.e. product or a thing), it is driven by a participatory design process, facilitates the discovery of issues and also promotes the creation of publics [32]. This contradicts what Ehn [38] has suggested; however, similar findings were discovered from a community project around the design and use of a Community Resource Messenger (CRM) system for homeless communities living in urban areas [30]. Although the CRM system was designed as a response to a practical need of a population, it still facilitated the creation of publics and their attachments around issues.

As designers, and particularly as engineers of these technologies for participation and civic engagement, there is often a desire to respond to people's requirements with a particular novel solution or a digital tool that addresses the issue. In the case of a commissioning toolkit, it could still be a product or a useful system, but it has to facilitate infrastructuring. Consequently, we argue that commissioning is changing the way we understand infrastructuring. Community commissioning platforms should not shy away from being designed as purposeful systems; however they should be built for uses that are defined through engaging with it and issues of concern. Moreover, as we illustrated with SeMS, commissioning platforms are great at facilitating access to the physical resources of the city (i.e. smart city sensors) in order to engage in the exploration of local issues. Commissioning in this instance is infrastructuring engagement around digital or physical infrastructure. Making those resources available for citizens and opening up smart city technologies for a more equitable society. The availability of physical tools (i.e. environmental monitors) can provide support for community action through enabling people to participate in the creation of new sources of data for the city that did not exist before.

Citizens accessing physical infrastructure through SeMS was actually a two stage process: (1) citizen sensing using hand-held monitors (2) and commissioning environmental sensor data from the UO. In the first stage, people engaged in the data collection themselves by using borrowed hand-held monitors to learn more about the issue and what goes into environmental monitoring – the issues with the technologies, the uncertainties with the readings and the value of the data. This helped the community get a personal perspective and take ownership of the issue in hand. Enabling citizens access to the smart city tools that are already used by city officials and scientist responded to critiques of citizen sensing projects, which are often derided because the types of sensors used by the public are considered to be 'toys' [40]. In the second stage, people commissioned stationary monitors to be placed in their neighbourhood by professionals at the UO who carried out the data generation. This meant that the community-commissioned monitors received the same attention and went through the same deployment process as they would if the data had been collected for scientific research or policy purposes.

Certainly, commissioned sensors from the SeMS helped generate data about the local community to inform issues of concern in the neighbourhood and enable people to voice their concerns by making them more visible to others through appropriating the toolkit's resources. Designing provisioning of existing smart city resources through commissioning, rather than creating a novel one off solution, is more likely to support capacity building (in terms of skills and knowledge) that would benefit the community in the long run and provide recurring and sustained participation around issues of concern. The SeMS design process and resulting platform described in this paper provides an example for other researchers and designers of how such commissioning of resources and provisioning of physical infrastructure through digital platforms could be configured. Commissioning platforms, such as SeMS have the ability to scale up or streamline the processes of infrastructuring, at the same time as preserving the components of participatory design for constituting publics to develop attachments to act upon [30, 70]. However, within this somewhat generic system for engagement, it is still important to recognise the diverse nature of these formed publics and provide different levels of support for taking action.

8.2 Communities' Role as Active Data Producers

The aim of this research was to uncover mechanisms to democratise data production for the smart city by enabling citizens to collect and explore data relevant to the issues important to them at the hyper-local scale. The SeMS toolkit and the process of sensor commissioning successfully provided mechanisms to carry out a citizen-led deployment of environmental monitors and helped generate data about issues important to communities. The toolkit also created a situation where data was demand-driven rather than the usual open data portal's ideology – 'If we put data out there, people will use it'. Local communities needed that hyper-local data in order to take action and advocate for change. Moreover, the data produced by citizens did not get siloed from the rest of the data powering the smart city, it became embedded into the dataset used by the decision-makers. Additionally, having the data for the whole city accessible in one place also enabled communities to compare the sensor readings from their area to other areas, thus giving them an idea of their neighbourhood matched up to others. The mechanisms of SeMs exemplified how we can move away from the tokenism engagement with the smart city to citizens being equal prosumers of data.

Furthermore, the online tools of SeMS enabled the commissioning process to scale and extend the participation through different forms of communications for people unable, or unwilling, to engage in face-to-face dialogue; for example, taking the proposal creation online provided a way for people who could not make or were not aware of community meetings to participate in the discussion and get their voices represented. Additionally, it also helped to document the process for transparency and reproduction, sharing the knowledge with other groups who may want to carry out their own investigations and submit a proposal of their own. Proposals were also looked over by expert professionals at the UO who could give communities guidance on how to get the most out of the deployment in terms of data quality and placements of the commissioned monitors. This process of technological distribution is generally decided behind closed doors and not published for public scrutiny. However, the decisions made of where and what data to collect will influence the resulting actions taken and the populations affected. We need to make sure that not only everyone has access to tools to produce data for the city, but also be able to understand the motivations and be able to interrogate data produced by others.

This however opens up issues around the ownership and people's rights to these data sources. There is ongoing debate around data ownership regarding its generation and rights to access[16]. This also extends to the idea that data has no owner, whereas the collection of data does. However, if the data is commissioned by the community, does this mean that the community owns this data? The SenseMySteet project and the UO, who deployed the commissioned monitors, both work in the spirit of transparency and openness, which means that the data is made publicly available using open licences. If data is in the public domain, who does it belong to, and can the community take ownership of it? By definition, open data *'can be freely accessed, used, modified and shared by anyone for any purpose – subject only, at most, to requirements to provide attribution and/or share-alike'*[17], and as defined by Open Definition, it has to be open both legally (licensed under open licence) and technically (without attached costs) in bulk and machine-readable format. Both of these statements speak true for our study.

