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Taxonomy of Environmental Sensing in Smart Cities

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This text analyses the impact of six sensing devices derived from smart cities and internet of things and suggests they are creating novel environmental practices. These practices depart radically from the commonly held epistemological paradigm that environmental data leads to environmental knowledge. Instead the paper outlines a variety of surprising practices that these devices enable. These findings suggest a need to reconsider the rhetoric used to describe these devices and an urgency for further ethnographic research on the practices and ethics of environmental sensing in smart cities.

Keywords: Environmental Sensing; Smart Cities; Internet of Things

Introduction

Much of the recent scholarship on smart cities has wrestled with the label of 'smartness' to try and disentangle its discourse and imaginaries (Vanolo 2013). But what if we leave this to the side and focus on how cities are already being shaped? This is not to disregard the effect of imaginaries but to place a focus on observable urban environmental practices.

The last decade has brought radical transformations in the way environmental sensing of pollutants is taking place. The classic model that has been adopted by governments is to erect expensive, stationary hardware at the sides of urban roads to measure data to identify long-term trends and conform to regulatory standards. Typically, this hardware will cost around £10,000 ($13,000). Yet recently, new kinds of low-cost (£150/$180) and portable 'smart' devices have emerged, built by hobbyists, entrepreneurs and researchers to measure air and noise pollution. These devices are targeted at members of the public who are asked to take part in environmental data gathering by installing them in their homes or carrying them with them every day. The best-known example of this is the Safecast radiation monitoring network (Safecast 2011). This emerged in response to the Fukushima nuclear disaster where volunteers built hardware and provided vital data for the public while the government was criticised for lack of sensor coverage and public data access. This incident became an exemplar of bottom-up smart technology and precipitated a global growth in the availability and use of similar sensing devices developed using crowdfunding platforms such as Kickstarter and often designed without input from environmental scientists or experts. A key component of this growth has been an academic and industry discourse valorising these devices as best practice exemplars of the smart cities and the Internet of Things (IoT). Fernandez (2013) for example argues "*the smart city becomes real when people can deal with open technologies to build their own public infrastructure for environmental monitoring*" (p.44). In the same vein the Fast Company magazine suggests these sensors are the "*perfect example of how Internet of Things will work in the future*" (Captain 2016, para. 8). The argument is that low-cost sensors make pollution 'visible' for non-expert individuals allowing them to see their personal exposure and avoid polluted areas as well as change their own behaviour to produce less pollution. On a collective level the devices are seen as producing vast quantities of data that can be aggregated to produce environmental datasets that are not available to governments and institutions. The assumption being that this leads to new knowledge that creates 'information power' (Carton and Ache 2017). According to Bria, each sensor box "*empowers citizens to improve urban life through capturing and analysing real-time environmental data*" (Bria 2014, 2). In return the people are said to become 'Smart citizens' that can renegotiate their relationship with governments and institutions (Townsend et al. 2010; Hemment and Townsend 2013; Hill 2013; Kresin 2013). At the heart of this argument is a positivist knowledge paradigm where technological data is framed as neutral and directly leading to knowledge. In effect, 'more' data is seen as creating 'more' environmental knowledge.

Yet, this argument doesn't reflect on the fact that these low-cost sensing devices might actually be fundamentally different from institutional environmental sensors (Kumar et al. 2015). In fact, the low-quality data generated by these sensors is often not comparable to existing data standards and the sensing process often takes place in ad-hoc settings and contexts. Despite the growing public awareness and importance of these devices there has been little research on them. Most studies focus on testbed evaluations of sensor hardware (Choi et al. 2009; Mead et al. 2013), yet few examine how sensing deployments take place in practice with communities. Bell and Dourish (2006) suggest that technologists largely frame their devices as future technologies that will function perfectly within a 'proximate future' that is just around the corner. The effect being that technological artefacts are seen as sketches and the community practices they generate are treated as "*irrelevant or at the very least already out-moded*" (p.134). In this way, smart sensors are similarly framed as anticipatory sketches of a future technology (Kinsley 2012) and the material practices they create in the present are largely not evaluated. As a result, only a few researchers (Zandbergen 2017; Pritchard, Gabrys, and Houston 2018) have probed the ways these sensors are creating new kinds of sensing practices. What is needed is an overview of the material practices these smart sensing devices are creating for communities.

Case studies

To engage this gap, this text offers a survey of six case studies of smart environmental sensing projects and devices see Table 1[1].

[1] These case studies are derived from my PhD thesis (Nold 2017) as well as two recent studies Meet je stad! and Pacco Test that will be described in more detail in forthcoming papers.

