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Harnessing sensing systems towards urban sustainability transformation

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Recent years have seen a massive development of geospatial sensing systems informing the use of space. However, rarely do these sensing systems inform transformation towards urban sustainability. Drawing on four global urban case examples, we conceptualize how passive and active sensing systems should be harnessed to secure an inclusive, sustainable and resilient urban transformation. We derive principles for stakeholders highlighting the need for an iterative dialogue along a sensing loop, new modes of governance enabling direct feeding of sensed information, an account for data biases in the sensing processes and a commitment to high ethical standards, including open access data sharing.

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INTRODUCTION

Rapid urban growth and related pressures on the global environment are challenging the governance and planning of cities[1–3]. Recent frameworks suggest various levers to bring about urban transformation towards sustainability[4–9]. However, urban planners and decision-makers struggle to implement the transformation processes in complex, real-world settings[9,10]. Effectively directing urban development towards more inclusive, resilient and sustainable urban systems[11,12] requires multi-dimensional and radical changes[13,14]. Latest debates have pointed to the oversight of the 'inner world' of sustainability in these systemic views of transformation, including the emotions, thoughts, identities and beliefs of individuals driving human behaviour, otherwise referred to as a 'deep leverage point'[15–17]. At the same time, there is a proliferation of data generated by massive ubiquitous sensing systems[18] allowing to capture and monitor human presence, action and even intention[19], yet imprinting themselves on our behaviours in unconscious ways, often steering unintentionally urban transformation[20]. This calls for a better understanding on how to harness these sensing systems for supporting the needed transformative change within urban planning.

Recent years have seen a massive development of sensors, increase of Earth Observation (EO) and geospatial mobile big data (such as mobile phone data or social media data), Volunteer Geographic Information (VGI) platforms, image analysis and motion detection. One-hundred and fifty billion networked measuring sensors are expected to be installed in 10 years and the Internet of Things (IoT) is forecasted to escalate data-driven decision-making[19]. These sensing systems promise many new opportunities to integrate knowledge about ecological, social and technological contexts of actions with the 'inner worlds' for triggering transformation[21]. For example, geographic information observatories now provide the potential to combine data about human preferences and behaviour data with biophysical data streams such as traffic counters, public transit, weather stations, news portals and air quality monitors[22]. Furthermore, smart building technologies increasingly integrate sensing systems in everyday objects[23], and digital twins of cities are linked to multiple real-time data sources to allow citizen feedbacks[24]. Such integrated sensing systems can help generate a holistic perspective of places, regions or the entire globe, facilitating both observation, experimentation and prediction about people, processes and structures forming the city, and their changes.

Here, we investigate the different forms of sensing systems and their role in urban sustainability transformation. We conceptualize the interactions between various types of sensing systems and highlight their risks and benefits for stakeholders through four global urban case studies. We assess how deliberate sustainability transformations arise based on the interacting spheres of transformation suggested by O'Brien[25], and identify which combinations of sensing systems support specific urban sustainability challenges. Based on these insights, we present a set of key principles to guide urban transformation processes towards 'good' Anthropocenes[14,26].

CONCEPTUALIZING PASSIVE AND ACTIVE SENSING

Passive and active sensing can be distinguished based on the types of technologies and level of stakeholder engagement. Passive sensing is generally associated with fast wireless communication, cyber infrastructure and the IoT, and the collection of real-time information without any active forms of stakeholder

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engagement[27]. This includes the collection of geospatial data about a given phenomenon using passive and active sensors (e.g. EO technologies, geospatial social media, mobile phone records), or the spatially explicit statistical data (e.g. population density measures). In contrast, active sensing technologies draw on voluntary contributions of people to collect geospatial data (e.g. survey research, Public Participation Geographic Information System (PPGIS), serious games). Active sensing aims to support consultation, engagement and empowerment of diverse stakeholders in urban planning through inclusion of the individual as both 'being the sensor'[28] and being sensed. It draws on the 'wisdom of the crowds' and public judgement in ways that provide spatially explicit information that can guide urban planning[29].

