Senseable City

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1 Introduction

Over the past decade there has been an explosion in the deployment of pervasive systems such as cell phone networks and user-generated content aggregators on the Internet that produce massive amounts of data as a by-product of their interaction with users. This data is related to the actions of people and thereby to the overall dynamics of cities, including how they function and evolve over time. Electronic logs of cell phone calls, subway rides, GPS-enabled buses, and geotagged photographs are digital footprints [10] that today allow researchers to better understand how people flow through urban space, and could ultimately help those who manage and live in urban areas to configure more livable, sustainable, and efficient cities [4].

These pervasive systems present the possibility of extracting and inserting real-time information about social dynamics into the built environment. This dynamic feedback loop of information about how a city functions has the potential to influence many aspects of urban management by assisting local authorities, service providers, enterprises, and even citizens themselves to make more accurate, informed decisions and as a result create a more efficient urban environment. In order for this to happen, we contend that it is necessary to first educate the public in understanding how individual choices build up to form emerging urban processes that affect the city and its inhabitants as a whole.

It should be noted that there are many projects that focus on specific aspects of urban pervasive systems, the study of digital traces such as cell phone calls, text messages and geotagged photographs [10, 23, 12], and the implementation of new mobile services [1, 18, 15] and interfaces [16, 26, 8]. Our approach is slightly different. The goal of our visualizations is to translate the invisible digital traces of cell phones and other urban actors relate these to urban space so that people can grasp the large-scale dynamics that occur within a cityscape. The ultimate intent of this work is to envision a future where urban actors can process existing information in real time directly from the city's digital infrastructure and make more informed decisions on their activities and social behavior within the city.

2 From the Urban Actors to the Urban Indicators

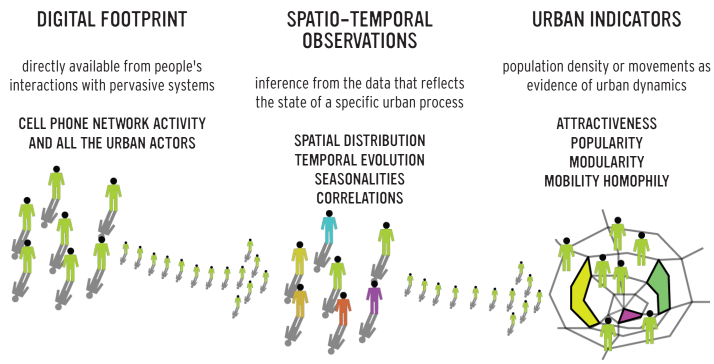

Figure 1. The process starts with the collection of digital footprints, then the analysis over space and time of their characteristics that feed the definition and application of several urban indicators.

The urban landscape in all its complexity and diversity is now being investigated and understood through a new set of urban actors that allow us to gather increasingly detailed, widespread and dynamic information.

Using information gathered from smaller urban actors with localization tags, including GPS, Wi-Fi spots, cellular antennas, Bluetooth, RFID and others, we are able to generate representations of dynamic localized flows. Overlaying these representations onto traditional maps offers insights into human social behavior, as it reveals people's activities in terms of both place and time [15]. The process of collecting, monitoring, modeling and creating/synthesising services is described briefly in the image above (Fig.1).

The *digital footprint* refers to a system of monitoring an urban area directly from activities of its population; with *spatio-temporal observations* it is possible develop an interface for viewing the information collected. This exploration of the data includes a spatial distribution of the population over time yet fails to identify the cause and effects of certain outcomes, for example the reactions of people to special events. From the density and the population movements we are able to define *urban indicators* (indices of attractiveness, similarity, popularity and connectivity).

One of the most promising features of urban actors is its

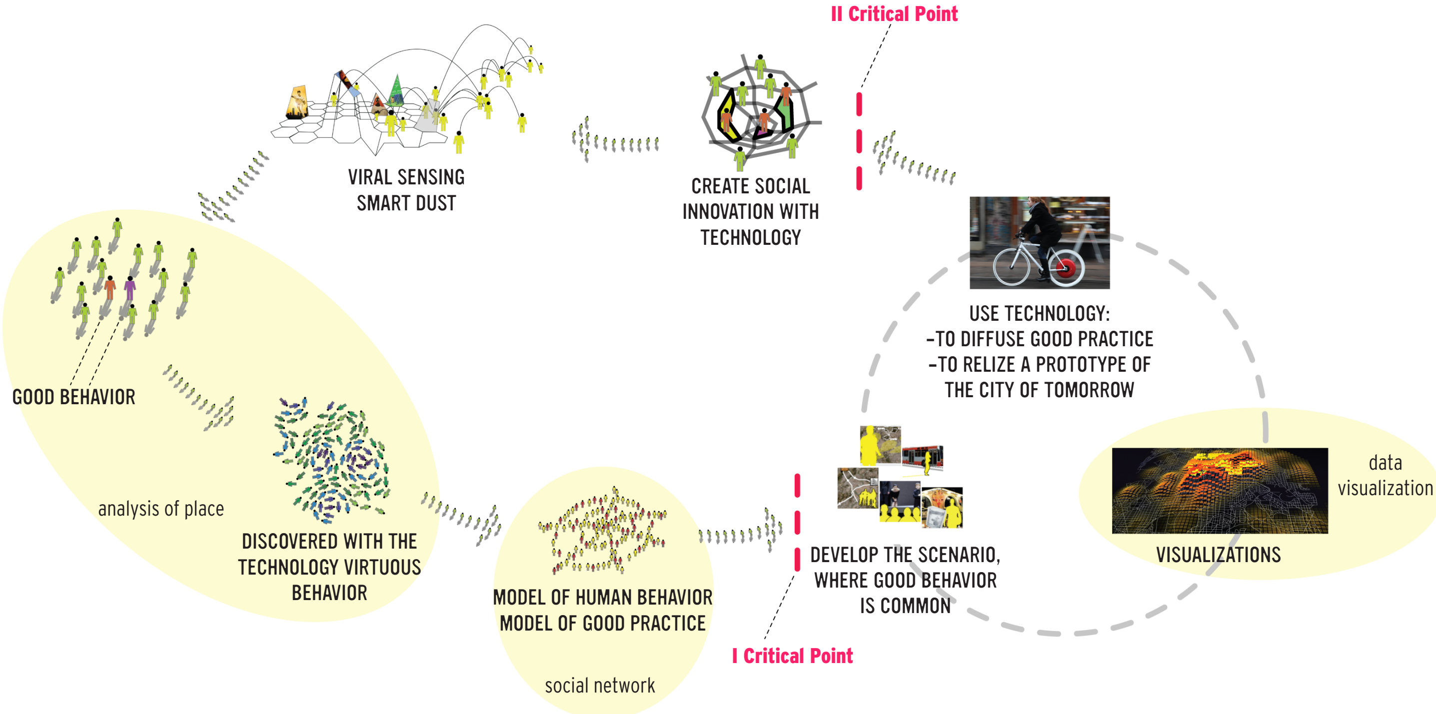

Figure 2. This image presents the author's vision of relations between pervasive computing and social innovation. We can insert real-time information about social dynamics into the built environment.

sensing ability. Sensor abilities are currently diffuse; they measure detailed location information, physiological variables (heart rate, galvanic skin response), or activities (accelerometers can be used to distinguish walking from running or sitting). In the near future, however, we will likely witness a convergence of these abilities into one sensor.

