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Citizen Sensing: An Action-Orientated Framework for Citizen Science

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Citizen Sensing, a correlative of Citizen Science, employs low-cost sensors to evidence local environmental issues and empowers citizens to use the data they collect. Whilst motivations for participation can vary, communities affected by pollution frequently have changemaking as their goal. Social innovation is closely aligned with citizen sensing, however the process of co-creating practices and solutions with citizens who wish to shape their world can be highly complex to design. Therefore, our research articulates an action-orientated framework which emerges from a 2-year pan European project by which follow-on communities may replicate sensing initiatives more easily. The authors examine five studies and explore the cross-cutting principles, phases, stakeholders, methods, and challenges which form this framework. The authors argue that whilst data collection and data awareness are crucial to the citizen sensing process, there are precursory and subsequent stages which are necessary to equip citizens to address complex environmental challenges and take action on them. Therefore, this paper focuses on the stages and methods which are distinctive to citizen sensing. It concludes with recommendations for future practice for citizen sensing and citizen science.

Keywords: citizen science, citizen sensing, social innovation, methods, action-orientated framework, changemaking, co-design

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INTRODUCTION

The world is currently facing complex urban environmental challenges. Large numbers of people living together on small areas of land can lead to environmental problems in air, water, noise and land pollution. These issues have detrimental effects on many aspects of human living such as health and well-being, particularly for those most vulnerable. Research demonstrates that air pollution in Europe is responsible for more than 400,000 premature deaths each year (European Environment Agency, 2015). As well as affecting health, air quality also has an effect on the environment and the climate. It is not just air pollution that is a pressing environmental challenge for many, 30% of the population in Europe are exposed to what is defined as unhealthy noise levels (World Health Organization, 2017). Continuous exposure to noise can have detrimental effects, including fatigue or illness from sleep deprivation, increased blood pressure, and a lower level for learning and creativity (European Commission, 2013).

Recently, the emergence of sensing with mobile devices, low cost and Do-It-Yourself sensors, and open data platforms has enabled citizen participation in data gathering using these technologies. Citizen Sensing (Gabrys, 2014; Suman and van Geenhuizen, 2020) has moved from an individual to a collective and transdisciplinary endeavor and has been applied in the field of

environmental monitoring, reflecting on the motivations of citizens to sense their environment. Previous research in the field has demonstrated: how participation is made meaningful (Aoki et al., 2017); the negative drivers that can hamper uptake, such as mistrust in information (Kera et al., 2013); the different motivations within communities conducting sensing initiatives (Balestrini et al., 2014, 2015); as well as insights about the role that awareness plays in motivating changes in behavior and policy (Kelly et al., 2012). Participants are often motivated by more than one factor (Raddick et al., 2013; Reed et al., 2013) and changes to motivation can occur over time.

However, there is a growing demand from citizens to engage in sensing as a means to answer their own questions, and gain information using mobile devices or other information and communications technologies (ICT) (Bria et al., 2015). This motivation typically stems from the citizens' acknowledgment that environmental issues, such as increasing levels of air and noise pollution in industrialized cities, have damaging effects on their health and well-being. Although a number of citizens are becoming aware of environmental issues that might affect their health, a study of over 25,000 citizens found that 59% of Europeans did not feel knowledgeable about air quality issues in their country (European Commission, 2013). Consequently, there is a need to both address the environmental issue, to inform citizens and support them in answering their own questions.

For citizen sensing to be beneficial to the those living with environmental issues, it is necessary to not only create awareness from the data that citizens gather but follow it up and apply it. When collaborating with citizens who are motivated in this way, the aim is to maximize the potential for addressing environmental issues through action and changemaking. Recent discourse regarding social innovation in a changing world has begun to explore similar concerns, proposing a more holistic and interdisciplinary endeavor (Light et al., 2017). Citizen sensing is well-positioned to achieve social innovation having the key characteristics to support it, namely, interdisciplinary, transdisciplinary approaches with platforms that enable exchange (Moulaert et al., 2017), however action-oriented processes aimed at change arguably remain understudied in citizen science.

Therefore, this paper presents a framework of an action-orientated process and methods that were developed through a 2-year project. The project explored how citizen sensing enables communities to capitalize on their insight from the data they collect toward identifying and resolving important environmental issues. This research suggests methods which can equip citizens to address complex environmental challenges and furthermore reveals potential avenues to foster sustainable, meaningful and impactful citizen sensing interventions that can lead to social innovation and ideally, systematic transformation. Our contribution should be useful for researchers and practitioners who are looking to deploy citizen sensing and citizen science projects alike.

BACKGROUND

The democratization of data is happening at the same time that there is a widening of opportunities for citizen participation in environmental monitoring. There are several examples where citizen science has been moving toward this more participatory position (Snyder et al., 2013; McQuillan, 2014). This has also been noted in the conceptual development of participatory sensing and the rise of open, low-cost technologies. In this section we describe developments in both citizen science and participatory sensing to articulate the theoretical background of citizen sensing.

Citizen science describes approaches in which laypeople engage in, and contribute to, science; it encapsulates all the various levels of engagement and the ways in which that data is gathered and evaluated (Cooper, 2016). Historically, citizen science projects tended toward a top down, hierarchical design where the experimental protocol is chosen and planned and where the data is for the sole use of professional scientists (Wiggins and Crowston, 2011). However additional models of public participation in scientific research do exist and have been formalized into five categories: "contractual" (communities recruiting professional research); "contributory" (observing and collecting data); "collaborative" (data collection and refining project design, analyzing data, disseminating results); "co-created" (the public and scientists design the inquiry together and share the majority of steps in a scientific process); and "collegial" (non-accredited individuals reaching recognition by field for their research) (Shirk et al., 2012).