It is worth noting that when communities handed over the task of data collection to the research team at the UO, they put a lot of trust in the process; however, that often meant they also handed over responsibility for appropriating the collected data. This was evident with some groups that participated in the study, where they commissioned the sensors to provide data for the community without having a particular aim to use it themselves in the future:

> *Air Pollution Monitors along Brunton Lane near the roundabouts would be beneficial to everyone.* (Posted on SenseMyStreet Proposals platform)

[16] https://royalsociety.org/-/media/policy/projects/data-governance/data-ownership-rights-and-controls-October-2018.pdf
[17] http://opendatahandbook.org/glossary/en/terms/open-data

Unfortunately, this meant that once the stationary monitor was installed, the group stopped interacting with the toolkit because there were no next steps planned with the data. Nevertheless the data that had been collected from the commissioned sensor was now part of the city dataset available to everyone. In that sense the data also became a shared responsibility of everyone involved. Whether it was a role of UO to steward and make this data accessible, data scientists to use this data to provide useful insights, and city officials to include those in the decision-making process and citizens to leverage those to draw attention to the issues and advocate for positive change in the community. Hence, we argue that there is need to move away from looking at data for decision-making that affects us all as something that is owned, and rather look at it more as a shared resource for everyone's benefit [90], making us more responsible of our decisions and actions around data production and use.

8.3 Configuring Commissioning for Creation of Community Networks

The SeMS toolkit enabled people to access the physical resources of the smart city in order to engage in the exploration of local issues. Hence, the question is: *Can the act of using or deploying the sensors be seen as a successful effort of infrastructuring?* We argue that availability of physical infrastructure and the act of participating itself does not facilitate the creation of – or is not sufficient enough by itself to form – the publics [32] needed to move towards citizens taking action. Commissioning process has to provide scaffolding to help achieve this. As we noted before, commissioning as infrastructuring has to facilitate engagement around digital or physical infrastructure (e.g. smart city sensors). In this sense, it needs to be integrated with activities supporting the usage of these physical things. The SeMS toolkit approached this through a four-step exploration process that facilitated the framing of issues, gathering support and developing attachments. Issue discovery was built into the system through participatory GIS and citizen sensing to align data generation with particular concerns and to help form publics around those issues. This aligns with the ideas of Marres [70] and Dantec and DiSalvo [30] regarding infrastructuring, where socio-technical processes and resources are put in place to support imagined futures.

Moreover, without going through the SeMS process, the physical infrastructure did not necessarily provide the effective use of the resources by communities. This was evident in a couple of cases where people signed up to borrow hand-held monitors without defining the issue (i.e. mapping it through the platform) they were interested in (by skipping the first step of the toolkit). Some of them did not collect the monitors and some just tested the monitors for a brief while and then stopped doing so. That is not to say, however, that self-discovery and learning about technology are not useful for framing issues. When reflecting on the process of commissioning, it seems that getting the commissioned sensors deployed was actually marking a start of additional activities that related to the effective use of data by citizens. In a similar way, as pointed out by [30]:

> *[...] infrastructuring comes as a result of the reconfigurations that occur around and with a technological intervention; that is, the deployment of the technology is a beginning, not an end.* [30, p .249]

Hence, there needs to be careful configuring of commissioning and the tools that facilitate it to promote further actions for the community. Documented way to achieve this is through *ownership* as it steers people towards future action [30], whether it is taking ownership and building attachments to issues [5, 33, 70] or taking ownership of the designed technology [34]. The SeMS toolkit worked well in helping people take ownership of the issues by publicly posting them and enabling people to attach personal opinions on the matter, which could then be investigated through data collection. Taking ownership of the designed technology (i.e. the toolkit and all the resources), however, appeared to be much more multifaceted. Commissioning systems are usually designed as generic platforms or systems that connect multiple platforms and bespoke sub-systems, which is referred to as design 'appropriation' [37] or an 'unplatformed' design [64] approach, implying the use of online platforms for purposes that they were not initially designed for. The SeMS toolkit could be considered as an unplatformed system because of its use of multiple configurable platforms like bespoke GIS web platform and proposals platform, Carto, and Google Drive, Forms, Calendar, mobile app and Scripting (with the addition of physical infrastructure in the form of scientific-grade environmental monitors). However, a hidden part of the toolkit was also the communication channels (e.g. Facebook, Twitter, and blogs) that groups used to exchange ideas and share information (also [3, 27]). These parts should not be excluded from the process of commissioning because they often already have an existing community and their technologies that could be integrated into the process.

The configuration of commissioning platforms should be fluid, flexible and ad-hoc to accommodate different communities, ways of doing things and routes to action, at the same time providing equal access to digital or physical infrastructure. Moreover, there is often more tangible value generated from in situ and informal social encounters where information exchange is happening. Carroll and Rosson [21] point out that the social context helps to concentrate focus and make the activities more goal-oriented. In other words, people are more likely to commit to responsibilities and make something of vital importance happen because success and failure in community-led projects largely depend on individual initiative-taking [22]. However, how things are actually done with regard to the responsibilities to make something happen is face-to-face and in small core groups of communities that have combined people with different skills. The findings from the toolkit usage suggest that there is an importance to planned action and establishing a strong community network. It is not only important for keeping up engagement with the toolkit, but also for sharing skills, increasing social capital and building community knowledge.

As mentioned before, the initial involvement in the design process was by active people and groups of advocates in already identified communities, enabling us to leverage the momentum and get the community resources out there. However, outside this group, more people signed up through the infrastructures that were set up as a result of the research. In a sense these groups and communities are also in competition with each other for literally the space in the city. Meaning changes and improvements in the built infrastructure could have negative implications in other areas of the city, e.g. diverting all the traffic from one area to another. Looking at the initial identified issues (Figure 3), there is a skew towards more issues being flagged in affluent areas.