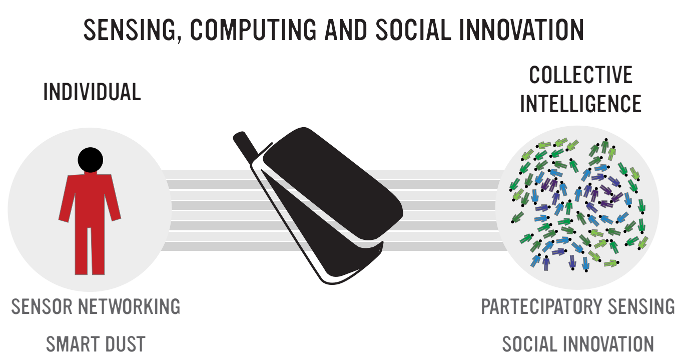

Figure 3. The mobile phone becomes an instrument capable of creating new forms of collaboration and participation. Each individual becomes a node in a network of sensors and participates in the construction of facilities for the community. Technology becomes a means of change in the relationships between people that leads to social innovation.[17]

The cell phone is the best candidate to realize this convergence [14], as it works at the center of everyday life, interconnecting local sensors with collective services. The mobile phone is the new gateway to *people-centric urban sensing* [6], a new sensor-networking paradigm that leverages humans as part of the sensing infrastructure.

Each device can capture, classify, and transmit many types of data with exceptional granularity. The perfect platform for sensing the world is already in our hands and houses an increasing number of built-in sensors: ambient light, orientation, acoustical, video, velocity, GPS. These sensors and an increasing number of others in mobile phones present new opportunities for defining places; ambient sound, light, and color convey a photo-acoustic signature. In-built accelerometers in some phones may also be useful to infer broad classes of user motion, often dictated by the nature of the place. By combining these optical, acoustic, and motion attributes, it may be feasible to construct an identifiable fingerprint of the place [2].
How can we insert real-time information about social dynamics into the built environment? Fig. 2 depicts the authors' vision of the process to combine digital information with the urban environment.

Observing the behavior of millions of people we find that there is a potential 93% average predictability in user mobility, an exceptionally high value rooted in the inherent regularity of human behavior [29]. Suppose we can identify green behaviors for the environment, i.e. promising signals for a sustainable development. and in order to e.g. reveal groups of users who often use public transportation instead of cars (fig.2 on the left). Through dynamic analysis of place with the use of spatial and temporal data we recognize this pattern and develop a model through the analysis of the network of phone calls (fig.2 on below). We chose a typology of virtuous behavior and develop a scenario about how it could be encouraged in the City of Tomorrow (I critical point in Fig.2) through new services, vehicles, and technologies. With these visualization we can show how users behave and we can convey a strong sense of the scenario foreshadowed. At this point should be found a city on which to experiment and develop products/services prototyped of the city of the future. Specific technologies will be useful to promote behavior change by citizens and create social innovation. In the figure we show as an example of these types of technologies, the Copenhagen Wheel, a retrofittable hub developed by the SENSEable City Lab at MIT, that transforms ordinary bicycles into hybrid e-bikes and that also functions as a mobile sensing unit that can communicate critical information about the city to the cyclist's mobile phone as well as to a central server. As smart objects, the bicycles sense the environment and create services not only for the cyclist as an individual but also for the community as a whole. In Copenhagen, where the wheel debuted at the *COP15 United Nations Climate Conference*, the data collected by Copenhagen Wheels feeds a portal where levels of pollution, traffic, and noise are constantly updated. The Copenhagen Wheel manages to optimize the flow of bicycles in town not only in terms of individual needs and interests, e.g. saving time, meeting friends, riding in areas with less pollution, but also collective needs and interests, e.g. fine-grain environmental monitoring in cities and increased understanding of the affect of traffic and environmental policy decisions.

After products and services such as the Copenhagen Wheel are available on the market (II critical point in Fig.2), users of these technologies will become a protagonist of change. Those that choose to use the new products and services will be transformed into new actor-sensors that collect new data which lead us to further insights investigate more and reactivate the sequence of events of this search process.
In the rightmost portion of the figure we see an inner loop highlighting the continuous exchange of information between the scenario development, data visualization, and prototype development of the product/service system. In these design activities we manage product and service innovation at the same time. The visualizations of data that is collected in this urban context are something in-between the textbook and the novel. They illustrate the scenario and spur the interest of the public, media, and scientific community; this interest will open opportunities to expand from the prototype phase to industrial product (II critical point), without which we cannot engage in social innovation or the spreading of positive behaviors in the population.

The digital skin is the sign of human presence in the digital dimension, media façade [4] that write the map of implicit interaction in the real dimension. These anthropic elements embody the aesthetic vectors essential to the transformation of digital environment into landscape.

3 Digital Skin of urban spaces

Urban space and cartographic space are inseparable: starting originally from rudimentary grids and later aerial perspectives to burgeoning digital mapping technologies of today, the cartography of urban space is always an important component in people's mental map of the city. The map has become a popular interface in illustrating data sets drawn from our increasingly digitally-enabled urban infrastructures including GPS [31, 30, 20], cell phone networks [25, 22] and other objects equipped with radio frequency ID tags [20, 5]. The purposes behind these types of visualizations vary from purely artistic endeavors to traffic monitoring to uncovering emerging patterns of urban activity.
The more general and common problems in the visual techniques are with this characteristics: the geometric shape of the path, its position in space, the life span, and the dynamics, that is, the way in which the spatial location, speed, direction, and other point-related attributes of the movement change over time [1,25].

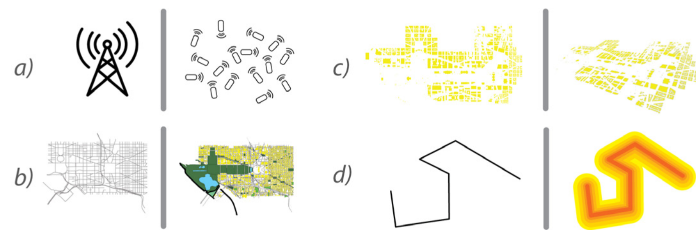

Fig. 4. Distinctive elements in the visualization of urban digital footprints.

Visualization of urban digital footprints seem focus on four distinctive elements:

Infrastructure and scalability. The type of data being used in these visualizations are generated by digitally-operated urban infrastructures in the course of everyday functions of the city (RFID, WiFi hotspots, GPS, cell phones).