Participatory sensing emerged principally from the open hardware and makerspace movements, and the tradition of participatory digital culture (Lovink, 2002; Kluitenberg, 2011; Barbrook and Cameron, 2015) at the same time as the commercial development of the Internet and digital industries. Participatory sensing shares some principles with citizen science and supports projects which exist in the "collaborative," "co-created," and "collegial" areas of the field. It does so primarily by employing everyday digital devices, such as mobile phones, for the public and professionals to gather and evaluate data (Burke et al., 2006). As affordable technologies are becoming more available, these digital devices are being used to empower groups of citizens to collect information on a shared issue of concern, for instance, local air quality. Furthermore, participatory sensing employs elements of citizen science and community-led data collection on mobile online platforms (Reddy et al., 2010). For example, the Air Quality Egg, a device which senses air pollution and includes an app and web dashboard to compare others' measurements; and Safecast, which senses radiation and provides open access to data.

Citizen sensing takes elements from both citizen science and participatory sensing and is gaining traction as a way to explain citizenship and environmental monitoring using sensor technology in digitally advanced urban environments (also referred to as Smart Cities) (Gabrys, 2014). In this context, citizen sensing promotes a concept of "just good enough data" to allow for people to create and understand datasets which are beneficial to them (Gabrys et al., 2016). Pritchard and Gabrys (2016) describe citizen sensing technologies as "*meant to provide a democratic corrective or challenge to the standard processes for monitoring environments, gathering data, and acting on those data*" (335). However, bottom-up empowerment and environmental change through sensing is hard to achieve. Providing the technology alone is not enough to lead people to make change in the world, on an individual basis or as

a community (also known as collective action). For example, user engagement studies on the citizen sensing platform, Smart Citizen, a crowdfunded open source platform for environmental monitoring, revealed a number of issues: lack of technical skills among users, difficulties with the usability and robustness of the sensing devices, a perceived lack of social interactions, purpose and motivation among community members, and problems with data reliability and meaningfulness have too often led to user disengagement with the platform (Balestrini et al., 2014, 2015).

Consequently, within citizen sensing, people are becoming more integrated into the creation of data that is meaningful by addressing issues on a local level, therefore making it more relevant to their lives. This can happen in a number of ways including: deploying sensors in their own environment (Kamel Boulos et al., 2011); becoming a sensor themselves by creating data with personal observations and viewpoints (Sheth, 2009; Kamel Boulos et al., 2011; Crowley et al., 2012); collecting indicators that annotate sensor data to make it more meaningful (Woods et al., 2016, 2020b; Coulson et al., 2017, 2018b) and collecting data through crowd-sourcing and processing the data in a collaborative manner (Borges et al., 2016). Additionally, studies found that embedding principles of co-design into citizen science can have action-oriented and transformative powers (Coulson et al., 2018a).

The following citizen sensing action-oriented framework has been developed by building on this background but aims to address the issues around purpose and motivation of concerned citizens who wish to tackle environmental issues. The following section describes the framework and the iterative development process. It also describes the cross-cutting principles that underpin the framework and articulate the range of key actors which are involved during the stages.

A FRAMEWORK FOR ACTION-ORIENTATED CITIZEN SENSING

The framework was developed through three stages, the first, a theoretical model was proposed following a literature review of the existing practices in citizen science, participatory sensing and citizen sensing. The second iterated upon the first stage using findings from studies of real-world citizen sensing project activities. The final version was validated using a co-designed approach to support collective aggregation during a reflection workshop with the entire delivery team, which included representatives from all participating organizations across Europe.

In the first iteration of the model, the project initially drew on the small number of existing process frameworks in the fields of citizen science (Winner, 1999; Hassen et al., 2015; Bürger schaffen Wissen., 2016; Henriquez, 2016; Jiang et al., 2016). The purpose of the first iteration of the theoretical framework was to underpin the stated aims and values of the project. Earlier framework prototypes provided a baseline process for the project partners to implement citizen sensing activities. As the study was conducted across three cities in Europe, the context and environmental challenge areas naturally differed in each, and this is discussed in more depth in the following section. The final version (**Figure 1**) was devised through a collective aggregation process by the project consortium, led by the authors and in collaboration with the project teams. It sought to interrogate the best practices arising from the project, informed also by participant evaluations of activities, methods and tools, and is used in the discussion to illustrate the elements of the framework. This final framework also draws from existing models of creative problem solving, mainly from the field of design thinking (Design Council, 2007; Sanders and Stappers, 2014; Woods et al., 2015). The co-design workshop where the final framework was aggregated and validated, also underpinned the approach for developing a toolkit for citizen sensing (Woods et al., 2018).

The framework for action-oriented citizen sensing (**Figure 1**) demonstrates an eight-stage process for supporting community action. Although, the discussion describes a linear process, the model describes that each citizen sensing campaign should be considered as a reflective process, with past projects feeding into future work. The intention is that all these stages are achieved in collaboration. To synthesize the framework further, the consortium identified four cross-cutting principles which were evident throughout the process of citizen sensing, and applicable as a foundation for governance and practice delivery, these are expanded below.

Cross-Cutting Principles

Empowerment

An internal state and the feeling of control or responsibility toward yourself and your environment. This can be encouraged with a combination of collaborative approaches and openness in technologies and data that address individual and community issues. This can lead to improved quality of life and greater power for change-making relative to corporations and governments.

Co-creation

A external attitude and the practice of collaborative development and a way to describe an approach in a project using methods and tools for people to work together on a level playing field. Co-creation is a process of jointly using a wide range of resources and ideas for creating new actions and objects.