In addition to learning from other communities' commissioning process, there are ways that technology can support interactions between people in different groups, help articulate shared concerns and values, facilitate information gathering and build shared knowledge between these hyper-local communities [21]. Going forward, there is a need to further identify the underlying relations that help constitute networks as supporting infrastructure for proximate communities [20, 21]. Furthermore, these should also be integrated into the design of the digital tools and processes for commissioning to promote creation of these networks, particularly for communities that are placed in a disadvantaged position. These are the immediate next steps for the SeMS as well as further assessing toolkit's infrastructure to act as a catalyst for civic advocacy and action through an evaluation of its longitudinal use and by the communities.

9 CONCLUSIONS

In this paper we described a two-year longitudinal study that led to the design, development and deployment of SenseMyStreet (SeMS), a sensor commissioning toolkit for communities. The SeMS toolkit enables people to use scientific environmental sensing equipment to investigate local issues and commission environmental sensors from the smart city, placing them in the neighbourhood to gather data relevant to community issues at a hyper-local scale. We outlined, in detail, the iterative co-design process of setting up SeMS and provided an overview of the processes and digital technologies linked to operating a sustainable sensor commissioning toolkit. This research illustrates how commissioning can be used to enable equitable citizen access to smart city technologies and democratise data production that powers decision-making. Our findings highlight how commissioning can provide further opportunities for collaboration, use of data, and joined up thinking and acting between hyper-local communities. The SeMS toolkit continues to operate as part of Urban Observatory at Newcastle, enabling communities and citizens to gather data relevant to issues important to them at a hyper-local scale and integrate that data into the smart city datasets used for decision-making.

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REFERENCES

[1] David M. Aanensen, Derek M. Huntley, Edward J. Feil, Fada'a al Own, and Brian G. Spratt. 2009. EpiCollect: Linking Smartphones to Web Applications for Epidemiology, Ecology and Community Data Collection. *PLoS ONE* 4, 9 (Sept. 2009). https://doi.org/10.1371/journal.pone.0006968

[2] Mags Adams, Trevor Cox, Gemma Moore, Ben Croxford, Mohamed Refaee, and Steve Sharples. 2006. Sustainable Soundscapes: Noise Policy and the Urban Experience. *Urban Studies* 43, 13 (Dec. 2006), 2385–2398. https://doi.org/10.1080/00420980600972504

[3] Nader Afzalan and Jennifer Evans-Cowley. 2015. Planning and Social Media: Facebook for Planning at the Neighbourhood Scale. *Planning Practice & Research* 30, 3 (May 2015), 270–285. https://doi.org/10.1080/02697459.2015.1052943

[4] Sherry R. Arnstein. 1969. A Ladder Of Citizen Participation. *Journal of the American Institute of Planners* 35, 4 (July 1969), 216–224. https://doi.org/10.1080/01944366908977225

[5] Mariam Asad and Christopher A. Le Dantec. 2017. Tap the "Make This Public" Button: A Design-Based Inquiry into Issue Advocacy and Digital Civics. In *Proceedings of the 2017 CHI Conference on Human Factors in Computing Systems - CHI '17*. ACM Press, Denver, Colorado, USA, 6304–6316. https://doi.org/10.1145/3025453.3026034

[6] Mariam Asad, Christopher A. Le Dantec, Becky Nielsen, and Kate Diedrick. 2017. Creating a Sociotechnical API: Designing City-Scale Community Engagement. In *Proceedings of the 2017 CHI Conference on Human Factors in Computing Systems - CHI '17*. ACM Press, Denver, Colorado, USA, 2295–2306. https://doi.org/10.1145/3025453.3025963

[7] Stefan Baack. 2015. Datafication and empowerment: How the open data movement re-articulates notions of democracy, participation, and journalism. *Big Data & Society* 2, 2 (Dec. 2015), 205395171559463. https://doi.org/10.1177/2053951715594634

[8] Madeline Balaam, Rob Comber, Ed Jenkins, Selina Sutton, and Andrew Garbett. 2015. FeedFinder: A Location-Mapping Mobile Application for Breastfeeding Women. In *Proceedings of the 33rd Annual ACM Conference on Human Factors in Computing Systems (CHI '15)*. ACM, New York, NY, USA, 1709–1718. https://doi.org/10.1145/2702123.2702328 event-place: Seoul, Republic of Korea.

[9] Mara Balestrini, Paul Marshall, and Tomas Diez. 2014. Beyond boundaries: the home as city infrastructure for smart citizens. In *Proceedings of the 2014 ACM International Joint Conference on Pervasive and Ubiquitous Computing Adjunct Publication - UbiComp '14 Adjunct*. ACM Press, Seattle, Washington, 987–990. https://doi.org/10.1145/2638728.2641557

[10] Mara Balestrini, Yvonne Rogers, Carolyn Hassan, Javi Creus, Martha King, and Paul Marshall. 2017. A City in Common: A Framework to Orchestrate Large-scale Citizen Engagement around Urban Issues. In *Proceedings of the 2017 CHI Conference on Human Factors in Computing Systems - CHI '17*. ACM Press, Denver, Colorado, USA, 2282–2294. https://doi.org/10.1145/3025453.3025915

[11] Michael Batty. 2013. Big data, smart cities and city planning. *Dialogues in Human Geography* 3, 3 (Nov. 2013), 274–279. https://doi.org/10.1177/2043820613513390

[12] Moritz Behrens, Nina Valkanova, Ava Fatah gen. Schieck, and Duncan P. Brumby. 2014. Smart Citizen Sentiment Dashboard: A Case Study Into Media Architectural Interfaces. In *Proceedings of The International Symposium on Pervasive Displays - PerDis '14*. ACM Press, Copenhagen, Denmark, 19–24. https://doi.org/10.1145/2611009.2611036

[13] Lasse Berntzen and Evika Karamagioli. 2010. Regulatory Measures to Support eDemocracy. In *2010 Fourth International Conference on Digital Society*. 311–316. https://doi.org/10.1109/ICDS.2010.74 ISSN: null.