Flows and contexts. The data are displayed dynamically over time and in geographic space in order to represent flows of activity (i.e. pedestrians and cars). Some visualizations attempt to represent activity almost in real time, often with a slight time lag for processing, such as a 15-minute delay.

2D and 3D perspective views. Depending on the objective of the visualization, some perspectives are in 2D, as in the representation of traffic flows, and others are in 3D to present concepts like the volume of activity in urban space.

Levels of data aggregation. The scale at which the data is presented in these visualization varies in detail and aggregation depending, for example, on the sensitivity of the information on the individuals used for the representation.
The following is a discussion of precedent projects that exemplify the most notable approaches to mapping urban dynamics.

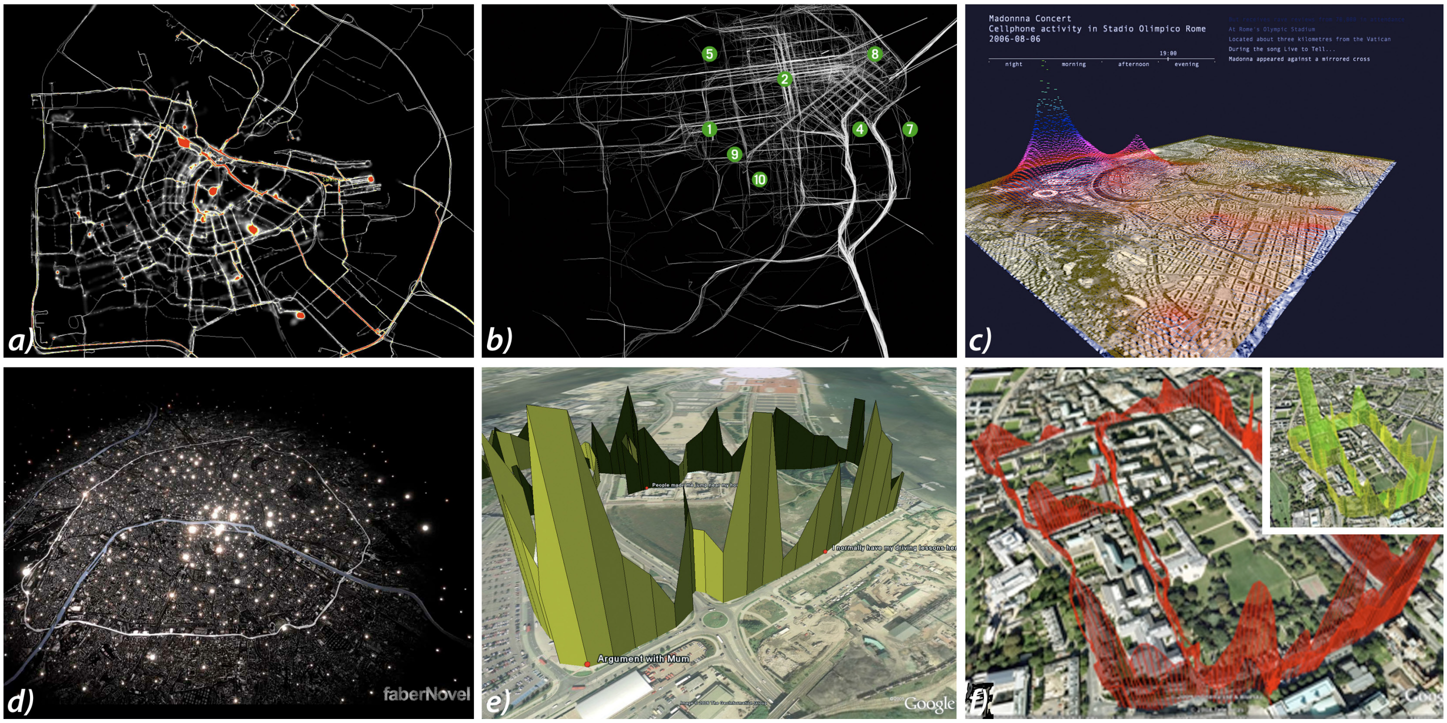

Fig. 5. Examples of visualizations of urban dynamics.

Amsterdam Real Time (2003) by the Waag Society and Esther Polak [31*] (Figure 2.a) focused on visualizing the connection between the structure of the city and the movements of Amsterdam's inhabitants. By examining people's mobility with the use of GPS, the project uncovered a map of the city based solely on people's activity in space. Similar to Cabspotting in San Francisco [30] (Figure 2.b) this visualization employs information flows to reveal the geographic space of the city, highlighting thoroughfares of movement but leaving out buildings and public spaces. Due to a lack of geographic references, it is difficult for those not familiar with the map of Amsterdam to understand the connection between the form of the built environment and the flows of people.

Nevertheless (Figure 2.b), using GPS systems to visualize urban dynamics is a powerful way to detail (Figure 2.d) the movements of tens of thousands of people. Extending this kind of mapping, however, to include larger number of individuals on the order of one million or more involves a high cost and a major organizational effort.

As mentioned previously, Cabspotting is similar to Amsterdam Real Time [31] in visualizing movement within the city and its design approach. Directed by Scott Snibbe [15], Cabspotting uses GPS technology (Figure 2.a) in San Francisco's taxicabs to trace their movement in real time through the city. The patterns traced by each cab create a dynamic sense of traffic flows through the city's arteries, revealing where traffic is moving quickly and where it is congested.

Real Time Rome [25] (Figure 2.c) and UrbanMobs [22] (Figure 2.d) introduce a 3D perspective view (Figure 2.c) and provide a sense of the collective emotions of a city. As the MIT SENSEable City Lab's contribution to the 2006 Venice Biennale, Real Time Rome took aggregated data from cell phones and mapped these calls onto the geography of the city during two special events over the summer of 2006: the World Cup finals match between Italy and France and a Madonna concert. The visualizations show peaks in the volume of calls during stirring moments (such as Italy scoring a goal during the World Cup match), revealing the emotional landscape of the city. Similarly, Orange Labs and Faber Novel developed UrbanMobs as a tool to showcase cartographies of collective emotion through the analysis and visualization of citywide cellular network traffic activity. Real Time Rome and UrbanMobs signal a shift in both the aesthetic qualities of visualizing dynamic urban data and in the methodology of positioning cell phones within urban space according to the location of cell phone towers that service those calls. This methodology may lose the detail of GPS data but in tapping into the network infrastructure of cell phones, it can harness vast amounts of data representing large swaths of the city, thus increasing the scale of representation.

Measuring and mapping people's emotional responses to the built environment itself is the goal of BioMapping by Christian Nold [20] (Figure 1.e). This community-mapping project utilizes a GSR (Galvanic Skin Response) device to measure how people react psychologically to different areas of the city. Over 1,500 people have contributed to this exercise in various cities to produce these communal emotion maps. Presented in 3D, the visualizations use Google Earth to relate people's emotional response to the geographic locations they traverse. BioMapping clearly presents the urban context of people's reactions to the built environment, and the GSR sensors and GPS scale the visualizations down to individual responses; however the number of people involved limits the extent to which these maps may present a collective psychogeogaphy of the city.