Change-Making

A process or outcome state, it goes beyond creating awareness of developing purely technological solutions. It involves change in individuals, communities, institutions, and/or cultures, and in thinking, attitudes, values and consciousness. It embraces change led by the community.

Openness

An ambition, this is about the transparency of the organization of the campaign, as well as the data and the actions. This extends to strategic priorities of open design; open science; open tech and data; and an ethos of supporting an increasingly open world.

Stages

The stages of the framework provide an overview of who is involved, what usually happens during that time. The stages also indicate the goals or milestones to reach which, when achieved,

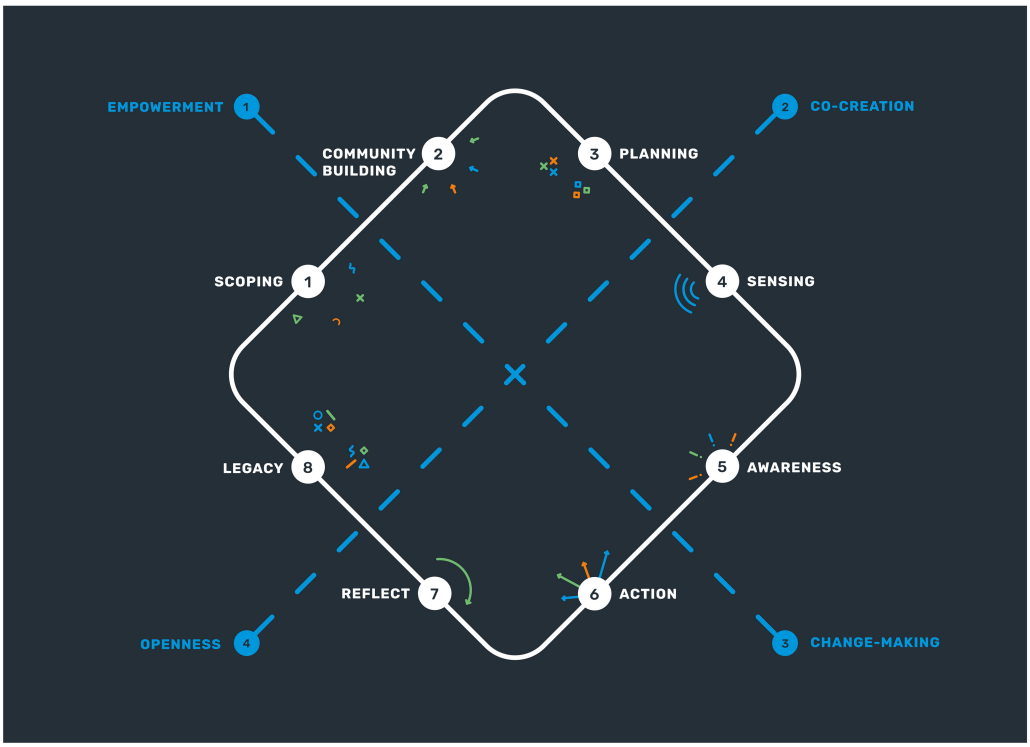

FIGURE 1 | A framework for action-oriented citizen sensing (Woods et al., 2018, pp. 16–17).

signify it is time to move on. Below summarizes these stages and points to the key participants. These participants are described in more detail below the stage summaries. Following this, the paper presents the findings of the case studies, which shine light on some of the specific activities and challenges found in each stage.

- *Scoping* is the first step and the stage when the important issues are discovered, mapped, and discussed by the key participants. Information is gathered by internet searches, collecting articles, news reports and academic literature or by conducting surveys and interviews. This is the stage when existing communities are found, and new ones start to form. There is no time limit on scoping; it can take only a few weeks or can be something that takes years.
  Key participants: community organizers; project teams; community members.
- *Community building* brings together everyone around an issue. The aim is for all participants to come to a shared understanding of the issue and decide on the goals of the campaign. It is when then the skills of the participants are identified and new skills are developed, and it is also when others are brought on board if there are any skills or expertize missing. Participants collectively agree on the organization of the project and how to document activities.
  Key participants: community organizers; project teams; community members.
- *Planning* is when participants collectively decide on the goals for the project, sensing strategies and protocols for collecting data. This includes a plan for collecting other types of indicators. It is when the sensing tools are created or developed from existing resources. Sensors are tested and calibrated. Participants learn about sensors and are introduced to approaches for understanding data.
  Key Participants: community organizers; project teams; community members.
- *Sensing* is the phase in which everyone collects data on the issue, i.e., pollution. The data can be uploaded to a publicly accessible online platform. Participants can also record observations about their lives and how they are affected by the issue. Note taking and collecting indicators is important as this information can support the findings of the sensor data and be used to show the impacts of the issue to other people and government officials.
  Key Participants: community organizers; project teams; community members.
- *Awareness* uses the information gathered during the sensing phase, the data is analyzed and discussed amongst the community. The analysis stage can include optional activities of data visualization; professional science or academic support. The aim is to build a collective awareness from the data. This includes an assessment of the personal observations and the other indicators collected as part of the project. Bringing together all this information is important for identifying potential areas for action and change.

Key Participants: community organizers; project teams; community members; data visualizers; external experts.