[14] Lasse Berntzen, Marius Rohde Johannesen, Stephan Böhm, Christian Weber, and Roberto Morales. 2018. Citizens as Sensors - Human Sensors as a Smart City Data Source. 11–18. https://www.thinkmind.org/index.php?view=article&articleid=smart_2018_1_30_40068

[15] Thomas Binder, Giorgio De Michelis, Pelle Ehn, Giulio Jacucci, Per Linde, and Ina Wagner. 2011. *Design Things*. MIT Press. Google-Books-ID: XTvKPmnEsk8C.

[16] Erling Björgvinsson, Pelle Ehn, and Per-Anders Hillgren. 2010. Participatory design and "democratizing innovation". In *Proceedings of the 11th Biennial Participatory Design Conference on - PDC '10*. ACM Press, Sydney, Australia, 41. https://doi.org/10.1145/1900441.1900448

[17] Alexandra Bolton, Lorraine Butler, Ian Dabson, Mark Enzer, Matthew Evans, Tim Fenemore, Fergus Harradence, Emily Keaney, Anne Kemp, Alexandra Luck, Neill Pawsey, Steve Saville, Jennifer Schooling, Miranda Sharp, Tom Smith, Jeni Tennison, Jennifer Whyte, Alan Wilson, and Chara Makri. 2018. *Gemini Principles*. Technical Report. Apollo - University of Cambridge Repository. https://doi.org/10.17863/cam.32260

[18] C. F. Calvillo, A. Sánchez-Miralles, and J. Villar. 2016. Energy management and planning in smart cities. *Renewable and Sustainable Energy Reviews* 55 (March 2016), 273–287. https://doi.org/10.1016/j.rser.2015.10.133

[19] Paolo Cardullo and Rob Kitchin. 2019. Being a 'citizen' in the smart city: up and down the scaffold of smart citizen participation in Dublin, Ireland. *GeoJournal* 84, 1 (Feb. 2019), 1–13. https://doi.org/10.1007/s10708-018-9845-8

[20] John M. Carroll, Jordan Beck, Shipi Dhanorkar, Jomara Binda, Srishti Gupta, and Haining Zhu. 2018. Strengthening Community Data: Towards Pervasive Participation. In *Proceedings of the 19th Annual International Conference on Digital Government Research: Governance in the Data Age (dg.o '18)*. ACM, New York, NY, USA, 65:1–65:9. https://doi.org/10.1145/3209281.3209312 event-place: Delft, The Netherlands.

[21] John M. Carroll and Mary Beth Rosson. 2003. A Trajectory for Community Networks Special Issue: ICTs and Community Networking. *The Information Society* 19, 5 (Nov. 2003), 381–393. https://doi.org/10.1080/714044685

[22] John M. Carroll and Mary Beth Rosson. 2007. Participatory design in community informatics. *Design Studies* 28, 3 (May 2007), 243–261. https://doi.org/10.1016/j.destud.2007.02.007

[23] Hafedh Chourabi, Taewoo Nam, Shawn Walker, J. Ramon Gil-Garcia, Sehl Mellouli, Karine Nahon, Theresa A. Pardo, and Hans Jochen Scholl. 2012. Understanding Smart Cities: An Integrative Framework. In *2012 45th Hawaii International Conference on System Sciences*. IEEE, Maui, HI, USA, 2289–2297. https://doi.org/10.1109/HICSS.2012.615

[24] Sandy Claes and Andrew Vande Moere. 2013. Street Infographics: Raising Awareness of Local Issues through a Situated Urban Visualization. In *Proceedings of the 2nd ACM International Symposium on Pervasive Displays - PerDis '13*. ACM Press, Mountain View, California, 133. https://doi.org/10.1145/2491568.2491597

[25] James S. Coleman. 1988. Social Capital in the Creation of Human Capital. *Amer. J. Sociology* 94 (Jan. 1988), S95–S120. https://doi.org/10.1086/228943

[26] Clara Crivellaro, Rob Anderson, Daniel Lambton-Howard, Tom Nappey, Patrick Olivier, Vasilis Vlachokyriakos, Alexander Wilson, and Pete Wright. 2019. Infrastructuring Public Service Transformation: Creating Collaborative Spaces between Communities and Institutions through HCI Research. *ACM Transactions on Computer-Human Interaction* 26, 3 (May 2019), 15:1–15:29. https://doi.org/10.1145/3310284

[27] Clara Crivellaro, Rob Comber, John Bowers, Peter C. Wright, and Patrick Olivier. 2014. A Pool of Dreams: Facebook, Politics and the Emergence of a Social Movement. In *Proceedings of the SIGCHI Conference on Human Factors in Computing Systems (CHI '14)*. ACM, New York, NY, USA, 3573–3582. https://doi.org/10.1145/2556288.2557100 event-place: Toronto, Ontario, Canada.

[28] Clara Crivellaro, Rob Comber, Martyn Dade-Robertson, Simon J. Bowen, Peter C. Wright, and Patrick Olivier. 2015. Contesting the City: Enacting the Political Through Digitally Supported Urban Walks. In *Proceedings of the 33rd Annual ACM Conference on Human Factors in Computing Systems (CHI '15)*. ACM, New York, NY, USA, 2853–2862. https://doi.org/10.1145/2702123.2702176 event-place: Seoul, Republic of Korea.

[29] R P Dameri and A Cocchia. 2013. Smart City and Digital City: Twenty Years of Terminology Evolution. In *Proceedings Itais*. 9.

[30] Christopher A Le Dantec and Carl DiSalvo. 2013. Infrastructuring and the formation of publics in participatory design. *Social Studies of Science* 43, 2 (April 2013), 241–264. https://doi.org/10.1177/0306312712471581

[31] Food and Rural Affairs (Defra) webmaster@defra gsi gov uk Department for Environment. 2018. *Air Pollution in the UK report- Defra, UK*. Technical Report. London. https://uk-air.defra.gov.uk/library/annualreport/

[32] John Dewey. 1954. *The Public and its Problems*. Swallow Press, Athens.