To identify various entry points for informing urban sustainability transformation, we link the passive and active sensing systems to the three spheres of transformation: the practical; the political; and the personal sphere[25]. These spheres provide priority points for intervention to achieve transformation[16,30]. The practical sphere includes planning interventions that directly contribute to sustainability goals in cities[25], and is mostly driven by entities directly operating or managing specific resources, such as planners, businesses or facility managers. The political sphere[10] includes instruments (e.g. rules, incentives), institutions and community engagement processes for governing urban solutions, and is carried out by entities acting on behalf of wider societal groups or organizations, such as national governments, municipalities, NGOs and academia. In order to tackle complex urban sustainability challenges in city planning and corporate activities, we, however, need open and transparent data flows and approaches for assessing how the practical and political spheres combine with the personal sphere to influence transformation[15]. This personal sphere, driven by individuals, guides perceptions of transformation and choices about how we live in cities. Figure 1 shows the three spheres embedded within one another in a defined hierarchy: the practical sphere is at the core of transformation and is related to observable and measurable outcomes. Such responses are, however, highly dependent on the political, economic, legal, social and cultural structures associated with the political sphere. This sphere defines how and in what ways transformation at the practical levels could happen. The outer sphere with individual and collective beliefs, values and worldviews, frames the issues and the solutions that are addressed, and can be highly powerful as it influences the other two spheres. In the following, we provide examples for the various types of sensing systems (see Table in the Supplementary information for additional information on the risks and benefits related to these sensing systems).

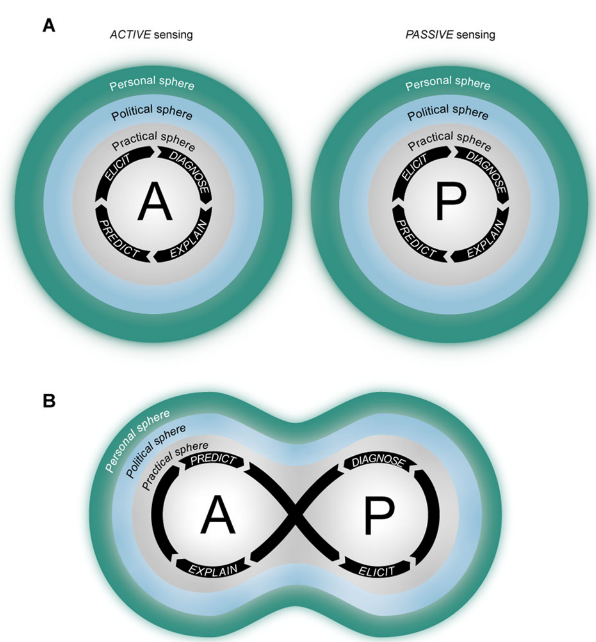


Fig. 1 Combinations of active and passive sensing to inform urban sustainability transformation. A The active and passive sensing in isolation; **B** how active and passive sensing can be combined across the spheres of transformation (practical, political, personal) through the actions of eliciting, diagnosing, explaining, and predicting.

Passive sensing of the practical sphere refers to the use of geospatial data informing decision-makers about key indicators of urban sustainability[31] (e.g. land use, population density, building stocks[32], service networks[33] and energy potential[34]), and assessing changes in natural and human-induced processes (e.g. biogeochemical cycles, land cover changes, and climatic variability and change)[35–37]. Passive sensing of the practical sphere also includes discerning the patterns of human activities, such as changes in travel in response to COVID-19 outbreak[38], detecting illegal fishing[39] or monitoring forest fires[40]. Active sensing of the practical sphere in the context of urban transformation commonly focuses on the deliberate collection of geospatial data using, for example, VGI but can also include active urban experiments through Urban Living Labs (ULL) of specific places, through multi-stakeholder participation and user involvement, co-learning and co-evaluation and refinement[41,42]. Active sensing of the practical sphere can employ a suite of methods including interviews, surveys, envisioning workshops[43], participatory modelling[44], serious games[45] and 3D simulation of landscape development[46].