- *Action* happens once there is a collective awareness on the issue at hand, participants work together to propose possible courses of action. The aim is to devise, organize and deliver a single or series of actions as a group that may generate a wider recognition of the issue. Actions can range from behavioral change of an individual, to public facing activities (i.e., a public intervention) aimed at creating further awareness or even a policy change. The aim is to have impact and make change for the better.
  Key Participants: community organizers; project teams; community members; media outlets; government officials; the public.
- *Reflection* is when participants reflect on the process to date and consider what worked and what did not. This can include looking at the data and seeing if there was change as a result of the action. This might require the participants to repeat or go back to previous phases, such as sensing.
  Key Participants: community organizers; project teams; community members.
- *Legacy* is created by looking toward the future of the project and planning for lasting impact. It should also include planning for sharing information and news to make sure there is sustainability and reuse of the project tools and the uptake for others. For those community organizations, it is a phase of writing reports and publications and for sharing the project assets that might be useful for other initiatives.
  Key Participants: community organizers; project teams; community members; academics, and external experts.

Key Participants

Within each stage, there is reference to key participants. This categorization of key actors in each stage can help to initiate activity but may also support the management of activities and move the process along.

The key actors involved are:

Community organizers who champion the activities of citizen sensing project to a wide audience. They also facilitate the process and organize the delivery of activity.

Project teams are a collective of key individuals who support the majority of the citizen sensing framework.

Community members are the citizens who are actively involved. They form a community through a shared interest in the environmental challenge which they find pressing. They are also the lead instigators in the actions for change as a result of their newly acquired knowledge from the sensing activities.

Data visualizers are brought on at certain points in the framework in order to help visualize the data that has been gathered about the environmental challenge at hand.

External experts are also brought it a certain point is the process to support the development of skills for the community member, for instance, in training them to calibrate sensors and collect data. They can also be brought in to support the understanding of data, during the awareness phase where they can support community members in making sense of the data they have collected and what other indicators may have an impact on the information gleaned.

Media outlets can be social media platforms or more conventional means of information dissemination (i.e., newspapers, TV and radio).

Government officials are the public authorities who advise or contribute to policy change and can instigate wider impact of change.

The public is the notion of everyone outside the core participant group, it is important to engage the public at certain points in the process. Specifically, during the initial scoping phase insights are gleaned from a wider range of citizens and citizen sensing is driven by a concern of a critical problem. The first step is to identify the individuals or communities which have like concerns and work collaboratively to help identify and develop a deeper understanding of what those concerns are.

RESEARCH APPROACH

The research draws on five case studies, which were instrumental in the development an action-orientated framework to citizen sensing. As previously mentioned, the five studies were designed to examine how open-source software, open-source hardware, digital maker practices and open-source design could be used by local communities to create their own sensing tools to examine their environments and address pressing environmental problems. The studies spanned citizen sensing activities in three cities in Europe: Amsterdam (The Netherlands), Barcelona (Spain) and Prishtina (Kosovo). The studies were driven by co-creation principles and citizen-led, however it should be noted that funding is a crucial resource in the development of many citizen sensing projects, and all of the case studies were part of a wider European Commission Horizon 2020 funded grant.

The consortium collectively developed the research design and protocols and defined the planning, delivery and evaluation of the studies. The data collected through in-depth case studies formed the foundation for this research. The case studies were conducted to answer the following questions: (1) How does the process of citizen sensing manifest itself? (2) What tools and methods support the process toward action-orientated outcomes as defined by participants? The lead authors conducted the research in collaboration with project teams who facilitated and supported the communities for each of the case studies. Discussions between the researchers and project teams followed the completion of this information to ensure comprehensive and cohesive data capture across the studies.

Table A1 in Appendix outlines the case studies examined in this research. It includes the duration of each case study, namely, the time which the project team was active in facilitating the process. However, this does not include the months or years that went into preparing the cases or the ongoing activities in which communities continue to participate in these areas. The table gives an overview of the number of community members involved, who were mixed in gender and aged between 18 and 80. It also illustrates the number of events from each study, including

but not limited to the weekly group meetings amongst the project team and community members.

The case studies operated in different context and varied in focus. The summaries below provide more details and the ambitions of each case study:

Case A—A total of 25 local residents measured air quality in small geographical location in the city of Amsterdam. They used existing information from the Dutch environmental defense organization (Milieudefensie) which stated that the Valkenburgerstraat and the Weesperstraat in the heart of Amsterdam were the most polluted streets of the city. Sensors were deployed in and around the residents' homes and collected data on NO2, particulate matter, humidity and temperature. This data was analyzed and interpreted in collaboration with experts and residents. Once the residents had the results, they organized a meeting with the Municipality to discuss the issue of air quality in their area. In addition, they worked with The Lung Foundation to create a campaign about air quality in the city and how citizens can find information about air quality in their post codes.

Case B—Prishtina is one of the most polluted regions in Europe. Citizen sensing was employed to investigate air pollution by empowering young people and affected communities to jointly break the institutional silence around air pollution through evidence-based campaigns and actions. For this case, a committee of young people aged 17–30 were recruited to plan, organize and run a pilot. This committee collaboratively designed the measurement strategy as well as the actions and protests that were arranged in response to their findings. The media coverage of this case was a significant outcome, mainly due to campaign actions which generated a public discourse never seen before in the country. As a result, for the first time, the Kosovo Environmental Protection Agency started to regularly publish their data and policy-makers committed to changes in the constitution that included the citizens right to clean air.

Case C—A second pilot in Prishtina had the same committee members as previous activities, as well as the same collaborative and participatory process. This time, air quality sensing was focused on areas around aging power plants. This pilot covered the spring and summer season, where the previous pilot covered the autumn and winter so that measurements were taken at all seasons throughout the year period. The sensing activities also included the measurement of bio-indicators, mapping lichen diversity as an indicator of environmental stress. An important outcome of this case was the way it which it demonstrated that citizen sensing had become embedded in the culture of Kosovo as a movement, and had evolved beyond the activities of the study.