[33] Carl DiSalvo, Marti Louw, Julina Coupland, and MaryAnn Steiner. 2009. Local issues, local uses: tools for robotics and sensing in community contexts. In *Proceeding of the seventh ACM conference on Creativity and cognition - C&C '09*. ACM Press, Berkeley, California, USA, 245. https://doi.org/10.1145/1640233.1640271

[34] Carl DiSalvo and Jonathan Lukens. 2009. Towards a Critical Technological Fluency: The Confluence of Speculative Design and Community Technology Programs. (Dec. 2009). https://escholarship.org/uc/item/7jz308ws

[35] Carl DiSalvo, Illah Nourbakhsh, David Holstius, Ayça Akin, and Marti Louw. 2008. The Neighborhood Networks Project: A Case Study of Critical Engagement and Creative Expression Through Participatory Design. In *Proceedings of the Tenth Anniversary Conference on Participatory Design 2008 (PDC '08)*. Indiana University, Indianapolis, IN, USA, 41–50. http://dl.acm.org/citation.cfm?id=1795234.1795241 event-place: Bloomington, Indiana.

[36] Carl DiSalvo, Phoebe Sengers, and Hrönn Brynjarsdóttir. 2010. Mapping the Landscape of Sustainable HCI. In *Proceedings of the SIGCHI Conference on Human Factors in Computing Systems (CHI '10)*. ACM, New York, NY, USA, 1975–1984. https://doi.org/10.1145/1753326.1753625 event-place: Atlanta, Georgia, USA.

[37] Alan Dix. 2007. Designing for appropriation. In *Proceedings of the 21st British HCI Group Annual Conference on People and Computers: HCI...but not as we know it - Volume 2 (BCS-HCI '07)*. BCS Learning & Development Ltd., University of Lancaster, United Kingdom, 27–30.

[38] Pelle Ehn. 2008. Participation in Design Things. In *Proceedings of the Tenth Anniversary Conference on Participatory Design 2008 (PDC '08)*. Indiana University, Indianapolis, IN, USA, 92–101. http://dl.acm.org/citation.cfm?id=1795234.1795248 event-place: Bloomington, Indiana.

[39] Marcus Foth. 2009. *Handbook of Research on Urban Informatics: The Practice and Promise of the Real-Time City*. Vol. 75. http://www.tandfonline.com/doi/abs/10.1080/01944360903167661

[40] Jennifer Gabrys and Helen Pritchard. 2018. Just Good Enough Data and Environmental Sensing: Moving beyond Regulatory Benchmarks toward Citizen Action. *International Journal of Spatial Data Infrastructures Research* (2018), 11.

[41] Andrew Garbett, Rob Comber, Edward Jenkins, and Patrick Olivier. 2016. App Movement: A Platform for Community Commissioning of Mobile Applications. In *Proceedings of the 2016 CHI Conference on Human Factors in Computing Systems - CHI '16*. ACM Press, Santa Clara, California, USA, 26–37. https://doi.org/10.1145/2858036.2858094

[42] Andrew Thomas Garbett. 2017. *Designing community driven participatory platforms : reconfiguring roles, resources, infrastructure, and constraints for community commissioning*. Thesis. Newcastle University. http://theses.ncl.ac.uk/jspui/handle/10443/3920 Accepted: 2018-06-25T13:21:08Z.

[43] Connie Golsteijn, Sarah Gallacher, Licia Capra, and Yvonne Rogers. 2016. Sens-Us: Designing Innovative Civic Technology for the Public Good. In *Proceedings of the 2016 ACM Conference on Designing Interactive Systems - DIS '16*. ACM Press, Brisbane, QLD, Australia, 39–49. https://doi.org/10.1145/2901790.2901877

[44] Amir Haj-Bolouri, Lennarth Bernhardsson, and Matti Rossi. 2015. Introducing PADRE : Participatory Action Design Research.

[45] Amir Haj-Bolouri, Lennarth Bernhardsson, and Matti Rossi. 2016. PADRE: A Method for Participatory Action Design Research. 19–36. https://doi.org/10.1007/978-3-319-39294-3_2

[46] David Hakken. 2003. A Social Informatics Approach to Knowledge in Cyberspace. In *The Knowledge Landscapes of CyberSpace*. Routledge, New York, New York, USA, 145–177.

[47] Muki Haklay. 2013. Citizen Science and Volunteered Geographic Information: Overview and Typology of Participation. In *Crowdsourcing Geographic Knowledge*, Sarah Elwood, Michael Goodchild, and Daniel Sui (Eds.). Springer Netherlands, Dordrecht, 105–122. https://doi.org/10.1007/978-94-007-4587-2_7

[48] Carl Hartung, Adam Lerer, Yaw Anokwa, Clint Tseng, Waylon Brunette, and Gaetano Borriello. 2010. Open Data Kit: Tools to Build Information Services for Developing Regions. In *Proceedings of the 4th ACM/IEEE International Conference on Information and Communication Technologies and Development (ICTD '10)*. ACM, New York, NY, USA, 18:1–18:12. https://doi.org/10.1145/2369220.2369236 event-place: London, United Kingdom.

[49] David Hasenfratz, Olga Saukh, Silvan Sturzenegger, and Lothar Thiele. 2012. Participatory Air Pollution Monitoring Using Smartphones. In *2nd International Workshop on Mobile Sensing*. 5.