Passive sensing of the political sphere involves the use of social media and IoT technologies by politicians or value articulating institutions to influence civic opinion or guide certain behaviours[47]. For example, social media companies often seek to persuade and influence individuals and groups to take certain actions[48] or to understand their civic and political participatory behaviour, both online and offline[49]. Others have started using IoT technologies to understand the complex evolution of legal systems[8]. Active sensing of the political sphere includes, for example, games that enable stakeholders and institutional decision-makers to assess the trade-offs associated with different sustainability and resilience policies[50]. They increasingly feature in climate change communication, participatory research and collaborative learning[45] and can often be part of ULL activities.

Passive sensing of the personal sphere draws on a range of methods to collate data on the individual, including their values, attitudes, beliefs, preferences and behavioural patterns. Like passive sensing of the practical sphere, this sensing system can also draw on social media, telecommunications, EO technologies and other sources of big data, for example to assess changes in behaviours through the collection of geospatial social media data (e.g. through Flickr, Twitter)[21,51,52]. In contrast, active sensing of the personal sphere involves eliciting citizens' behaviour and perceptions based on geospatial data collected and produced by volunteered citizens, planners and researchers in everyday living environments. It involves inviting citizens to express their values, preferences or behavioural patterns individually or in groups[53]using a variety of methods, e.g. interviews[54], geographical ecological momentary assessments[55], mail-based or online surveys, workshops, serious gaming[56], participatory mapping[57] and cognitive psychological methods[58,59].

COMBINING ACTIVE AND PASSIVE SENSING TO INFORM URBAN TRANSFORMATION

We acknowledge that sensing technologies alone cannot trigger change. However, combined active and passive sensing (Fig. 1B) provides important benefits for informing urban sustainability transformation, compared with traditional urban planning systems, which treat these systems in isolation (Fig. 1A). We consider the transformational role of new combinations of active and passive sensing through a workflow including four separate actions of eliciting, diagnosing, explaining and predicting (Fig. 1B)[60,61], which are anchored in a geographic context.

Eliciting involves identifying the different elements of each sphere of transformation relevant to the change process in the specific urban contexts. It is mostly conducted using passive sensing but is increasingly done in a hybrid manner using the active participation of local volunteers.

The diagnosing action involves exploring the interlinkages between the elements at a given point in time and space. It is also mostly driven by passive sensing but can be supported by the active participation of stakeholders to identify key entry points into the system. From an urban planning perspective, eliciting and diagnosing enable a more detailed understanding of the boundary conditions that influence transformation at a specific moment. Practical questions that can be addressed during this action include for example: 'To which extent changes in behaviour have occurred?', and 'How do these passively observed behaviours match with stated preferences?', or 'What levels of agreement or disagreement about priorities for transformation exist across systems?'

The explanation action reflects on the sensed data by assessing the validity and uncertainty embedded in the intertwined results as a basis for managing risks associated with system transformation. Here, planners can obtain more detailed insights into issues of spatial data quality across system dynamics[62], for example, differences in spatial accuracy between active and passive sensing data and different types of uncertainty linked to the integration of passive and active sensing data[63–65]. Planners can draw on both active and passive sensing systems to ask questions like 'How well does the active and passive sensing data explain known changes in the urban system?' and 'What level of confidence can we assign to the combined results?'.

The prediction action aims to assess the potential for future change by integrating passive and active sensing into a modelling environment. It is the basis to define and design desired pathways of transformation[66] and ultimately to inform institutional decision-makers about the needed governance adjustments. As long-term monitoring is usually missing in active sensing, predictions are usually based on models harnessing passive sensing. However, long-term monitoring involving the combination of active and passive sensing systems is crucially needed to better understand and predict drivers to and roadblocks of transformation within and across the practical, political and personal spheres[10]. Additionally, predictions that combine active and passive sensing data are needed to identify where and how new policy and legal options can nudge changes to existing institutional arrangements to dismantle the roadblocks and trade-offs to transformation.

The eliciting, diagnosing, explanation and prediction actions should not be considered in isolation in urban transformation processes (Fig. 1A). Rather, we argue that the results from each stage should feed into a dynamic relationship between the passive and active sensing (Fig. 1B), supporting knowledge co-creation processes and fostering dialogues and social learning about transformation opportunities and risks among scientists, planners, businesses, governments and citizens[5,67]. Such dialogues enable deeper understanding of how different modes of governance interact with transformations and the roles of routines, cultures, ideals and social groups in supporting or impeding transformation[68].