Project / Device	What is sensed?	Funding Context	Participants
AirProbe	Air Pollution (carbon monoxide, nitrogen dioxide, gasoline and diesel sensor, ozone, temperature humidity)	Academic	Paid Recruits
WideNoise	Sound level, geo location	Academic	Public / Recruits
Air Quality Egg	Air Pollution (nitrogen dioxide, carbon monoxide, temperature, humidity)	Commercial Kickstarter	Public
Smart Citizen Kit	'Ambient' (nitrogen dioxide, carbon monoxide, temperature, humidity, light & sound level, Wi-Fi)	Commercial Kickstarter	Public
Meet je stad!	Temperature, humidity, geo location	Community	Residents of Amersfoort
Pacco Test	Water Quality (pH, dissolved oxygen, electrical conductivity, oxidation reduction potential, temperature)	Community	River Stakeholders

Table 1. Overview of the six case studies with the different phenomena being sensed, their funding contexts and participants.

Table 1 shows the breadth of the six case studies, including sensors focused on a range of pollutants/phenomena, funding contexts and targeted participants. Yet, what makes them comparable is their focus on low-cost sensors whose data is uploaded to the internet, their focus on engaging participants and a common reference to notions of 'smartness' and 'internet of things'. The aim of comparing them is to identify the range of sensing practices and develop a taxonomy that might highlight patterns across the devices.

The survey is based on my PhD study (Nold 2017) that involved multiyear ethnographic observations across Europe of the AirProbe, WideNoise, Air Quality Egg and Smart Citizen Kit. Due to my paid position on the EveryAware team, I was involved in configuring the AirProbe and WideNoise devices and had privileged access to the coordinators of the Air Quality Egg and Smart Citizen Kit. This allowed me to follow the sensing devices across their lifetime (2011- 2014) from design, usage with participants and later academic and policy outputs. In addition, the research involved extensive interviews with participants and users of the sensing devices. The Meet je stad! and Pacco Test case studies are based on interviews with the respective project coordinators. Theoretically, the approach of this survey is based on a framework from actor-network theory (Latour 1987) with attention to the concept of the 'device' as a gathering agent of different agendas (Law and Ruppert 2013). This social science approach focuses on practices as relationships enacted by humans, technologies and other kinds of nonhuman actors. This empirical approach is particularly useful for highlighting tensions between rhetoric and observed reality.

AirProbe

This device was built as part of 'EveryAware' [2], an EU funded academic research project. It combined a hardware sensor box, neural net calibration model, smartphone app and an online gaming platform. Yet, throughout its development there was ambiguity about the goals of the project and what the device should be sensing. Some of the researchers were trying to generate data for air quality modellers as a public health policy instrument, while others wanted to use it as an online platform for running experiments on the public. The final implementation of the sensor system was a mixed reality game where paid participants were asked to carry smart sensors in multiple European cities. Other participants were playing an online game of guessing pollution levels at different city locations. What mattered to the researchers was that they could alter the rules of the game, such as the in-game currency pay-out rate, to see how the users would change their behaviour. Yet, the hardware sensing devices proved unreliable and provided misleading data to the participants. This was so pronounced that some of the participants reported that they had 'learnt' that air pollution was higher in

[2] http://cs.everyaware.eu

parks than next to busy roads. For many of the researchers this was not a problem, since the sensors were merely a vehicle for running tests on the participants inside a virtual laboratory. In this case, the low-cost and networking capabilities of the smart sensors were crucial for enabling experimentation on the public. To summarise, in this case study the smart sensors were being used for '**running tests on the public**'.

Air Quality Egg and Smart Citizen Kit

These two commercial devices were based on the same gas sensors and are functionally very similar[3]. They were both promoted to the public by the project coordinators as visualising environmental exposure. Yet, in both cases the devices produced uncalibrated data that users found hard to understand or use. Both devices provided raw electrical resistance values from the gas sensors rather than pollutant concentrations in the parts-per-million or billion ranges, which prevented users from comparing their measurements against official data. The Air Quality Egg coordinators publicly acknowledged "*that any single datapoint that we collect has low value while the breadth, resolution, and update frequency of the network has high value*" (Air Quality Egg 2012). Interestingly, both projects placed the focus not on the environmental data but on the smart networking capabilities that allowed data to be sent to the network. A promotional video for the Smart Citizen Kit described the usage like this: "*I use my kit everyday, normally I take it in the morning just to have a global awareness of what is going on*" (Acrobotic Industries 2013). While another user suggested, "*I check it every day to see how the information is updated and how the data is uploaded for other people to see*" (ibid). Rather than focusing on nitrogen dioxide as a gas with health impacts, both devices framed the data as abstract network traffic that demonstrates the integrity of a smart network. The Air Quality Egg was partly funded by a company that was hosting the project's data in order to demonstrate the potential of their internet of things platform. While the language of environmental pollution was used to encourage people to back the devices, the focus of the projects was on prototyping globally distributed smart sensing networks. In this case study we see environmental sensors being used as a vehicle for '**deploying smart networks**.