Case D—This case took place in Barcelona where citizens tested technologies and methodologies in citizen sensing which focused on supporting the understanding of data. The pilot examined noise pollution in the city, as this had been deemed the most pressing challenge by the community organizers, project team and community itself. As a result, the citizens formed into a cohort of 25 community champions who gained a shared level of understanding of the sensing process, methods and skills which they could subsequently pass on to the citizens participating in Case E.

Case E—The Plaça del Sol in the area of Gràcia, Barcelona has historically suffered from people loitering, drinking and creating high levels of noise in the neighborhood. The project team and community champions from Case D, collaborated with the local residents to evidence the problem. Equipping residents with the technology and through an initial iteration of the citizen sensing framework. As an outcome, the community members and project team formed a citizens' assembly event in the Plaça del Sol to bring attention to the issue and share their findings with a wider audience. This event received significant international media coverage, including articles and interview with the citizens. This case leveraged the community members voices and they were able to speak out on their ongoing problems with noise pollution and get the recognition from media and government that they needed to take steps toward resolution.

Once all case studies were completed they were analyzed by the research team. Themes around process, methods, outcomes where gathered and evaluated using comparative analysis. This highlighted the similarities and differences from each case and how the research questions on processes and methods had developed over the 2-year project period. The cases were presented back to the project partners and through a co-design workshop the cases were compared against the initial framework and iterated on to create the final action-oriented framework for citizen sensing. The following section extends the discussion on the final framework. The authors describe the stages, but primarily the methods that are used in each stage. In addition, common challenges from each stage are highlighted for those who wish to use this framework.

FRAMEWORK STAGE, METHODS AND CHALLENGES

The following section provides an overview and examination of each stage in the framework. It describes the ways each can be identified and the milestones that need to be achieved in order to move on to the next stage. Furthermore, it provides a selection of methods that were used across the project case studies, often shared, validated and iterated with participants by each case. These methods were defined and developed through the co-design workshop with all consortium partners. Common challenges or pitfalls are also described, with pathways or suggestions on how to overcome these issues. These elements are summarized in **Table A2** in Appendix and presented in further detail below.

Scoping: Summary

Citizen sensing is driven by a concern of a critical problem. The first step is to identify the individuals or communities which have like concerns and work collaboratively to help identify and develop a deeper understanding of what those concerns are.

Scoping: Methods

Scoping activities can help map out the issues of interest and the work that has gone before, both locally and internationally. This stage can include a literature review on the subject, group meetings open to the public or with targeted groups and experts.

- *Geographical mapping* visualizes the issues of concern during collaborative workshops. This is aimed at finding the existing grassroots organizations (i.e., neighborhood association to citizen movements, NGOs and cooperatives) which are mapped to understand the landscape to examine the linkages and where the gaps remain. It discovers the pressing environmental issues and where things are happening. It also allows participants to understand how and where the critical problem may be affecting them and to speak to others about the issues. For instance, during *Case D*, a community mapping activity resulted in a database of 274 community groups which were categorized by emergent themes: environmental, social, infrastructure and services, cultural, educations, economical, health, and politics.
- *Commons mapping* supports the sharing of resources and motivations for joining a citizen sensing endeavor. It stems from the notion that everyone has something to contribute (i.e., time, skills, resources, or networks). Collectively creating a wealth of potential resources from the outset and fostering a culture of sharing within the project.
- *Collaborative delivery schedule* fosters investment and motivation into citizen sensing. Participants are more invested and willing to drive activities they have devised themselves. Devising the delivering schedule in a collaborative way supported ownership within the cases and the participants would feel more empowered knowing that they had formed the project from the start.

Scoping: Challenges

It is important to understand the local situation, as understanding the culture and motivations of the citizens and their communities is important in creating successful change. Finding out other organizations which have carried out similar activities in this area ensures that this work is built upon, rather than starting from scratch, replicating activities, or encountering similar pitfalls.

Community Building: Summary

There is value in bringing together citizens who have distinct motivations and skills: for e.g., community of concerned residents working a community of makers. Community building is essential to citizen sensing as it revolves around people coming together to tackle a challenge or concern. The process of community building identifies and defines the shared voice and values which guide the citizen sensing campaign. Fostering community cohesion and communication is crucial to the sustainability of the community throughout the process. Community building is also about developing relationship between various people (i.e., experts in the field and government officials) who can support changemaking as the project evolves.

Community Building: Methods

Engaging and recruiting the community will involve forming the issue, tapping into a desire to participate, building a time timeline and an understanding of the process, as well as forecasting what might occur along the way.

- *Recruitment* and the strategies for finding participants can be varied and also applied to different context. There is no one size fits all approach to recruitment, as it is highly dependent on context (cultural, political, social and economic) and the intentions of the community itself. Within *Case B*, the community organizers sought to recruit people between the age of 18–25 to harness the potential of the youth population. To achieve this, the organizers created a mixed method approach to recruit young activists, including: participating in youth-related events; reaching out through social media, mainstream media, radio, newspapers and TV; providing a 3-day workshop to introduce young people to citizen science, data collections and campaigning for change.
- *Onboarding kits* are integral to a productive community of participants. The onboarding kit can welcome and guide new participants into the project and the teams as it is comprized of both informative resources and community-building tools. It breaks down the stigma that citizen sensing is just about collecting data.
- *Empathy timeline* (Woods et al., 2020a) encourages participants to look at both sides of the problem and how the team understands their role in it. This method involves asking community members to think about the complexities of the issue at hand. Community members are aware of their own subjective viewpoints of the issue at hand, the empathy timeline challenges this. Reflexivity is achieved by having community members discuss the ways they are affected by the issue, but also the way they contribute to it. This facilitates community building by bringing people together to discuss issues in a way that they perhaps have not done before.