[50] Luke Hespanhol, Martin Tomitsch, Ian McArthur, Joel Fredericks, Ronald Schroeter, and Marcus Foth. 2015. Vote as you go: blending interfaces for community engagement into the urban space. In *Proceedings of the 7th International Conference on Communities and Technologies - C&T '15*. ACM Press, Limerick, Ireland, 29–37. https://doi.org/10.1145/2768545.2768553

[51] Lindsay H. Hoffman. 2012. Participation or Communication? An Explication of Political Activity in the Internet Age. *Journal of Information Technology & Politics* 9, 3 (July 2012), 217–233. https://doi.org/10.1080/19331681.2011.650929

[52] Yen-Chia Hsu, Paul Dille, Jennifer Cross, Beatrice Dias, Randy Sargent, and Illah Nourbakhsh. 2017. Community-Empowered Air Quality Monitoring System. In *Proceedings of the 2017 CHI Conference on Human Factors in Computing Systems (CHI '17)*. Association for Computing Machinery, New York, NY, USA, 1607–1619. https://doi.org/10.1145/3025453.3025853

[53] J J Huck, J D Whyatt, P Coulton, and A Gradinar. 2014. Mapping Traffic Pollution Exposure: the Quantified Self. *Proceedings of the GIS Research UK 22nd Annual Conference* (2014), 11.

[54] Piotr Jankowski. 2009. Towards participatory geographic information systems for community-based environmental decision making. *Journal of Environmental Management* 90, 6 (May 2009), 1966–1971. https://doi.org/10.1016/j.jenvman.2007.08.028

[55] Ian G. Johnson, Alistair MacDonald, Jo Briggs, Jennifer Manuel, Karen Salt, Emma Flynn, and John Vines. 2017. Community Conversational: Supporting and Capturing Deliberative Talk in Local Consultation Processes. In *Proceedings of the 2017 CHI Conference on Human Factors in Computing Systems - CHI '17*. ACM Press, Denver, Colorado, USA, 2320–2333. https://doi.org/10.1145/3025453.3025559

[56] Ian G. Johnson, Aare Puussaar, Jennifer Manuel, and Peter Wright. 2018. Neighbourhood Data: Exploring the Role of Open Data in Locally Devolved Policymaking Processes. *Proc. ACM Hum.-Comput. Interact.* 2, CSCW (Nov. 2018), 83:1–83:20. https://doi.org/10.1145/3274352

[57] Ian G. Johnson, John Vines, Nick Taylor, Edward Jenkins, and Justin Marshall. 2016. Reflections on Deploying Distributed Consultation Technologies with Community Organisations. In *Proceedings of the 2016 CHI Conference on Human Factors in Computing Systems - CHI '16*. ACM Press, Santa Clara, California, USA, 2945–2957. https://doi.org/10.1145/2858036.2858098

[58] Sunyoung Kim, Jennifer Mankoff, and Eric Paulos. 2013. Sensr: evaluating a flexible framework for authoring mobile data-collection tools for citizen science. In *Proceedings of the 2013 conference on Computer supported cooperative work - CSCW '13*. ACM Press, San Antonio, Texas, USA, 1453. https://doi.org/10.1145/2441776.2441940

[59] Cornel Klein and Gerald Kaefer. 2008. From Smart Homes to Smart Cities: Opportunities and Challenges from an Industrial Perspective. In *Next Generation Teletraffic and Wired/Wireless Advanced Networking*. Springer, Berlin, Heidelberg, 260–260. https://doi.org/10.1007/978-3-540-85500-2_24

[60] Lisa Koeman, Vaiva Kalnikaite, Yvonne Rogers, and Jon Bird. 2014. What Chalk and Tape Can Tell Us: Lessons Learnt for Next Generation Urban Displays. In *Proceedings of The International Symposium on Pervasive Displays - PerDis '14*. ACM Press, Copenhagen, Denmark, 130–135. https://doi.org/10.1145/2611009.2611018

[61] Vassilis Kostakos, Jakob Rogstadius, Denzil Ferreira, Simo Hosio, and Jorge Goncalves. 2017. Human Sensors. In *Participatory Sensing, Opinions and Collective Awareness*, Vittorio Loreto, Muki Haklay, Andreas Hotho, Vito D.P. Servedio, Gerd Stumme, Jan Theunis, and Francesca Tria (Eds.). Springer International Publishing, Cham, 69–92. https://doi.org/10.1007/978-3-319-25658-0_4

[62] Stacey Kuznetsov, George Davis, Jian Cheung, and Eric Paulos. 2011. Ceci N'Est Pas Une Pipe Bombe: Authoring Urban Landscapes with Air Quality Sensors. In *Proceedings of the SIGCHI Conference on Human Factors in Computing Systems (CHI '11)*. ACM, New York, NY, USA, 2375–2384. https://doi.org/10.1145/1978942.1979290 event-place: Vancouver, BC, Canada.

[63] Stacey Kuznetsov and Eric Paulos. 2010. Participatory Sensing in Public Spaces: Activating Urban Surfaces with Sensor Probes. In *Proceedings of the 8th ACM Conference on Designing Interactive Systems (DIS '10)*. ACM, New York, NY, USA, 21–30. https://doi.org/10.1145/1858171.1858175 event-place: Aarhus, Denmark.