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[3] The case studies refers to the original Kickstarter versions of the Air Quality Egg and Smart Citizen Kit. Later versions of the devices use different sensors and hardware configurations.

Meet je stad! (Measure your city)

This project involves residents of the small town of Amersfoort in Holland, exploring data in relation to climate change. The focus is on the process, experience and learning involved in creating one's own sensors rather than trying to measure specific pollutants. The project coordinators highlight the importance of self-discovery and fun without pre-defined goals and conceptualise the sensors as building blocks: "*if you have a box of Lego, you start building whatever the Lego allows you to build and you get better by doing it and you have to start small and just tinker with it, only then you start to appreciate the capabilities that you have*" (author interview). They suggest this sensor 'tinkering' or 'fiddling' provides the participants with 'sensor literacy' that extends their skills. Participants start with basic temperature and humidity sensors rather than complex air quality sensors since the data is not considered as important as the learning process itself. In the interview, the organisers contrasted their approach with scientific methods that inhibit participants because they do not have specialist knowledge to get started with sensing. They also argue that their approach enables participants to critically assess institutional environmental data and builds social relations that are key to developing climate resilience at the level of a town. In this case study, 'sensing' is used to provide practical skills and politicise the generation of knowledge to '**create community resilience**.

Pacco Test

This project's goal was to create a sensing device that would make water quality understandable and allow communities and stakeholders in Brussels to take care of local water bodies. Unfortunately, the project coordinators were overwhelmed by the technical challenge of building and calibrating the sensing device. They were disappointed because they felt that it could not measure high-enough quality data and after a year of development decided to abandon the device. Nevertheless, the team were pleased that the project process had managed to gather a coalition of actors to manage a local pond as a common resource. The coordinators suggest that the development of the sensor brought local residents, politicians, councillors and technical experts together and agree that maintaining the pond was not just a technical or managerial topic but a 'community thing'. The project prototyped a novel governance system that designated a resident with the role of 'pond master'. "*When there's a change in the water parameters* *that is alarming people, then there is a roadmap on how to intervene and who needs to intervene*" (author interview). The concept of the Pacco Test was that certain data thresholds would dictate actions such as turning on a fountain to increase the oxygen in the pond. The sensor development process meant that competing interest groups such as fishermen and ecologists had to work together to communally agree governance thresholds for the pond. Despite the abandonment of the sensor hardware, the charitable funders perceived the project as a success because it had gathered such a broad range of actors together. In addition, a politician who had taken part in the project suggested that it would support their effort to designate the area as a smart city. In this case study, the smart sensors were used for '**gathering coalitions**'.

WideNoise

WideNoise is a free smartphone app that creates geo-located sound measurements and collects meta data via sliders and textual tags[4]. The device has a complicated history having been designed as a commercial demo and then adopted as an instrument within academic research. The technical ability of device to sense decibel is poor, but it is easy to use. As part of the EveryAware research project, the app was deployed in relation to Heathrow airport in London, where it was framed as measuring aircraft noise as a contentious issue. The official metrics used to legislate noise at Heathrow airport rely on modelled averages that do not take into account the sudden sensory impact of the loud aircraft. This gap meant that local residents and activists welcomed the app as a tool for demonstrating what they saw as the 'real noise' of the aircraft. Most of the local participants used the app to try and capture the sensory disturbance of the loud flights. "*I was going to take some quiet ones [measurements] and but don't want them to just pull down the average. I wanted to stress the loudness. That's what Heathrow already has is averages. I thought we were trying to say in reality the loud noise that we are in*" (interview quoted in Nold 2017). The way the participants used the app was to capture peak intensities, which they felt better represented the sensory impact of the aircraft rather than the airport's averaging metric. Furthermore, the pressure group in their press release argued that "*the number of people*

[4] This case study refers to version 3.0 of WideNoise later renamed WideNoise Plus as used during the EveryAware project.

logging readings and the passion of those contributing at community meetings demonstrates how people are worn down by the noise from Heathrow" (HACAN ClearSkies 2012). The pressure group didn't focus on the decibel content of the data as environmental knowledge. Instead, for both the local participants and the pressure group the physical practice of gathering environmental data itself became a political act. In this case study, smart sensors were not used for their epistemic content but for '**creating political pressure**'.