We explore these differences with reference to four global cases, including Zürich (Switzerland), Singapore, Dar es Salaam (Tanzania) and Lahti (Finland). Short descriptions of the sustainability challenges experienced in these case studies as well as the mechanisms and processes harnessing sensing systems to support the urban transformation are provided below (see case studies in the Supplementary information for a detailed description). Table 1 provides then a frame of thinking about the risks and benefits of various types of passive and active sensing dynamics across the three spheres of transformation for various stakeholders.

The metropolitan area of Zürich is experiencing ecological, economic and social challenges in the fight against urban sprawl. A recent 'control-and-command' policy, directly addressing the extent, range and type of land use, fuelled ongoing social exclusion and gentrification processes by putting pressure on public services and spaces and accelerating the redevelopment of old housing stocks[69]. A bottom-up active sensing process engaging the local community with planners and authorities was launched to drive the urban transformation process towards inclusive and liveable neighbourhoods[70]. Passively sensed data and a postal survey helped elicit practical and personal factors hindering the transformation and provided the basis for a more in-depth diagnosis of the challenges related to the transformation but did not feed into the active sensing process of the participatory workshops. The uncoupled passive and active sensing processes led to a loss of key information needed for implementation, which slowed down the process, as several intensive pilot processes were necessary to gain the support of the citizens for implementing the spatial development plan.

As an island state, Singapore is highly depending on its natural ecosystems. While the economic benefits of urban development are regularly used in the top-down planning processes, comparable information for natural capital is missing and highly reliant on the values that local beneficiaries attribute to these assets. The Natural Capital project[71] collected a wealth of passively sensed data and conducted several active sensing campaigns to elicit and diagnose the health of Singapore's ecosystems and the potential supply of ecosystem services[72]. This information was integrated into a 3D virtual interactive platform[73] to assist the Singaporean government agencies in decision-making and formulating key recommendations for the future management of natural capital. While there was an iterative process between the active and passive sensing, the sensing process ran in parallel to the traditional planning processes and only helped increase awareness for natural capital. Furthermore, the Natural Capital tool was fed by proprietary data belonging to the decision-makers, hindering its full use by planners.

In Dar es Salaam, rapid population growth is coupled with uncontrolled and geographically extensive urban development. At the same time, the city is vulnerable to several climate risks, particularly frequent flooding. Reliable and up-to-date digital spatial information of the city's infrastructures, local assets and climate risks is a critical bottleneck[74,75]. Passive sensing through satellites and drones coupled with machine learning and artificial intelligence has been used to elicit and diagnose city's infrastructures and physical environment. Active sensing in the form of participatory mapping by students and local communities complemented EO data into locally valuable data products with validated labels and attributes[76]. This has been a major change to the previously prevailing situation, where the data gap has been severe and planning and investment decisions had to be made without up-to-date information of the local situations. Furthermore, local ownership and capacities to react to flood risks on the basis of local knowledge have substantially improved, since the residents have been engaged voluntarily to map their own living environment[75,76].

The city of Lahti aims to combine an ambitious sustainability strategy with high-quality participatory planning practises. To realize their visions, the city has developed an ongoing participatory master plan process[77] that integrates land use and transportation planning within a large-scale participatory planning process. The city uses passive and the active sensing datasets that

Table 1. Typology of active and passive sensing combinations informing urban transformation, featuring benefits and risks of the combinations for stakeholders.