Community Building: Challenges

It is important to plan the management and governance of the project team to determine how the communities will manage themselves. Setting up spaces and times when the team meet is crucial. As is identifying the skills and resources available in a community in order to plan how the group might bring on any missing skills or address any other gaps. This is also a crucial point at which the team should decide on how they want to document the process, as this documentation can provide useful evidence in the formation of arguments in latter stages. The timing of community building is essential and follows the scoping phase but happens before planning the sensing activities. It may also take a long time, specifically when taking into account the skills available in the team and finding new members to fill any gaps. However, community building does not end when planning begins, it extends throughout the life of the project.

Planning: Summary

This stage is focused on preparing the community members for data collection, interpretation, and the resulting action. The decisions made at this stage affect the type of sensing conducted and the kind of data which is collected. The community members have to be prepared for the tasks and through a greater understanding of the research process.

Planning: Methods

The goals of the sensing activities need to be well-defined as it will influence how the collection of data can be achieved. This includes what kind of the data is collected and the methods and tools needed to obtain this information. It is important to note that not all methods of data collection are technology dependent, community members can act as sensors by recording information on their local environment.

- *Community Level Indicators (CLIs)* (Woods et al., 2020b) make the invisible visible. CLIs are objective measurements collected by the community so as to complement the sensor data. These criteria are chosen by the community and reflect the collective goals of the project. In citizen sensing, people sometimes struggle to understand how data is relevant to their lives, or how it is connected to the challenges they face. This is especially true when decisions about what constitutes an important barometer of change are taken in a non-transparent way and do not relate to the community's concerns. CLIs connect the dots between sensor data and real life. They also help those involved to see the impact of their actions by tracking and measuring real change. This process encourages participants to collaboratively choose what information can be collected. This is also an approach that people use after the project to see if, and how, their actions have made a difference. During *Case E*, community members used the CLIs to co-create one or two indicators which could be used for data annotation in combination with the sensor data. The tool was useful in two ways: (1) It allowed community members to overcome a culture of blame and see the issue was not as straightforward as it initially seemed; (2) it gave the community members an opportunity to discuss strategies to make sense of the sensor data and plan approaches to build on the sensor datasets to reveal deeper insights into the problem. One option devised by the community members was to track the number of people present in a public square, where the community was afflicted by noise pollution. One community member achieved this by photographing the number of people in the square from her balcony. She used these images alongside the sensor data, also deployed in her home, to show government officials noise pollution was a real issue. This allowed the community members to evidence that the high level of noise was directly related to the number of the people socializing in the square at night.
- *Sensing strategies canvas* allows participants to co-create a plan for deploying sensors and recording data. It combines expert knowledge of the scientific process with community engagement in the decision-making process. Having experts present and on-hand to advise helps understand what is achievable with the resources available, and how to gather valid data. Tools that help achieve this can include, a sensor deployment map, a calendar for data collection, and sensing strategy cards.
- *Calibration* ensures that collection of data is valid and aligned to scientifically reliable measures. It requires training, specifically for community members who are new to citizen sensing activities. This activity develops technological skills amongst community members, as they become aware of the methodological processes associated with sensing. Community members should be made aware that without calibration, the data of the project is scientifically meaningless.

Planning: Challenges

Working with community members who have varied knowledge using digital devices can be challenging. This is why Planning is an important phase, as it builds capacity of everyone involved and supports a high standard of information. Diverse backgrounds can often mean diverse and varied levels of education and understanding in the scientific process and in data collection.

Sensing: Summary

Sensing is the phase in which the data is collected. The data should be uploaded to a public and accessible online platform. Participants can also take note and record observations about how they are affected by the issue. Collecting these, and other indicators (i.e., CLIs), can support the sensor data and be used to demonstrate the impacts to external individuals and government officials.

Sensing: Methods

The sensing stage and collection of data can be conducted in a variety of ways including through sensors or mobile devices, taking photos, and collection of supplemental information.

- *Open hardware* has been pivotal in democratizing the sensing process. Most commercial sensors are expensive and cannot be altered to accommodate bespoke needs of the project. Developing open hardware for the sensing stage does require technical knowledge, which may be out with the capacity of community members. In *Case A*, the community members wanted to address daily decision when living in a city with continuous exposure to air pollution. The project team, along with experts from the local university, the Institute for Public Health and the Environment and the SenseMakers network developed air quality sensors which were distributed to the community members and use in line with the co-designed sensing strategy. *Cases D* and *E* used an existing open-source sensing kit and platform to capture noise levels in Barcelona. The kit was Arduino compatible and the design files are open-source. It comprised of a sensor shield, data-processing board, battery and a case. The shield contained sensors which measured noise levels, but could also capture air quality, temperature, humidity and light intensity. Once connected to Wi-Fi the senor can stream data to the online platform.
- *Sensing guides* are field guides that keep those who have limited knowledge of technology and the process of data capture on track during a project (i.e., how, what and when things are to be measured). Sensing guides also double as reinforcements for community members to understand basic operation and how to maintain the technology. In *Case E* a series of take-home booklets were developed that demonstrated the sensing process. The booklets were co-designed with community members from *Case D* (which had occurred a few month

prior) who had found that keeping abreast of the sensing process was challenging.
- *Data journals* give data the context, which is needed, but often undetectable by sensors. It captures annotated information, which can discover false-positives and outliers of the data. Within an environmental sensing campaign, community members can make observations of personal and physical effects, that can indicate patterns between the data and affected individuals. It also allows for community members to develop their own understanding of the data and enquire into how they can use this new understanding.

Sensing: Challenges

Sensing is a challenging phase, and support for community members who are conducting the collection of data is critical. This support may come from the project team or expertize may need to be sought elsewhere.