Another project that visualizes data gathered directly from consenting individuals is CamMobSense in Cambridge, UK [5] (Figure 2.f). Using sensors mounted on pedestrians and cyclists, CamMobSense monitors pollution in the city and relays the collected data to a website in real time. It presents a low-cost distributed sensor model where people themselves collect data that can be visualized to better understand the environmental impacts of urban functions such as transportation. This in turn can help those who manage urban regions make more informed decisions.

Finally the Obama | One People project utilizes aggregated data from cell phones and overlays the call dynamics onto an aerial photograph of Washington D.C., highlighting the areas directly involved in the Presidential Inauguration such as the Mall and Pennsylvania Avenue. The visualization employs data spanning a week and highlights in 3D the peaks and troughs in cell phone activity before, during and after the special event itself. While the aggregated data does not reveal details of individual movements, it does reveal collective dynamics over the course of a week in large swaths of the Nation's Capital.

Why do we need a *Digital Skin*?

a) It provides a tool to explore human movement dynamics in a metropolitan area. By analyzing a mass of individual cell phone traces, we can build a human-city interaction system for understanding urban mobility patterns at malleable temporal and geographic scales.

b) The tool would enable the incorporation of different advanced data analysis methods used in computational social science, and it would provide a unified interface for performing sophisticated analytic tasks. With the use of real-time data on their respective cities, urban planners would be able to promptly detect and correct phenomena that reduce the livability and sustainability of the city: instead of waiting months to evaluate the impact of their planning activities, urban planners could switch to a more reactive, real-time management of the city.

c) After that we recording human activities at extreme detail we need of digital skin to simplify the analysis of data and at the same time to enlarge the awareness about new ways of collecting information and their potential in terms of services and connections with the idea of privacy. How do people stay anonymous? Displaying information we can have an idea of how we can used the information generated by users and how the techniques of *camouflage* and *hiding in the crowd* [9*] can make any user anonymous.

4 Place and Visualization

In light of the above discussion, we identified the following specific requirements to guide the design of another project: *Obama | One People*. [28]

The visualizations creates a "*digital skin*" of urban spaces, with a simple and clear visual language system. They convey the social dynamics of a crowd, which are real phenomena, using informational data.

Visualizations should establish a strong relationship between the crowd and the urban landscape. For this reason, we considered the spatial representation of the information as a given, as it reflects the geographic nature of the data. The visualizations are interactive and simple and allow the user to explore the evolution of the event in space and time. They are not meant to be visual analytics tools, however, and therefore do not provide quantitative details on the data. To achieve the data, there should be a good balance between aesthetics and functionality. Inspired by Norman's work [21], we use color, saturation, and luminosity to increase the aesthetic and emotional impact of the project.

Finally, from a technical perspective, *Obama | One People* would ideally run on a real-time stream of data. However, due to time restrictions on data collection from the telecom provider's network it was not possible to represent the event as it occurred.

On January 20, 2009, Washington D.C. hosted its largest crowd history for the Inauguration of President Barack Obama. This crowd presented great challenges to both federal and municipal authorities in terms of management, transportation, security, and emergency response. Where would people congregate and how would they get there? When would they arrive and depart? From where would they come? The authorities had difficulty in estimating how many people would attend the event. Early estimates predicted over 3 million people, and it was only after the week of the inauguration that the city was able to release an official estimate of 1.7 million people. The 2009 presidential inauguration illustrates a strong case for the value of gathering data about large crowds in real time so that decision makers may understand and manage special events as they occur.

Our access to aggregated data on the volume of mobile phone calls from a large telecom operator presented us with the opportunity to explore the possibilities of using such data to understand the dynamics of large-scale spe-