Discussion

This survey of six case studies has demonstrated that smart cities, and the Internet of Things are creating diverse and novel environmental sensing practices that are intertwined with a range of existing agendas. Smart sensors are:

- running tests on the public,
- deploying smart networks,
- creating community resilience,
- gathering coalitions,
- creating political pressure.

This list of practices is not meant as an exclusive taxonomy of environmental sensing, but represents archetypal practices that are recognisable across a variety of other sensing projects. What is striking is the range of radically different practices the environmental sensors support and generate. Yet, all the case studies have one thing in common; the quality of the data from the environmental sensors was not the focus of the projects. In none of the studies do we see the sensor being used in a straightforward way to represent the state of the environment. None of the case studies created meaningful visualisations of environmental exposure that would allow people to reduce their health impact. There was no simple translation from a measured data point towards more knowledge about the environment in time or space. Instead, the sensors functioned as part of larger project goals such as running academic experiments, building commercial networks, creating community resilience, gathering local coalitions or creating political impacts. Nevertheless, all the projects described themselves as using sensors to gather knowledge about the environment.

So, what is going on here? Many people would not recognise experimenting on the public or building technical networks as 'environmental'. Indeed, smart sensing devices offer something radically different from existing environmental sensors and institutional datasets produced by industry and governments. Instead of creating certainty about health effects or locating pollutants, these devices are enacting new forms of smart city environments that I have previously termed 'neo-environmental sensing' (Blok et al. 2017). What matters with neo-environmental devices is their low-price, modularity, networking, tinker-ability, public engagement and high publicity impact. Their unique ability is to enact new kinds of 'environments' that are highly intentioned with a variety of agendas that stretch beyond pollutants. Fundamentally their aims are to enrol people and actors into sensing practices that lead to these different agendas being fulfilled. Across the case studies, the suggestion is not that the sensors or the data were 'useless' but rather that they function as social and institutional agents that drive complex agendas. These findings challenge the epistemic framing of these devices that I examined earlier. What is needed is a new language for articulating the complex and subtle enactments of the environment taking place in these sensing practices that would benefit the broader smart cities and environmental sensing literatures.

Yet, this survey also highlights political and ethical questions about which kinds of environmental practices should be enacted. Is it ethical to involve the public on the promise of measuring pollutants when they are only generating arbitrary data, or treating them as subjects of a behavioural experiment? Yet on the contrary, in the WideNoise study, a group of activists managed to transform a technically inferior measuring device into a useful tool for communicating their reality of noise by focusing not on its epistemic content but its political potential. Some of the practices from this survey seem to empower communities while others mislead. This range of practices has the potential to have dramatic impacts on vulnerable pollution affected communities. Yet, these impacts cannot be identified merely by analysing the discourse of smart cities or the possibilities and limitations of the sensor hardware. Instead these differences only come to the fore through an ethnographic focus on people's practices with smart technologies. The issue revolves around the extent to which participants can take ownership of smart devices that are by design: technically complex, networked and institutionally distributed. Further research is needed to identify what allows some people to take control of these devices and develop good practice guidelines for ethical environmental sensing in smart cities. A helpful starting point might be to reject claims that smart sensing devices create neutral knowledge and engage with processes of critical ‘tinkering’ as suggested by the Meet je stad! study. Ultimately, it is only by focusing on ‘sensing practices’ that we can understand the ways that smart city technologies have already changed our world.

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References

Air Quality Egg. 2012. “Why Sensor Calibration and Precision Is the Wrong Conversation.” 2012. https://www.kickstarter.com/projects/edborden/air-quality-egg/posts/208180?

Acrobotic Industries. 2013. “The Smart Citizen Kit: Crowdsourced Environmental Monitoring.” *Kickstarter*. http://www.kickstarter.com/projects/acrobotic/the-smart-citizen-kit-crowdsourced-environmental-m.

Bell, Genevieve, and Paul Dourish. 2006. “Yesterday’s Tomorrows: Notes on Ubiquitous Computing’s Dominant Vision.” *Personal and Ubiquitous Computing* 11 (2): 133–43. doi:10.1007/s00779-006-0071-x.

Blok, Anders, Kelton Minor, Rolien Hoyng, Marquet Clément, Kelton Minor, Christian Nold, and Meg Young. 2017. “Data Platforms and Cities.” *Tecnoscienza* 8 (2): 175–219.

Bria, Francesca. 2014. “Digital Social Innovation: Interim Report.” https://waag.org/sites/waag/files/public/media/publicaties/dsi-report-complete-lr.pdf.