Awareness: Summary

Data should be collected and shared amongst community members. However, in order for them to initiate change, they must understand what the data means. Understanding the data empowers community members. Transparency in the awareness of data can be evidenced to support action at a policy level.

Awareness: Methods

When the data has been collected, it needs to be interpreted. This process will be informed by the type of data that has been collected. The analyzed data is presented in a visual form, which can be easily understood by a wide range of people.

- *Awareness sheet* relates measurements to tangible impacts, which may become actionable responses to new knowledge formed. It helps to make sense of the complexities of the environment issues and how it impacts citizens. For instance, if monitoring air pollution, and awareness sheet supports community members in understanding the health impacts, like what is the legal limits on air quality in their region and how might exposure effect their long-term health.
- *Data discussion sheet* is about understanding the issues around data itself, and initiates discussions on data ownership and notions of privacy, storage management and what other data should be collected as a result.
- *Data dashboards* support the visualization of data, in order it to be more accessible and open for those evolved and further afield. Dashboards should visualize data that can communicate the issues and research questions identified by the community members. Dashboards can be a key facet in developing knowledge and understanding for the community and be a cannon for further action in the project.

Awareness: Challenges

This process of data analysis and interpretation may be within the capacity of the project team or community members. However, it might also need to be outsourced or data visualizers brought in to process the information, or to train others to do so. Data awareness should be conducted as soon as the sensing phase is complete. A quick turnaround can keep motivation high, and the group can use their insights to consider actions for change.

Action: Summary

Action can be the start of policy change or be the first steps to solving the critical concerns of the community. The community members use their insights to achieve the collaborative project goals. It allows for the community members to feel empowered by their new knowledge and to communicate it with others or use it to make a case for change.

Action: Methods

When the data has been collected and analyzed, the process of planning and co-designing actions for change begin. Actions should be community-led but can receive support from project teams and community organizers. Having ideas are devised and delivered by community members increasing the potential impact the action will have on the community itself.

- *Digital presence* allows for community members to disseminate the findings and communicate widely their critical concerns. These can be on existing platforms (i.e., Twitter, Facebook, and blogs) or through a specifically designed website. This presence can serve as a reference to media outlets or government officials and can be helpful in raising awareness and recruiting new community members for further endeavors.
- *Future newspaper* (Woods et al., 2020c) supports the creation of creative action-orientated ideas. By thinking into the future, ideas for the present and pathways to achieve collaborative goals can be devised. This was most apparent in *Case D*, where community members used the future newspaper approach to imagine a world where the data collected was actionable and outcomes were reported on by national media outlets. The headlines generated allowed them to co-design an intervention in a public square, using the sensors and other lo-fi materials to develop a noise box, which could visualize the level of noise, indicating when levels had hit about healthy limits.
- *Co-creation assemblies* are open sessions to discuss and prototype desirable futures. It is important to get a wider range of perspectives by holding this in a public space or inviting external experts, government officials or even project skeptics. Critical issues are unpacked and grouped into subthemes, which form the premise for round table discussions. Applied in *Case E*, the community members organized an event in the geographical area of concern. This was a small plaza, which was often populated by many people and created a lot of noise that affected the residents who lived there. The community members, in this case the residents, facilitated a co-creation assembly to discuss the issue with the people in the square and start a dialogue about the issue of noise in their area. The discussions were captured and added to a report, along with the findings from previous stages that was prepared and delivered to government officials.

Action: Challenges

Actions should be devised and delivered after the data has been collected and awareness has brought forth an understanding of the problem.

Reflection: Summary

A phase of reflection takes stock of what was successful and what could be improved in the future projects. For instance, the use of certain methods and tools could be better placed at different times, or different participants invited for the activities. It is also the stage to review the sensing strategy and data collection, to consider if the hardware could be improved for future use.

Reflection: Methods

Reflection is when community members, organizers and project teams collaborate on developing the sensors and the methods. It is a point where surveys can be distributed to participants to discover whether the process has developed their capacities, knowledge and understanding of citizen sensing, or sensing more generally.

- *Questionnaires* allow community members to share their experiences of the project and understanding of the critical environmental challenges. The surveys also provide for important feedback in developing future iterations of the project. A questionnaire was distributed in *Case D* to identify what was successful and where the tension points were for the community members. These insights were used to develop *Case E*, changing the order in which some methods were delivered.
- *Project appraisal* a more open approach to reflection would be the pilot appraisal, which brings together participants to hold an open discussion around how the project was delivered. Another method for project appraisal used in some during *Cases D and E*, was sticker-dot voting. Methods are printed on cards and participants use sticker-dots to indicate which method they enjoyed the most. This is followed by a conversation if appropriate.
- *Graduation ceremony* is intended to further cement the community engagement between members and the project organizers and project team. Graduating community members feel validated in their achievements and capabilities. Celebrating these as a group solidifies the community and enhances scope for long term engagement, as was noted in *Case D*, many of whom continued to work on future iterations of the project and on citizen sensing activities.

Reflection: Challenges

Deciding when the reflection stage should end presents a challenge, as there are often new insights or outcomes from sensing, or the actions taken. Planning a gathering for key participants helps with closure but also celebrating the achievements of the group.

Legacy: Summary

The purpose of citizen sensing is to make change. This is the stage where the impact of actions can be considered in the long-term. The continuous relationship between key participants is important for legacy and activities can go beyond the project or citizen sensing activities.

Legacy: Methods

Ideally, legacy would be measured by the change in the world which could be directly relating to the activities of the project. This can be achieved in the short-term by keeping track of changes made from outside the community, like policy amendments or change or by making the information and process available through an open-source platform.