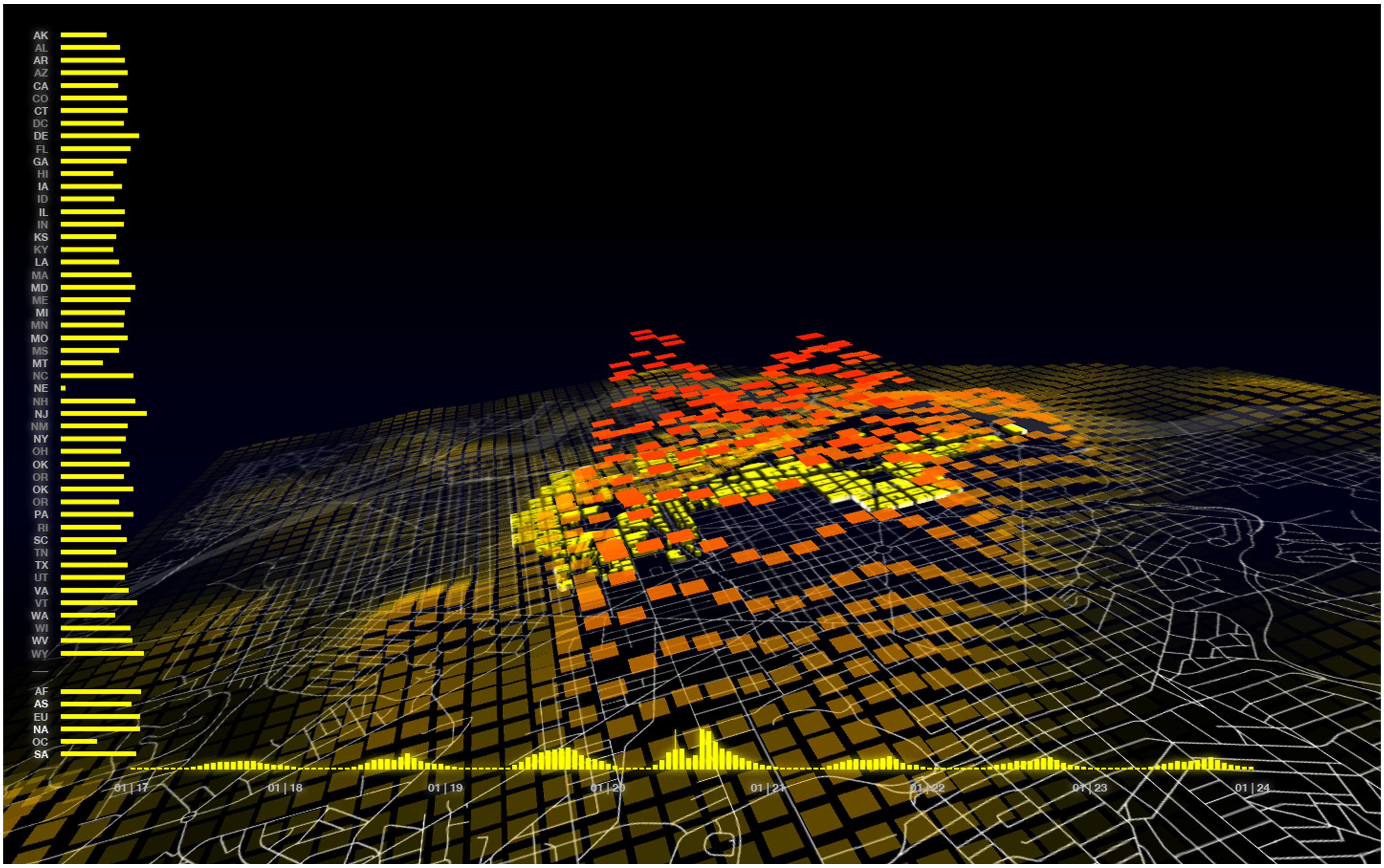

Fig. 6. The City visualizes call activity in the week of the inauguration. Superimposed on the map of Washington, D.C. is a 3-D color-coded animated surface of square tiles (1 tile represents an area of 150 x 150 meters). Each tile raises and turns red as call activity increases and likewise drops and turns yellow as activity decreases. On the left, a bar chart breaks down the call activity by showing the normalized contributions of calls from the 50 states and 138 foreign countries grouped by continent. The timeline at the bottom illustrates the overall trends of call activity in the federal areas of Washington, D.C., which are represented with 3-D yellow models on the map at the center of the screen.

cial events. The *Obama* | *One People* visualizations seek to explore such questions as: Who was in Washington, D.C. for President Obama's Inauguration Day? When did they arrive, where did they go, and how long did they stay? We furthermore interpret the resulting visualizations of call data as revealing the psychogeography of the city during a special event. Guy Debord, a French theorist, defined psychogeography in 1955 as the *the study of the precise laws and specific effects of the geographical environment, consciously organized or not, on the emotions and behavior of individuals.* [7]

Thus, another question *Obama* | *One People* explores is: when and where did the crowd in Washington D.C. sense the need to share thoughts, information, and feelings with others who were not present? Not only does Project O map the invisible flows of communications over the geography of the city, it also begins to gauge the collective emotional pulse of the city at a large scale and over time. Below we discuss the two visualizations produced to present our analyses of aggregated phone calls in during this event: *The City and The World.*

4.1 The City

The City illustrates two pieces of information about the Presidential Inauguration: 1) where the crowd came from and 2) the emotional flows of the massive event in Washington, D.C.

The City summarizes this information by relating call activity to the geography of Washington, D.C. We overlay the map of the Nation's Capital with a 3D color-coded animated surface of square tiles, with one tile representing a geographic area of 150 by 150 meters. Each tile rises and turns red as call activity increases and likewise drops and turns yellow as call activity decreases. On the left side of the screen, a dynamic bar chart breaks down the call activity by showing the normalized contributions of calls from the U.S.'s fifty states and 138 foreign countries grouped by continent. The timeline at the bottom illustrates the weeklong trend of call activity in Washington, D.C., which follows the 3D square tiles that rise and fall on top of the map of the city.

In this visualization, it is possible to see peaks of call activity as the crowd anticipates Obama's oath, a drop in call

Fig. 7. The World visualizes call traffic to and from the capital. Variations in call activity are represented here as flows of people coming to Washington, D.C. and then leaving the capital to go back to their home states and countries. The world map links Washington, D.C. to capitals abroad. Packets move to and from Washington depending on whether call activity increased or decreased in relation to the previous hour. The timeline on the bottom of the screen shows the overall trends of call activity in the federal areas of Washington, D.C., thus allowing the flows of people to be associated with the events highlighted in The City.

activity as the crowd listens to Obama's address, and more peaks when the crowd celebrates the inauguration of the new president. Through their cell phones, those present at the historic event share their impressions with friends and family in vast numbers: on the morning of January 20th, call activity was two to three times stronger than usual, and it rose to five times the normal levels after 2 p.m. as President Obama took his oath and people began to celebrate.

4.2 The World

The World reveals the international nature of Inauguration Day. By using the area codes and country codes of the cell phones present in Washington D.C. during the week of the inauguration, this visualization traces the trajectories of people traveling from all over the U.S. and the world. We interpret the variations in call activity as flows of people arriving in Washington, D.C. and then departing the capital to go back home. The visualization employs a world map to link the city of Washington to US states and countries abroad. Packets of information representing 100 calls for US states and 10 calls for foreign countries move to and from Washington depending on whether call activity increased or decreased in relation to the previous hour. The timeline on the bottom of the screen shows the overall trend of call activity in Washington, D.C., relating the flows of people to events in the city.

This visualization shows that people from almost every corner of the world and almost all fifty states attended the inauguration. The aggregated call data indicates that, there were people present from at least 138 countries, totaling over half of all the countries in the world. This is likely a conservative estimate, as the data used came from only one domestic telecom carrier. Among the foreign countries represented, the main international callers are from Canada, Great Britain, and France, which registered a five-fold increase in call activity. In the U.S., the top calling states are also the country's most populous: California, Florida, New York, and Texas. Notably, Georgia also figures in the list of top five callers on Inauguration Day, even though it ranks ninth in US population.

5 Place, Behavior and Interaction

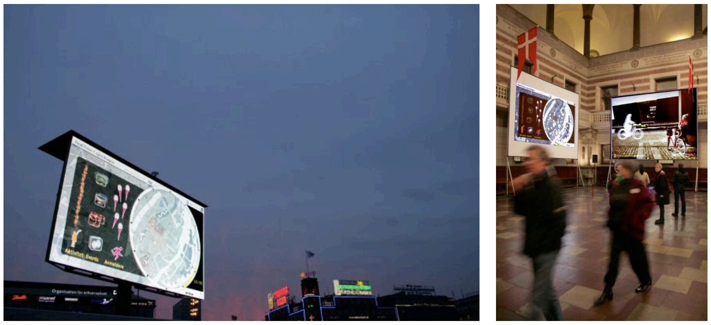

Fig. 8. Real Time Copenhagen displays.

Real Time Copenhagen displays the pulse of the city during Copenhagen's annual Culture Night as it unfolds in real time. The overlaying of the movements of people during events - as captured through the intensity of mobile phone usage- on a map of the inner urban area gives us an understanding of the macro movement dynamics taking place in the city. Meanwhile, the tracking of volunteers through GPS provides a more personal glimpse of the individual movement traces that are being created on the night. The casual observer can use the visualization to choose the most appropriate routes through the city and the events that they would like to see. In doing so, there is a realization that they have become an agent of change in the shifting urban environment that surrounds them.

Real Time Copenhagen explores different interface modalities that create connections between virtual data and the actual physical world where users access the data. Interfaces to Real Time Copenhagen can be more closely positioned to the built environment in terms of interior spaces (Fig.9, A) and/or outdoor spaces (Fig.9, B), they can be linked to moving vehicles, e.g. public transportation or car infotainment center, or they can be closely located to the user himself via a Smartphone, PDA, laptop, or others.