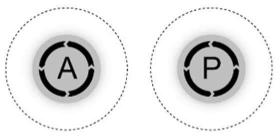
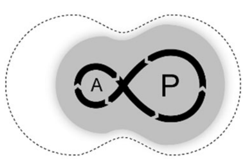
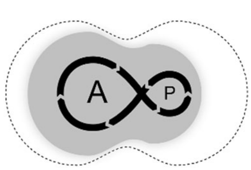
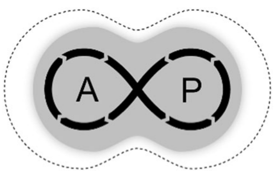
Type of combination	Applied to global case studies	Benefits	Risks
Uncoupled passive and active sensing Applies both passive and active sensing without interactions  Case 1: Zurich, Switzerland	Elements of the sensing systems: Geospatial statistical data, surveys, planning workshops, database of passive sensing data. Spheres of transformation: The uncoupled passive and active sensing processes did not allow an objectively informed land use planning. While the active sensing process enabled social learning among citizens, planners and authorities (personal sphere) and empowered the local community to engage in the political process and local activities (political sphere), it only weakly built on available knowledge. The resulting implementation of the legal binding plan (practical sphere) required afterwards several intensive pilot processes, as stakeholders did not agree on the concrete implementation measures in space.	General: Fast to set up and obtain results. Passive sensing alone can support fast elicitation processes, while active sensing alone can support public engagement. Spheres of transformation: Active sensing alone can foster learning among individuals (personal sphere) and strengthen social capital of wider societal groups (political sphere), resulting in community actions (practical sphere). Passive sensing alone can provide background knowledge for transformation in the various spheres, in particular for planners in the practical sphere and regulating bodies of the political sphere.	General: Difficult to anticipate how well or where outputs intersect to inform the solution space of transformation; difficult to separate causalities from confounding factors; potential issues of procedural and recognition justice; disregard of compatibility of active and sensing data e.g. different time scales of data collection; geographic scale mismatches; issues of representation of diverse knowledge systems. Spheres of transformation: Weak political moderation inhibits changes in planning interventions (practical sphere). Changes in individual worldviews, values and beliefs (personal sphere), and legal systems (political sphere) developed by governing bodies cannot be clearly linked to planners' interventions (practical sphere). Risk of misuse of knowledge and misguided transformation in the practical sphere.
Dominant role of passive sensing Integrates both sensing types with a focus on passive sensing systems.  Case 2: Singapore	Elements of the sensing systems: Geospatial statistical data, Earth Observation data and social media data, co-design and planning workshops. Spheres of transformation: The strong passive sensing component created a knowledge base about Singapore's natural capital. The integration of this knowledge into a participatory 3D virtual platform actively engaged various agencies (political sphere), but the agencies did not want to directly use the open source software and the related ecosystem services data (practical sphere). Passive sensed data were communicated through several news channels, highlighting Singapore's natural capital and strengthening the agencies to continue to include it into their decision-making (personal sphere).	General: Effective at describing actual situation; ample data; reproducible and transparent; useful for long-term assessments. Spheres of transformation: High potential for generating a knowledge basis for planners, businesses and facility managers to define urban plans and management strategies (practical sphere); high-quality passively sensed data from a trusted source can trigger awareness for sustainability challenges by regulating bodies in the political and even individuals in the personal spheres.	General: Datasets often incomplete, especially personal information (e.g. age, gender, education); poor utilization of passive datasets, as active sensing is weak in defining passive sensing (e.g. data access, temporal and spatial scales, data units). Spheres of transformation: Weak governing bodies in the political sphere impedes the delineation of conditions necessary for practical transformation and for defining priorities in actions. Major ethical challenges in individual data ownership and sharing (personal sphere). Neglect of solution space concerning individual and groups behavioural motivations and preferences (personal sphere).
Dominant role of active sensing Integrates both sensing types with a focus on active sensing systems.  Case 3: Dar Es Salaam, Tanzania	Elements of the sensing systems: Earth Observation data, participatory mapping and modelling, citizen observation, co-design and planning workshops. Spheres of transformation: Integrating passive and active sensing has enabled creation of up-to-date spatial information of the city and thus substantially narrowed the previously	General: Allows geospatial data production through local data collection and validation; creates community ownership to data; data production process is based on open source software and open access licensing of the datasets. Spheres of transformation: Facilitates planning, investment by government, investors and	General: Production of digital urban planning data is challenging when rapid urban growth takes place and digital planning data production and utilization is not yet institutionalized. Spheres of transformation: Since the data production is integrating passive and active sensing, data utilization and updating by planners and businesses (practical