[64] Daniel Lambton-Howard, Robert Anderson, Kyle Montague, Andrew Garbett, Shaun Hazeldine, Carlos Alvarez, John A. Sweeney, Patrick Olivier, Ahmed Kharrufa, and Tom Nappey. 2019. WhatFutures: Designing Large-Scale Engagements on WhatsApp. In *Proceedings of the 2019 CHI Conference on Human Factors in Computing Systems (CHI '19)*. Association for Computing Machinery, Glasgow, Scotland Uk, 1–14. https://doi.org/10.1145/3290605.3300389

[65] A. Larkin and P. Hystad. 2017. Towards Personal Exposures: How Technology Is Changing Air Pollution and Health Research. *Current environmental health reports* 4, 4 (Dec. 2017), 463–471. https://doi.org/10.1007/s40572-017-0163-y

[66] Christopher A. Le Dantec, Mariam Asad, Aditi Misra, and Kari E. Watkins. 2015. Planning with Crowdsourced Data: Rhetoric and Representation in Transportation Planning. In *Proceedings of the 18th ACM Conference on Computer Supported Cooperative Work & Social Computing*. ACM, Vancouver BC Canada, 1717–1727. https://doi.org/10.1145/2675133.2675212

[67] Hui-Chieh Li. 2015. Optimal delivery strategies considering carbon emissions, time-dependent demands and demand–supply interactions. *European Journal of Operational Research* 241, 3 (March 2015), 739–748. https://doi.org/10.1016/j.ejor.2014.09.022

[68] Siân E. Lindley, Anja Thieme, Alex S. Taylor, Vasilis Vlachokyriakos, Tim Regan, and David Sweeney. 2017. Surfacing Small Worlds through Data-In-Place. *Computer Supported Cooperative Work (CSCW)* 26, 1-2 (April 2017), 135–163. https://doi.org/10.1007/s10606-017-9263-3

[69] Vittorio Loreto, Muki Haklay, Andreas Hotho, Vito D.P. Servedio, Gerd Stumme, Jan Theunis, and Francesca Tria (Eds.). 2017. *Participatory Sensing, Opinions and Collective Awareness*. Springer International Publishing, Cham. https://doi.org/10.1007/978-3-319-25658-0

[70] Noortje Marres. 2007. The Issues Deserve More Credit: Pragmatist Contributions to the Study of Public Involvement in Controversy. *Social Studies of Science* 37, 5 (Oct. 2007), 759–780. https://doi.org/10.1177/0306312706077367

[71] Taewoo Nam and Theresa A. Pardo. 2011. Smart City As Urban Innovation: Focusing on Management, Policy, and Context. In *Proceedings of the 5th International Conference on Theory and Practice of Electronic Governance (ICEGOV '11)*. ACM, New York, NY, USA, 185–194. https://doi.org/10.1145/2072069.2072100 event-place: Tallinn, Estonia.
[72] Greg Newman, Jim Graham, Alycia Crall, and Melinda Laituri. 2011. The art and science of multi-scale citizen science support. *Ecological Informatics* 6, 3 (July 2011), 217–227. https://doi.org/10.1016/j.ecoinf.2011.03.002
[73] Office of National Statistics. 2018. Average commute and percentage travelling by car for the UK and constituent countries - Office for National Statistics. https://www.ons.gov.uk/employmentandlabourmarket/peopleinwork/employmentandemployeetypes/adhocs/008986averagecommuteandpercentagetravellingbycarfortheukandconstituentcountries
[74] Patrick Olivier and Peter Wright. 2015. Digital civics: taking a local turn. *interactions* 22, 4 (June 2015), 61–63. https://doi.org/10.1145/2776885
[75] Sean Peacock, John Harlow, and Eric Gordon. 2020. Beta Blocks: Inviting Playful Community Exploration of Smart City Technologies in Boston, USA. In *Making Smart Cities More Playable: Exploring Playable Cities*, Anton Nijholt (Ed.). Springer, Singapore, 131–147. https://doi.org/10.1007/978-981-13-9765-3_7
[76] I. Pierangeli, M. J. Nieuwenhuijsen, M. Cirach, and D. Rojas-Rueda. 2020. Health equity and burden of childhood asthma - related to air pollution in Barcelona. *Environmental Research* (Feb. 2020), 109067. https://doi.org/10.1016/j.envres.2019.109067
[77] D. Puiu, P. Barnaghi, R. Tönjes, D. Kümper, M. I. Ali, A. Mileo, J. Xavier Parreira, M. Fischer, S. Kolozali, N. Farajidavar, F. Gao, T. Iggena, T. Pham, C. Nechifor, D. Puschmann, and J. Fernandes. 2016. CityPulse: Large Scale Data Analytics Framework for Smart Cities. *IEEE Access* 4 (2016), 1086–1108. https://doi.org/10.1109/ACCESS.2016.2541999
[78] Aare Puussaar, Ian G. Johnson, Kyle Montague, Philip James, and Peter Wright. 2018. Making Open Data Work for Civic Advocacy. *Proc. ACM Hum.-Comput. Interact.* 2, CSCW (Nov. 2018), 143:1–143:20. https://doi.org/10.1145/3274412
[79] Carlo Ratti and Matthew Claudel. 2016. *The City of Tomorrow: Sensors, Networks, Hackers, and the Future of Urban Life.* Yale University Press, New Haven ; London.
[80] Caitlin Robinson and Rachel S. Franklin. 2020. The sensor desert quandary: What does it mean (not) to count in the smart city? *Transactions of the Institute of British Geographers* n/a, n/a (Sept. 2020). https://doi.org/10.1111/tran.12415 _eprint: https://rgs-ibg.onlinelibrary.wiley.com/doi/pdf/10.1111/tran.12415.
[81] Rudolf Giffinge, Christian Fertner, Hans Kramar, Robert Kalasek, Nataša Pichler-Milanović, and Evert Meijers. 2007. *Smart cities – Ranking of European medium-sized cities.* Technical Report. Centre of Regional Science, Austria, Vienna. http://www.smart-cities.eu/download/smart_cities_final_report.pdf
[82] Flora Salim and Usman Haque. 2015. Urban computing in the wild: A survey on large scale participation and citizen engagement with ubiquitous computing, cyber physical systems, and Internet of Things. *International Journal of Human-Computer Studies* 81 (Sept. 2015), 31–48. https://doi.org/10.1016/j.ijhcs.2015.03.003
[83] Tom Saunders and Peter Baeck. 2015. *Rethinking Smart Cities from the Ground Up.* Technical Report. Nesta. 72 pages.
[84] Sean Peacock, Aare Puussaar, and Clara Crivellaro. 2020. Sensing our Streets: Involving Children in Making People-centred Smart Cities. In *The Routledge Handbook of Placemaking* (1 ed.), Cara Courage, Tom Borrup, Maria Rosario Jackson, Kylie Legge, Anita Mckeown, Louise Platt, and Jason Schupbach (Eds.). Routledge & CRC Press, 130–140. https://www.routledge.com/The-Routledge-Handbook-of-Placemaking/Courage-Borrup-Jackson-Legge-Mckeown-Platt-Schupbach/p/book/9780367220518
[85] S. Andrew Sheppard. 2012. wq: a modular framework for collecting, storing, and utilizing experiential VGI. ACM, 62–69. https://doi.org/10.1145/2442952.2442964
[86] Renee Sieber. 2006. Public Participation Geographic Information Systems: A Literature Review and Framework. *Annals of the Association of American Geographers* 96, 3 (Sept. 2006), 491–507. https://doi.org/10.1111/j.1467-8306.2006.00702.x
[87] K. Su, J. Li, and H. Fu. 2011. Smart city and the applications. In *2011 International Conference on Electronics, Communications and Control (ICECC).* 1028–1031. https://doi.org/10.1109/ICECC.2011.6066743
[88] Wei Tan, M. Brian Blake, Iman Saleh, and Schahram Dustdar. 2013. Social-Network-Sourced Big Data Analytics. *IEEE Internet Computing* 17, 5 (Sept. 2013), 62–69. https://doi.org/10.1109/MIC.2013.100
[89] Andrea Taylor, Richard Wilson, and Stefan Agamanolis. 2009. Supporting carers in their caring role through design. In *Proceedings of the 27th international conference extended abstracts on Human factors in computing systems - CHI EA '09.* ACM Press, Boston, MA, USA, 3985. https://doi.org/10.1145/1520340.1520605
[90] Linnet Taylor and Nadezhda Purtova. 2019. What is responsible and sustainable data science? *Big Data & Society* 6, 2 (July 2019), 2053951719858114. https://doi.org/10.1177/2053951719858114 Publisher: SAGE Publications Ltd.
[91] Nick Taylor and Keith Cheverst. 2010. Creating a Rural Community Display with Local Engagement. In *Proceedings of the 8th ACM Conference on Designing Interactive Systems (DIS '10).* ACM, New York, NY, USA, 218–227. https://doi.org/10.1145/1858171.1858209 event-place: Aarhus, Denmark.
[92] Nick Taylor, Justin Marshall, Alicia Blum-Ross, John Mills, Jon Rogers, Paul Egglestone, David M. Frohlich, Peter Wright, and Patrick Olivier. 2012. Viewpoint: empowering communities with situated voting devices. In *Proceedings*