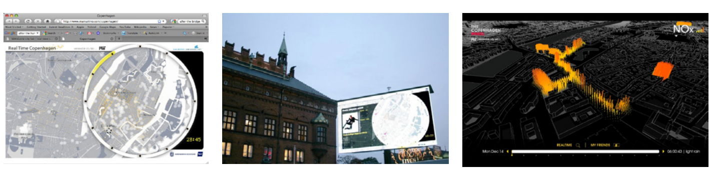

Figure 9 A, web-site Real Time Copenhagen 2009.
B, Real TIme in Copenhagen 2009.
C, Real TIme in Copenhagen 2010.

From this project we can derive the following design methodology:

a) identification of the real-time information available;
b) comparison between the data and the objectives of the system;
c) identification of spatial information and geographical boundaries;
d) creation of a map of the selected area;

e) study and experimentation with users of RGB color combinations;

f) interactions simulations with simulated data and interface definition;
g) usability testing;

h) testing prototype.

Fig. 10. Real Time Copenhagen | design method.

The Real Time Copenhagen project aims to adapt a common format for interchanging real-time location-based data and a distributed platform able to collect, manage and provide such data in real time [1]. In this way, the city's most informative real-time map can be created, letting users broadcast their location and have site-specific information pushed on them per request. Real Time Copenhagen can be divided into a number of manageable channels (layers) such as mobility, events, GPS and aggregate information. Instead of implementing the project with a top-down approach, e.g. the definition of standards, we consider a bottom-up approach in terms of a case study that allows for experimenting with the platform. For future development of Real Time Copenhagen, a city will be chosen whose local authority becomes a key partner and active agent in the entire process, which is then open to and involves potentially all city inhabitants and businesses in the given metropolitan area.

This mapping however is not limited to representing the city; it instead becomes an informative instrument upon which city inhabitants can base their actions and decisions. In this manner the real-time map and the city context are engaged in a dynamic relationship of feedback and change. This is the ultimate aim of leading to an overall increased efficiency and sustainability in making use of the city environment.

In order to identify the functional elements needed to construct such an instrument we chose the real-time control system as an analogy with which we can start. In the past decades, real-time control systems have been developed for and deployed in a variety of engineering applications. In so doing, they have dramatically increased the efficiency of systems through energy savings, self-organization/repair, regulation of the dynamics, and increased robustness.

5.1 Dynamic FeedBack Loop

The aim of the Real Time Copenhagen visualizations is to create a feedback loop that returns real-time information about urban dynamics to users so they may make more informed decisions in their daily activities. We view this project as a large-scale, public, interactive installation geared toward the understanding of spatial interactions, sense-making, and processes involved in social collaboration.
To monitoring the implicit interactions we use interaction patterns to model the behaviors of citizens during their everyday interactions with the media façade and other people. [11]

The patterns of everyday interactions have been studied by numerous disciplines. Sociologists, for instance, represent what Goffman calls the *strips of activity* as detailed narratives, setting the general context and describing specific behaviors.[27] Artificial intelligence researchers, such as Roger Schank and Robert Abelson, choose to use "*scripts*"—predetermined, stereotyped sequences of actions that define well-known situations.

Our interaction patterns provide detailed instructions for the oft-implicit communications between actors, and are derived from observations of cell phone activity.
We can summarize feedback loops as follows:

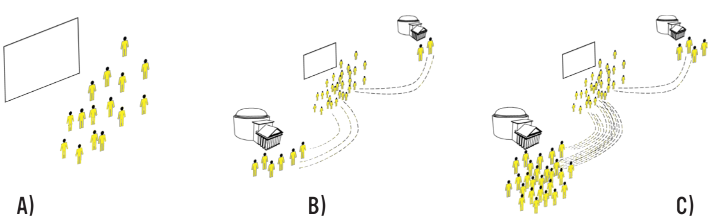

Fig. 11. Real Time Copenhagen | Dynamic FeedBack Loop.

A) People are involved in the interaction implicitly [25], i.e. they do not know they are being monitored; with this type of monitoring, the Copenhagen experiment emphasized the quantity of people that crowded the various events during the Culture Night.
B) After the first few hours we distinguish patterns that indicate place preferences of the population, we observe how people in a square watching a screen are constrained in their choices from this patterns;
C) We observe how the hubs (successful events) self-generate.

The Real Time Copenhagen project intends to demonstrate possible methods and support the design of a feedback loop in order to understand connection between individual mobility patterns and population density. What path will people choose when they can see the population density of a given area? What is the threshold population density that would incite people to change their path choice? As various forms of media are playing an ever-increasing role in providing information, people the people are becoming more influenced by context. If they are looking for a fun place, they will gravitate to places with more people, and if they want to stay away from crowds, will exhibit the opposite behavior. The effects of *word-of-mouth* communication are accelerated by the dynamic feedback loop.This could give inspiration and guidance for urban and transportation planners in city design and development, resulting in more attention to this new form of *collaborative processes* [24] of populations affecting urban development.

6 Place and Sensors

In this final section, the Copenhagen Wheel and a test deployment of 10-environmental sensing kits (that are one of the components of the wheel) will be used as an example of how a detailed sense of 'place' can be revealed through pervasive sensing and how this might influence personal and municipal decision-making in cities.

Designed by the SENSEable City Lab at MIT and unveiled at the COP15 United Nations Climate Conference in December 2009, the Copenhagen Wheel transforms ordinary bicycles into hybrid electric bikes that can capture the energy dissipated while braking and cycling and store it for when the rider needs a bit of a boost. However, the hub also contains a suite of environmental sensors, including CO, NOx, temperature, noise (dB) and humidity. These sensors collect information at 1-second intervals and transfer it to the hub-controller and the integrated communication and locationing device then sends this data to the controller on the bike's handlebars (a smart-phone) where it is processed and used to power applications that relate to a cyclists health, community or the environment.

As such, with the benefits of cheap electronics, The Co-

Fig. 12. The Copenhagen Wheel.

penhagen Wheel is more than a new type of electric vehicle to get you from a to b. By harnessing the feedback loop of information fed both by the sensors in the wheel and the decisions of the cyclist, it becomes a smart, networked device that has the power to encourage people to ride further and more frequently. The key to this is that the wheel can collect and transmit information, to the rider's mobile phone on the handlebars (in our case, an iPhone) and also to the web in real-time. In turn, the iPhone and web application compiles the information so that the rider can easily access it, either during their commute, pre or post-ride.

Harnessing the real-time feedback loop of information is crucial to promoting a continued culture of cycling, revealing a sense of place in the city and assisting citizens in decision making processes. Equally important is the design of the interface and data visualization (both on the rider's phone and on the web) through which the information is viewed. The data must be easy to navigate, not be distracting to the rider and relevant to a cyclist's need and concerns. The following paragraphs will outline the interface designed for the iphone and the potential for this to also exist on a web platform. Finally the potential of the environmental data that was collected in Copenhagen during December 2009 will be discussed.

To begin with, Fig. 13 shows the *splash-screen* for the iPhone interface. It is broken into three function categories: ride, analyze and share.