- *Storylines* convey a narrative and can take many forms but should be community-led. It will vary on the context of the project but should aim to be powerful stories which convey achievement, empowerment and greater understanding of the projects. Initially, the community members of *Case E* were very skeptical of citizen sensing and what it could do for them in tackling noise pollution. However, community members from a previous project presented their own journey and development of understanding during a public meeting. This helped prospective community members to understanding the inner workings of citizen sensing and also the impact it would have on their lives.
- *Training the next generation* is aimed at having the learners become the teachers and scaling up activities for the future. Training of future generations in about understanding the process of empowerment and how it stems from knowledge, skills and perceptions. This occurred in both *Case C and D*. In *Case C* the community members created a partnership around a local school to monitor the air quality in the area, but also to deliver an education programme from the school pupils, with an aim to develop and recruit the next generation of citizen sensing participants. In *Case D*, the community champions were trained in sensing skills and technologies so that they could support the community members of Plaça del Sol during their sensing campaign.

Legacy: Challenges

Capturing and evidencing legacy is an ongoing issue for many, this spans beyond the boundaries of citizen sensing. It is important to understand this from the start. Having the right processes, methods and ways for documenting the project will be of great help when it comes to demonstrating the legacy of the project.

DISCUSSION

The notion of "quality of life" both for individuals and communities, is integral to our motivation to address environmental issues and climate change. It is in this framing that we see social innovation and empowerment through citizen sensing provide new ideas with the potential to improve quality of life for those affected. The following discussion presents a summary of insights that addresses a growing space defined by civic approaches to technology use and awareness, the capabilities of IoT sensors to track data over time, and the ability to draw these strands together to

inform an action-oriented framework for citizen sensing. Although, this could be presented as the operationalization of citizen sensing, the outcome is greater than a new framework to optimize the activity, or citizen science more broadly. It is intended, at the core, to support community activism and an ability to lead changemaking and social innovations for example leveraging communication opportunities with policymakers.

The findings from the five case studies provide insights on specific activities and challenges in each stage of the framework. Namely, that data collection and data awareness are central to the citizen sensing process, and accessibility can be enhanced through sensing guides and data dashboards. Other tools and activities (i.e., data journals and data discussion sheets) deepen understanding of the context of the sensor data, and of the issues around data itself.

The case studies demonstrate that there are precursory and subsequent stages and activities which have proven important to the citizen sensing process if social innovation is to be realized, an often-overlooked area much of the literature. These include citizens being enabled to specify the critical problem and how it is affecting them, singularly and collectively. Similarly, to co-create the plans for the citizen sensing project, combining expert and community knowledge. The social dimension is significant here, to build a productive community equipped to address complex environmental challenges. The step from awareness to action was enabled in the case studies by visualizing the meaning of data and use of futures methods, wherein thinking into the future created pathways to change. Here action is not an end in itself. It is followed by reflection, and legacy, in a trajectory toward change and impact.

This study demonstrates the multiple and significant dimensions of citizen sensing. Crucially, the findings bring to light factors beyond the technology that enable people to make change in the world. These include the discovery of relevance, and understanding of, the way community members are affected by the issue, and how they contribute to it. This is evident in the cross-cutting principles which both address intrinsic and extrinsic motivation, governance and the ambition for a more open and just world. The principle contribution is to enable interventions that can lead to action and change. This action-oriented approach enables communities to become leaders in actions addressing important environmental issues.

RECOMMENDATIONS FOR FUTURE PRACTICE

Research has a vital role to play in supporting an action-oriented approach, particularly when making a claim for change-making. We demonstrate despite citizens taking more interest and control in sensing there is a continued role for engagement of scientists and researchers in the trajectory toward change. In each case study there was specialist science input, the ability to translate citizen concerns to questions and strategies is a specialist role, as is the development of technologies and platforms to support activities, and visualization of data.

We provide the following additional brief recommendations for research to support citizens who wish to shape their world, these points are categorized for consideration under community and researcher.

Community

- Communities may be living with the environmental issue over an extended period of time, its relevance to them does not begin or end with the research study.
- It important to account for the social dimension of the co-creation process when planning community engagement.
- The first step to communities building ownership around data and technology is their relevance to building evidence around the environmental issue.
- Enable citizens and communities to become leaders in actions addressing important environmental issues.
- Other benefits–not just environmental sensing, learning skills, feeling empowered, seeing change in the community.

Researcher

- Change needs to be supported and provided for from the outset, these are the steps to do it through.
- Privilege action in the moment over the long tail of research, and tangible outcomes for the community over concerns internal to the research community.
- Technology and data are not the panacea—respond to communities' needs not solely through technology use.
- Data collection and awareness practices are enhanced by activities to deepen understanding of the sometimes-subjective nature of the issue.
- Pathways to change and impact are opened by enabling the step from awareness to action.

CONCLUSION

These insights and recommendations can be of value to researchers and communities who are looking to deploy citizen sensing projects to effect positive impact. They complement recommendations developed for action-orientated citizen sensing and for the fields of citizen sensing and citizen science looking to make real change with research impacts.

DATA AVAILABILITY STATEMENT

The raw data supporting the conclusions of this article will be made available by the authors, without undue reservation.

ETHICS STATEMENT

The studies involving human participants were reviewed and approved by WAAG Society. Written informed consent for participation was not required for this study in accordance with the national legislation and the institutional requirements.

AUTHOR CONTRIBUTIONS

SC provided the initial outline, content of the paper, finalized the paper, and content for submission. MW provided feedback during the paper development and at the end. Both authors contributed to the article and approved the submitted version.

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SUPPLEMENTARY MATERIAL

The Supplementary Material for this article can be found online at: https://www.frontiersin.org/articles/10.3389/fcomm.2021.629700/full#supplementary-material

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