Table 1 continued

Type of combination	Applied to global case studies	Benefits	Risks
	existing data gap (practical sphere). Spatial up-to-date information has informed land use planning and action-oriented decisions of the government, international investors and global organizations (political sphere) and in the local communities (personal sphere).	global organizations, and community actions based on digital data (practical and political spheres); creates substantially improved individual and local community ownership and capacities to react to flood risks on the basis of local knowledge (personal and practical spheres).	sphere) is dependent on political commitment and institutionalization of data production (political sphere); detailed level open access data of the city (e.g. drone images) may also offer opportunities for misuse by governing bodies (political sphere); maintaining active sensing is critical for successful data production and utilization process at all action levels (practical, political and personal spheres).
Balanced sensing Includes balanced used of passive and active sensing with weak interactions.  Case 4: LAHTI, Finland	Elements of the sensing systems: Geospatial statistical data, participatory mapping, co-design and planning workshops, joint database for active and passive sensing Spheres of transformation: Using passive and active sensing in a balanced way provides concrete planning support system for informing the transformation, especially in the practical sphere and also in personal and political spheres. The database combining active and passive sensing information supported the diagnosis and explanation actions in the sustainability transformation (practical and political spheres).	General: Supports understanding of reciprocal human-environment interactions (personal sphere); harnessing both active and passive sensing data across different sectors helps overcome the difficult trade-offs during the transformation processes. Spheres of transformation: Rapid and incremental transformation in the practical sphere, driven by planners and businesses; increased individual stewardship for transformation process (personal sphere); agile transformation of the political sphere, carried out by regulating bodies.	General: Established dialogical decision-making culture is needed; difficult to assess the direction and intensity of the transformation due to incremental changes (practical and political spheres); challenging to harness leverage points across the spheres, in particular personal sphere. Spheres of transformation: The amount of active sensing data can become excessive and choosing between the most usable datasets and possible expiry dates remain challenging for planners and businesses (practical sphere); exhaustion of participants can become a challenge (personal sphere) and offer opportunities for political misuse (political sphere).

are stored in the same geospatial database, which is then used across all sectors in the city to provide data for planning processes. The active sensing data creates conditions for the city officials to make decisions and plans based on understanding the values, needs and behaviour of the citizens, and linking them closely with the characteristic of the physical environment and sociocultural context. The dataset enables planners from different sectors to diagnose and explain the challenges, and suggest planning solutions based on integrated passive and active sensing. This strong participatory approach has strengthened the social capital and empowered the local community to engage in the political process[78] and has made it possible for planners to re-evaluate the city strategy goals where needed.

Based on the four global case studies, we argue that the use of sensing in informing transformation is being slowed down by a lack of coordination between active and passive sensing systems, hindering transformations across the three spheres. When passive and active sensing is uncoupled, the urban transformation process is often based on weak knowledge and overlooks available passive sensing, which can lead to manipulative actions by planners and regulating bodies in the active sensing process (Table 1, Case Zürich). However, even when there is active and passive sensing in place, they can be decoupled from decision-making, thus not supporting transformation despite the potential to do so (Table 1, Case Singapore). A dominance of passive sensing in a coupled passive–active system allows planners and businesses for effective urban transformation of the practical sphere, but requires building trust between data producers, data owners and data users (Table 1, Case Singapore). In the case of a dominant active sensing process, the passively sensed data is turned into locally valuable data products, increasing data ownership in individuals and local communities, and ultimately also triggering important changes in the personal sphere (Table 1, Case Dar es Salaam), but securing a long-term voluntary process requires engagement of governing bodies and a strong transformation in the political sphere. Finally, the Lahti case (Table 1, Case Lahti) shows that when active and passive sensing are used in a balanced manner, social capital can be strengthened and individuals and the local community empowered, fostering transformation in the political sphere and increasing stewardship of citizens for the process.

Reaching a full integration of the passive and active sensing in a dynamic process between eliciting, diagnosing, explaining and predicting, requires, however, not only an active exchange between the sensing systems, but also the integration of the practical, political and personal spheres (Fig. 2). Actors, institutions and processes need to be established in such a way to allow weaving multiple forms and systems of knowledge across planning sectors and transformation processes. Such a full integration would allow for different spatio-temporal dynamics and real-time assessments of the complex relationships and dependencies between the three spheres of transformation. This would address mismatches between fine and global-scale data through processes of internal and external validation by scientists, planners and citizens.