Fig. 13. Ride, Analyze and Share – the three components of the iPhone interface.

A. Ride: real-time decision making

The Ride screen (fig. 13) allows the cyclist to control the bike while riding. This includes the amount of motor assist desired and gear changing. It is also where 'critical' real-time information is shown. Only showing 'critical' information is important - an interface that resembles an in-car navigation system is too dangerous for bikes and we additionally want to promote a self-made decision taking process. Taking an example, if the rider has been exposed to a harmful level of pollutants for an extended period of time, the screen will flash a warning that allows the rider to choose themselves if they wish to divert from their present route. Similarly, the rider receives real-time weather, road condition and noise warnings. Finally, if a friend from Facebook or another social networking site/service has a Copenhagen Wheel and is nearby, the rider will receive a friend proximity notice and can take action to meet up if they desire. This particular service, named I crossed your path is not only producing social capital, but is also bridging between the virtual and physical worlds and making some of our online social interactions have physical and place-based meaning.

Fig. 14. Cyclists control the amount of motor assist they require, change gears and get real-time updates through the 'Ride' screen.

B. Analyze: future decision making

The Analyze screen (Fig. 14) is predominantly accessed pre or post ride. Through it, cyclists can locate their bike, analyze data from recent trips and make decisions in relation to future rides. This data falls into one of three categories: personal health (calories burnt, effort expended, exercise targets met etc.), the environment (noise and environmental pollution exposure, temperature, road conditions etc.) and community (number of friends that crossed paths etc.).
In health terms, the analyze screen is where the Copenhagen Wheel becomes like a personal trainer. It can tell the rider whether they are reaching their personal best or how much of their recommended daily exercise they have completed – encouraging them to ride more if they haven't reached their goals. In environmental terms, we envision schemes like Green Miles – a bit like a frequent flyer program, only good for the environment. Here cyclists keep track of the number of 'green' miles they are riding rather than the un-environmentally friendly miles that they would have collected if they were traveling by car or other transport mode. These miles could be traded and provide an incentive to ride a bike more frequently. Lastly, allowing cyclists to analyze where and when they cross paths with known friends helps to build a community of connected riders and builds social capital in cities.

Fig. 15. Cyclists can analyze health, environmental and community data that their wheel is collecting through the 'Analyze' screen.

C. Share: decision making through aggregated data

Both the Ride and Analyze screens are useful in that they further promote cycling to the cyclist themselves. However, it is through the Share screen (Fig. 15) that the real power of networked data collection and the potential for this to influence decision making in cities is unleashed. The Share screen allows cyclists to share their data with their friends, but also, if they wish, with their city. Sharing data between friends gives the cyclist access to a larger pool of information from which they can make more intelligent cycling decisions. For instance, a friend's previous routes will have recorded road conditions and pollution levels over time – helpful when a rider is planning a journey in a new part of town. (Fig. 16).

Fig. 16. The 'Share' screen allows cyclists to share the data their wheel is collecting with friends, or with their city.

Meanwhile, when many cyclists donate the information their wheel is collecting to their municipality, the city gains access to a new scale of fine-grained environmental information. Given the amount of data that can potentially be collected, this information will be viewed and analyzed on the web, not on a mobile platform. Through developing an intelligent, user-friendly web interface, cities, community groups or interested individuals can: cross-analyze different types of environmental data on a scale that has never before been achieved before; build a more detailed understanding of the impact of transportation, on a city's infrastructure; or study dynamic phenomena like urban heat islands. Ultimately, this type of crowd sourcing can influence how the city allocates its resources, how it responds to environmental conditions in real-time or how it structures and implements environmental and transportation policies. In particular, schemes like *Green Miles* could be expanded so that all citizens can participate in plans to reduce emissions, perhaps paving the way for cities to enter carbon-trading schemes.

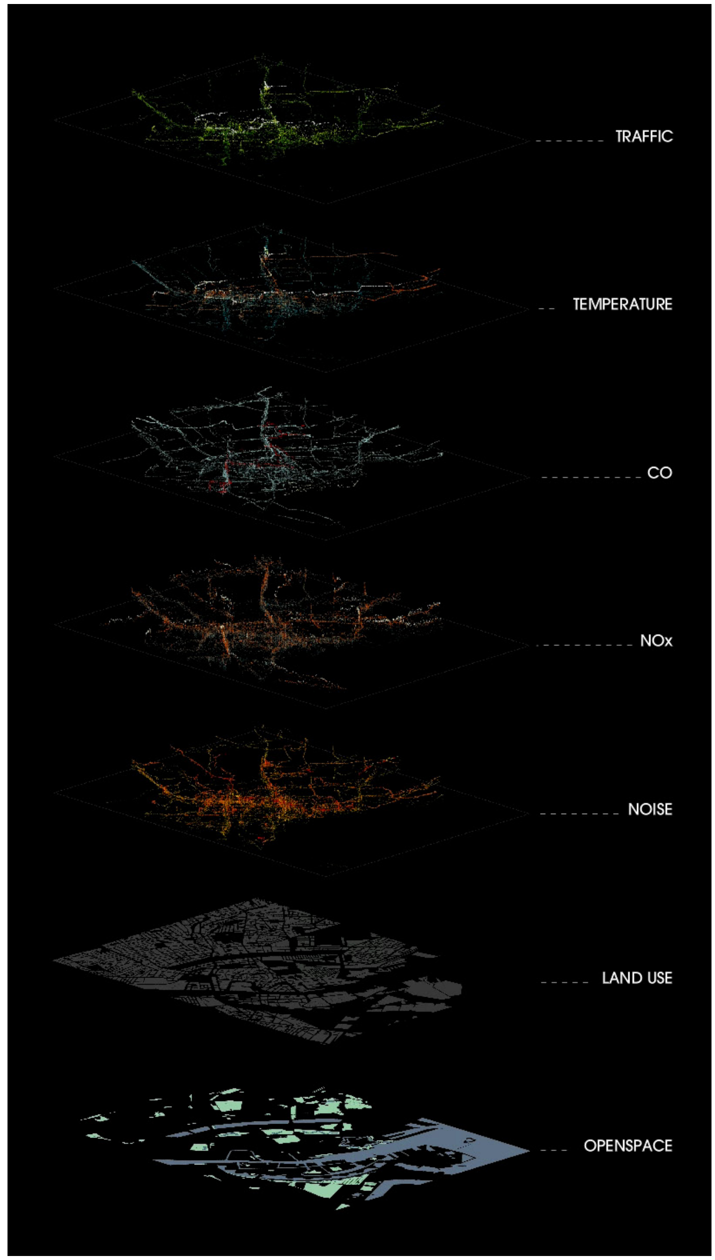

Fig. 17. Different levels of information monitored by sensors in C.W.