of the 2012 ACM annual conference on Human Factors in Computing Systems - CHI '12. ACM Press, Austin, Texas, USA, 1361. https://doi.org/10.1145/2207676.2208594

[93] Matthew Tenney and Renee Sieber. 2016. Data-Driven Participation: Algorithms, Cities, Citizens, and Corporate Control. *Urban Planning* 1, 2 (July 2016), 101. https://doi.org/10.17645/up.v1i2.645

[94] Anthony M Townsend. 2013. *Smart cities: big data, civic hackers, and the quest for a new utopia* (1 ed.). W.W Norton & Company.

[95] Nina Valkanova, Robert Walter, Andrew Vande Moere, and Jörg Müller. 2014. MyPosition: sparking civic discourse by a public interactive poll visualization. In *Proceedings of the 17th ACM conference on Computer supported cooperative work & social computing - CSCW '14*. ACM Press, Baltimore, Maryland, USA, 1323–1332. https://doi.org/10.1145/2531602.2531639

[96] Ignasi Vilajosana, Jordi Llosa, Borja Martinez, Marc Domingo-Prieto, Albert Angles, and Xavier Vilajosana. 2013. Bootstrapping smart cities through a self-sustainable model based on big data flows. *IEEE Communications Magazine* 51, 6 (June 2013), 128–134. https://doi.org/10.1109/MCOM.2013.6525605

[97] John Vines, Rachel Clarke, Peter Wright, John McCarthy, and Patrick Olivier. 2013. Configuring participation: on how we involve people in design. In *Proceedings of the SIGCHI Conference on Human Factors in Computing Systems - CHI '13*. ACM Press, Paris, France, 429. https://doi.org/10.1145/2470654.2470716

[98] Vasilis Vlachokyriakos, Rob Comber, Karim Ladha, Nick Taylor, Paul Dunphy, Patrick McCorry, and Patrick Olivier. 2014. PosterVote: expanding the action repertoire for local political activism. In *Proceedings of the 2014 conference on Designing interactive systems - DIS '14*. ACM Press, Vancouver, BC, Canada, 795–804. https://doi.org/10.1145/2598510.2598523

[99] Vasillis Vlachokyriakos, Clara Crivellaro, Christopher A. Le Dantec, Eric Gordon, Pete Wright, and Patrick Olivier. 2016. Digital Civics: Citizen Empowerment With and Through Technology. In *Proceedings of the 2016 CHI Conference Extended Abstracts on Human Factors in Computing Systems - CHI EA '16*. ACM Press, Santa Jose, California, USA, 1096–1099. https://doi.org/10.1145/2851581.2886436

[100] J. Zaman and W. De Meuter. 2015. DisCoPar: Distributed components for participatory campaigning. In *2015 IEEE International Conference on Pervasive Computing and Communication Workshops (PerCom Workshops)*. 160–165. https://doi.org/10.1109/PERCOMW.2015.7134012

[101] Sergio Zubelzu and Roberto Álvarez. 2015. Urban planning and industry in Spain: A novel methodology for calculating industrial carbon footprints. *Energy Policy* 83 (Aug. 2015), 57–68. https://doi.org/10.1016/j.enpol.2015.03.025

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