Captain, Sean. 2016. “How The World Will Transform Once There Are Environmental Sensors Everywhere.” *Fast Company*. http://www.fastcoexist.com/3054781/elasticity/how-the-world-will-transform-once-there-are-environmental-sensors-everywhere.

Carton, Linda, and Peter Ache. 2017. “Citizen-Sensor-Networks to Confront Government Decision-Makers: Two Lessons from the Netherlands.” *Journal of Environmental Management* 196 (July). Elsevier Ltd: 234–51. doi:10.1016/j.jenvman.2017.02.044.

Choi, Sukwon, Nakyoung Kim, Hojung Cha, and Rhan Ha. 2009. “Micro Sensor Node for Air Pollutant Monitoring: Hardware and Software Issues.” *Sensors* 9 (10): 7970–87. doi:10.3390/s91007970.

Fernandez, Manu. 2013. “Smart Cities of the Future?” In *Smart Citizens*, edited by Drew Hemment and Anthony Townsend, 43–46. Manchester: FutureEverything.

HACAN ClearSkies. 2012. “Do-It-Yourself Noise Challenge to BAA: Wherever You Are, Download the Widenoise App and Use It on Planes.” *Neighbournet.Com*. http://neighbournet.com/server/common/conhrw158.htm.

Hemment, Drew, and Anthony Townsend, eds. 2013. *Smart Citizens*. Manchester: FutureEverything. http://futureeverything.org/wp-content/uploads/2014/03/smartcitizens1.pdf.

Hill, Dan. 2013. “On the Smart City; Or, a ‘manifesto’ for Smart Citizens Instead.” *City of Sound*. http://www.cityofsound.com/blog/2013/02/on-the-smart-city-a-call-for-smart-citizens-instead.html.

Kinsley, Sam. 2012. “Futures in the Making: Practices to Anticipate ‘Ubiquitous Computing.’” *Environment and Planning A* 44 (7): 1554–69. https://doi.org/10.1068/a45168.

Kresin, Frank. 2013. “A Manifesto for Smart Citizens.” *Waag Society*. http://waag.org/en/blog/manifesto-smart-citizens.

Kumar, Prashant, Lidia Morawska, Claudio Martani, George Biskos, Marina Neophytou, Silvana Di Sabatino, Margaret Bell, Leslie Norford, and Rex Britter. 2015. “The Rise of Low-Cost Sensing for Managing Air Pollution in Cities.” *Environment International* 75 (Febuary). Elsevier Ltd: 199–205. doi:10.1016/j.envint.2014.11.019.

Latour, Bruno. 1987. *Science in Action: How to Follow Scientists and Engineers through Society*. Cambridge, MA: Harvard University Press.

Law, John, and Evelyn Ruppert. 2013. “The Social Life of Methods: Devices.” *Journal of Cultural Economy* 6 (3): 229–40. doi:10.1080/17530350.2013.812042.

Mead, M.I., O.a.M. Popoola, G.B. Stewart, P. Landshoff, M. Calleja, M. Hayes, J.J. Baldovi, et al. 2013. “The Use of Electrochemical Sensors for Monitoring Urban Air Quality in Low-Cost, High-Density Networks.” *Atmospheric Environment* 70 (May). Elsevier Ltd: 186–203. doi:10.1016/j.atmosenv.2012.11.060.

Mol, Annemarie. 1999. “Ontological Politics. A Word and Some Questions.” In *Actor Network Theory and After*, edited by John Law and John Hassard, 74–89. Oxford and Malden, MA: Blackwell Publishers.

Nold, Christian. 2017. “Device Studies of Participatory Sensing: Ontological Politics and Design Interventions.” UCL.

Pritchard, Helen, Jennifer Gabrys, and Lara Houston. 2018. “Re-Calibrating DIY: Testing Digital Participation across Dust Sensors, Fry Pans and Environmental Pollution.” *New Media & Society*. doi:10.1177/1461444818777473.

Safecast. 2011. “Safecast: Open Environmental Data for Everyone.” *Safecast*. http://blog.safecast.org.

Townsend, Anthony, Rachel Maguire, Mike Liebhold, and Mathias Crawford. 2010. “A Planet of Civic Laboratories: The Future of Cities, Information, and Inclusion.” Palo Alto. http://iftf.me/public/SR-1352_Rockefeller_Map_reader.pdf.

Vanolo, Alberto. 2013. “Smartmentality: The Smart City as Disciplinary Strategy.” *Urban Studies*, July. doi:10.1177/0042098013494427.

Zandbergen, Dorien. 2017. “‘We Are Sensemakers’: The (Anti-) Politics of Smart City Co-Creation.” *Public Culture* 29 (3_83): 539–62. doi:10.1215/08992363-3869596.