PRINCIPLES FOR INFORMING URBAN TRANSFORMATION USING SENSING SYSTEMS

Building on the knowledge acquired in the case studies, we present a set of four principles guiding urban sustainability

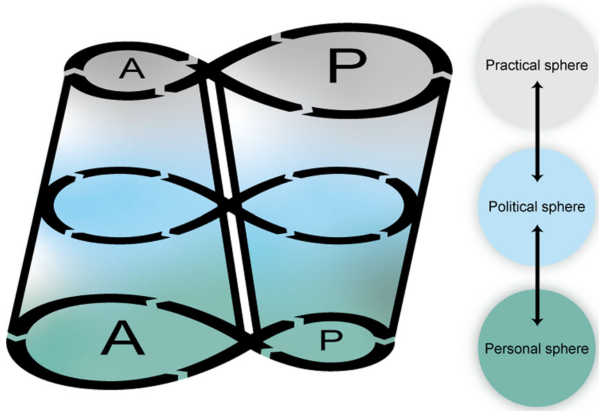


Fig. 2 Combined active and passive sensing loops across the spheres of transformation. The sensing systems are integrated in an iterative dialogue along the sensing loop.

transformation and present ways forward for stakeholders to successfully realize transformations when harnessing passive and active sensing. We do not claim to define a theory of change per se but highlight the role of sensing as a basis for catalysing transformation in the three spheres.

Full integration of the spheres of transformation in an iterative dialogue along the sensing loop

When there is a two-way dialogue between passive and active sensing, goals are negotiated and knowledge is co-produced between the sensing systems, supporting a value-driven informed navigation towards sustainability (Case Lahti). Feedbacks from the active to the passive sensing help raise awareness of the triggered changes and ultimately improve the fit between the ecological, social and technical contexts, allowing adaptation in face of changes[10]. Focusing on 'doing' rather than just 'reaching understanding' is known to help integrate different perspectives and drive transformation[79]. In particular, design approaches, informed by passive sensing, can bring knowledge into a societal discussion and avoid the obstruction of emerging, more innovative and sustainable transformation pathways (Case Zurich). Co-design and co-production can however end in lock-ins when current pathways are not transcended, especially when governance systems, mindsets and urban infrastructures are rigid and create path dependencies (Case Singapore).

Commitment to new modes of governance enabling direct feeding of sensed information from the practical and personal sphere into the political sphere

Our case studies show that urban sustainability transformation can be fostered by activating individuals' values, preferences and behavioural patterns; however, collective actions are also necessary to influence planning outcomes. New modes of governance are needed to dynamically integrate data flows from active and passive sensing systems in order to facilitate the formation of shared values and agreement on preferred actions regarding transformation towards urban sustainability[80] (e.g. Case Lahti). Running the active and passive sensing processes in conjunction with an official planning process to allow feedback between sensing and decision-making would increase the relevance of the sensing process and help define necessary adaptations of policy and legal–institutional aspects to support sustainability transformation. Furthermore, voluntary engagement of local communities combined with automated mapping methods could offer cost-efficient ways to harness the sensing systems (e.g. Case Dar es Salaam).

Account for data biases and issues of representation and exclusion in the sensing processes

More data does not guarantee better evidence. Active sensing can help in giving value to passively sensed data and better define ownership for locals (Case Dar es Salaam), but differences in scale effects and data quality across sensing systems need to be carefully managed[62]. Further, attention should be directed to issues of 'whose voices' are considered or ignored in the planning process when drawing on passive and active sensing. Social and spatial injustice can be created by inequitable distribution of sensors across the area at stake[81], reduced modularity and reduced interconnectedness through highly connected systems[82]. Striving for consensus regarding the selection and use of the data can lead to power plays, and requires active engagement to tackle the politics of sensing processes to avoid replicating existing power asymmetries[83].