6.1 Data Collection Discussion

To further validate and explore the potential of mobile environmental sensing units, the Copenhagen Wheel project used environmental sensors on ten courier-ridden bicycles for one day during December 2009. The sensors incorporated a GPS and sensed temperature, relative humidity, noise, carbon monoxide CO and nitrogen oxides NOx (NO + NO2). These were sampled at one-second intervals for many hours during the day producing environmental data samples in excess of one million for subsequent analysis.

The following points outline the potential benefits of the data collected from the deployed sensors.

1) the data on time, bicycle position, velocity and acceleration can be utilized in many ways including route determination (cycle ways versus trafficked streets), average cycle times etc. (Fig. 18).

2) temperature data can be used to determine sensible heat flux disposition within the city, the monitoring of urban heat island effects, anticipated energy usage for heating and cooling, etc.

3) Relative humidity is important for determining latent heat fluxes through the city, assess the usefulness of enhancing cooling by waterways, fountains etc.

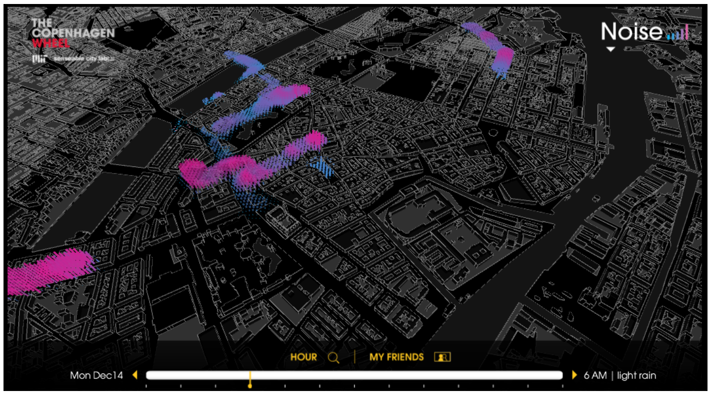

Fig. 18. Interactive Data Visualization in Copenhagen Wheel

4) Noise is becoming a rapidly growing concern in cities, and in some cases is beginning to outweigh air quality considerations. There is much to be gained by comprehensive monitoring noise throughout the city. (Fig 19)

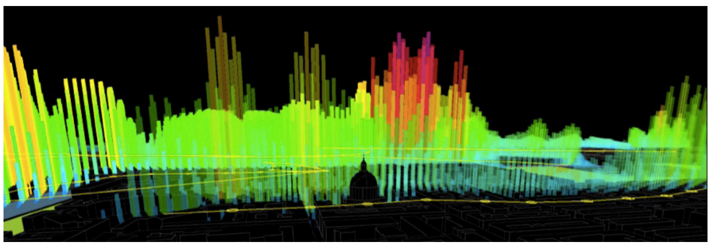

Fig. 19. Bird view of noise level collected while cycling in Copenhagen during December 2009.

5) CO is a measure of the efficiency of combustion in vehicles and may be used to reflect changing driving patterns and the sensitivity of air quality to larger scale environmental features such as the wind speeds over the city.

6) NOx (or the NO2 part of NOx in some cases) is a major pollutant of concern for urban air quality. This is particularly the case in Europe where the annual average regulated concentration is 2.5 times smaller than the US figure. See Figure 20 below.

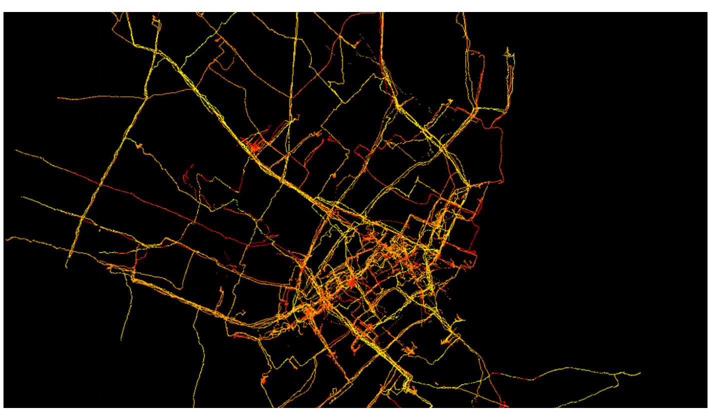

Fig. 20. NOx data collected while cycling in Copenhagen during December 2009.

The current environmental sensors that were used are a trade-off between cost, size, accuracy and energy requirement and it appears from first analysis that the results are only marginally satisfactory [24*]. However, it is widely acknowledged that price, size and energy requirements will continue to decline and that accuracy will increase. Additionally, this growth will undoubtedly accelerate with cost reductions resulting from the increased use of such sensors and as the benefit of having pervasive and mobile sensing over two or three regulatory but static monitoring stations within a city, are realized. As such, pervasive sensing and model-data fusion is the most likely future scenario to address urban problems involving many multiple issues e.g. mobility, air quality and energy use. An overriding theme here, and one which we have tried to address through the discussion of interface design, is that there are typically two types of feedback, the first of which provides information and allows the receiver to make informed decisions either in real-time or in the future. As was mentioned in the beginning of this chapter, a citizens mobile phone is becoming increasingly central to this activity. The second type of feedback aims to encourage specific group behavior, e.g. emergency evacuation or traffic control. In both cases, visualization will be critical to translate the information into a form that is readily assimilable and actionable and the changed perception of the public will be a dominant outcome of both the new data streams and their visualization.

7 CONCLUSION

This chapter discussed the design process, visualization projects, and interaction projects that considered how crowds behave in urban areas, how interact with this crowds, and how we can connect each individual with the community.

Obama | One People showed from a local and an international perspective that the The 2009 presidential inauguration was a multi-day event and that drew people from all over the US and the world. Visualizations such as Project Obama | One People are extremely valuable for those who manage and act within urban space.

Real Time Copenhagen was publicly displayed during a major event in Copenhagen and presented the real-time cell phone activity and location of thirty volunteers with GPS signals.

The *Copenhagen Wheel* generated information about the environment, including road conditions, carbon monoxide, NOx, noise, ambient temperature and relative humidity. It contributed to a fine-grained database of environmental information from which we can all benefit.

7.1 Promoting behavioral change

Looking at the Digital Skin of urban spaces one identifies emerging patterns of human behavior. There are no models to understand and decode the meaning of these patterns, but research on the implicit interaction of the population with the urban actor can produce a rich understanding of the social systems. The Digital Skin clearly illustrates information generated by group of people and different patterns within this information. They are a first step in revealing collective patterns of social dynamics, and data such as call activity can offer insights into how people inhabit the city at different times and locations.

Having the results of these analyses in real time, urban planners would be able to promptly detect that reduce the livability and sustainability of the city: instead of planning urban interventions and waiting months to evaluate their impact, they could switch to a more reactive, real-time management of the city. Moreover, these kinds of visualizations, if accessed through an appropriate interface, could also be of value to the urban dwellers themselves. The ultimate goal of this work is to build urban interfaces where people can deposit and extract information on the functions of the city in real time and thus work together to build more efficient, intelligent and sustainable cities.

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