Promote high ethical standards, responsible research and openness of sensed data for the benefit of stakeholders

A major challenge is that amidst the open data movement, companies, businesses and also government agencies (Case Singapore) are increasingly becoming data owners (e.g. the mobile phone companies' data on people's mobility during the COVID-19 pandemic). This raises questions about how active and passive sensing systems can be open to the world and used for social good[84]. By ensuring access to sensed data, interested stakeholders can engage in evidence-based decision-making and the monitoring of development progress. An active participation of the data users to determine semantics and ontology of the data[85], be it during an urban transformation process itself or in the Semantic Web community, is essential to communicate uncertainties and develop adaptive solutions. Data users need to understand how the raw data has been processed and for which purpose it has been collected (Case Lahti). In particular, data collected by active sensing of the personal sphere need to be coupled with informed consent and protected or anonymized to ensure privacy. Finally, the collection and handling of data needs to comply with the data protection rules relevant to each country and region.

Table 2 outlines concrete suggestions about how stakeholders can integrate passive and active sensing within and across the practical, political and personal spheres. Such mechanisms, integrated in a dynamic process with short cycles between passive and active sensing, will allow more rapid shifts in the practical, personal and political spheres, thus increasing the feasibility of actions within a given context[10], and ultimately accelerating urban transformation. However, it is still unclear how such loops would fundamentally alter decision support systems and knowledge management. In particular, with the proliferation of real-time data-driven decision-making, there is an increasing tension between the practical and personal sphere. Research in cognitive and behavioural sciences will be essential to investigate how such integrated mechanisms modify individual's perception for problems, use of information and the development of solutions, ideas and knowledge. Ultimately, it might require revisiting existing decision-making models. Furthermore, the privacy and security paradoxes, spanning the tension between a desire to collect individual data and the pursuit of anonymity, will require more knowledge in jurisprudence. Changes in data collection methods will have implications on equality of representation of different societal actors and data credibility, and might require new ethical codes for the use of the value-driven data. New data technology architectures integrating passive and active sensing will be needed and fitted to various types of governance. Innovative data ontologies and grammars will have to be introduced. Finally, new skills of decision-makers will be

Table 2. Mechanisms to integrate passive and active sensing within and across the practical, political and personal spheres.

Spheres of transformation	Concrete suggestions for stakeholders
Practical sphere Driven by entities directly operating or managing specific resources	- Use of creative, but informed design approaches (e.g. Geodesign[43], point cloud modelling[76]) - Active curation of sensed data - Ensure legibility of sensed data - Explicit integration of the sensing loop in planning processes
Political sphere Driven by entities acting on behalf of wider societal groups or organizations	- Ensure access to sensed data - Coherent representation of diverse knowledge systems - Ensure informed consent and protected or anonymized information to ensure privacy - Install national and local data protection rules in place - Active acknowledgement of the politics of sensing processes - Engage in evidence-based decision-making
Personal sphere Driven by individuals	- Active participation in defining data collection efforts - Voluntary engagement in data collection (e.g. citizen science)

required to manage data and processes leveraging integrated passive and active sensing loops in dynamic real-world contexts.

CONCLUSIONS

In conclusion, while the proliferation of sensed data promises unimagined new opportunities to transform cities towards sustainability, it will require a careful integration of the passive and active sensing systems. Integrating important insights from the political and personal spheres into the development of practical solutions will enlarge the solution space for responding to the global challenges. However, such system integration will need to be complemented by open accessibility to data and an active participation of data users in the choice of data products and related sensors. Information flow from active and passive sensing will need to be carefully coupled with existing urban planning and other decision-making processes in order to foster new understandings of choices, which can be made by citizens, planners and corporate stakeholders to facilitate transformations toward urban sustainability.

DATA AVAILABILITY

All data generated or analysed during this study are included in this published article (and its Supplementary Information file).

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AUTHOR CONTRIBUTIONS

A.G.-R., M.S., C.R. and N.F. conceptualized, designed the contribution, curated the data, wrote the draft and coordinated tasks. A.G.-R., M.N., N.F., N.K. and M.K. contributed to the case studies. All co-authors participated in the writing retreat and contributed to manuscript editing.

COMPETING INTERESTS

The authors declare no competing interests.

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