HUMAN-SENSOR DIALOGUE IN PARTICIPATORY SENSING

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Abstract

Participatory sensing is an emerging field that uses pervasive technology to create new forms of sensing networks combining people, personal devices, and other sensors. Pervasive computing technology forms an essential component, used to report data and coordinate activities. This thesis reviews research in participatory sensing and key fields related to it: pervasive computing, observation networks and public engagement with science.

After examining wider issues in sensor-based interaction from pervasive computing literature, this thesis investigates human-sensor dialogue; specifically how to develop new forms of dialogue in future participatory sensing experiences. The term 'dialogue' is used in broad sense, encompassing affordances and ongoing relationships between sensors and users. The thesis examines participatory sensing activities centring on two studies involving groups of young people collecting and visualising environmental sensor data using automatic and manual sensors. Participant observation methods are used for in-situ, naturalistic evaluation using observations, video footage and system logs and data.

A framework for human-sensor dialogue is developed as a tool to help analyse the dialogue in participatory sensing experiences and inspire new forms of dialogue in future experiences. It highlights five activities to which dialogue can relate: planning, testing, navigation, capture and reflection. These are interleaved throughout an experience, affecting how it takes shape and resulting from the design of the devices and the whole experience. The framework is demonstrated by applying it to the experiences in the previous two studies.

The framework is used to prototype a new experience intended for longer term engagement. It is used to elicit requirements for the new experience, structuring the activity and highlighting the desired transitions. The resulting prototype application is described, outlining the activity setup, key features and technical details. This application uses handheld devices as mobile sensors, wirelessly connected to fixed environmental sensors, which collect, process, and store the restating data.

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1 Introduction

This thesis is about participatory sensing and specifically how to support new forms of human-sensor dialogue as part of future participatory sensing experiences. In this introduction chapter a brief overview of participatory sensing will be given and the motivation for exploring the area will be explained. The contributions made by the thesis will be outlined and the approach taken to the research will be described, giving details about some of the related projects that have fed into the work. Finally the structure of the thesis will be described, acting as a guide to the rest of the document.

1.1 Participatory Sensing

As computer technology becomes more pervasive, mobile devices and digital communications technologies are becoming more and more embedded into people's everyday lives. As the 21st century progresses people will find themselves interacting with many thousands of computers each day, embedded into the surrounding environment and artefacts or more remote, accessed through communications networks. Coupled with this, "Web 2.0" ideas and technology have fostered a rise in user generated content through blogging, podcasts, wiki sites such as Wikipedia, and media sharing sites like YouTube and Flickr. This has equipped individuals with not only the capability to access information wherever they are but also record and report it, and also share and discuss it. Adding to this further, the rise of social networking websites has brought about new means of mass-engagement and participation, potentially coordinated through pervasive technology to rapidly engage thousands of individuals in campaigns, petitions, supporting a common cause or simply to share a common experience; the "flash mob" phenomenon and viral trends represent one aspect to this, whilst recent political campaigns have also highlighted another aspect to it.

Environmental concerns are heightened in the current era, as a clearer understanding of the adverse effects of human activity upon the environment is developed. This further raises the importance of sensing the world, gathering data to further study and mitigate these effects. Participatory sensing seeks to marry these themes with the fields of sensor networks and information gathering, using pervasive technology to collect and combine scientific data with community-gathered information. Traditional 'municipal' or national scale monitoring systems, concerned with air pollution or traffic conditions, can be supplemented with fine grained local information, harnessing the potential of the array of devices carried by people in their daily lives. Mobile phones, PDAs and GPS devices for example, utilising their built in sensing capabilities and information provided by their users, or perhaps extending these with supplementary sensors, separately obtained or integrated within a new generation of personal devices.

Participatory sensing (Burke et al., 2006) relies on human-in-the-loop techniques, taking advantage of the every day actions of users to provide opportunities for sensing, or interactively working with them to dynamically respond to changing conditions or sudden events; participants may be invited to confirm readings nearby, alter their route to account for gaps in sensor coverage or even propose objectives and new investigations based on their own experiences. Not only does participatory sensing aim to combine specialised sensing systems with more general and more mobile data collection, but also bring together specialists and experts together with individuals and grass-roots participation.

With the heightened focus on humankind's effects on the environment, interest in participatory sensing has centred around environmental monitoring, however techniques can be used across many areas and new applications are emerging in different domains. Participatory sensing does not only supplement sensor networks, but also provides a means to gather data in different ways, using the insight of local participants to build a deeper understanding of the issues and to engage those individuals and communities in the process of investigating and responding to these issues.

The integration of more powerful computing and communications technology into personal devices, and into the environment at large, means that the ability to gather, process and report information continues to improve. This presents increasing opportunities for participatory sensing, though these capabilities also present challenges, both technical and human. Technical challenges are raised in terms of realising the devices, protocols and infrastructure for these systems, developing the means to fully exploit the opportunities provided and process, store and analyse the data that is collected. Human challenges are presented in understanding how these new systems can fit into people's lives, how to represent and interpret the capabilities of them and how to manage privacy and data integrity when dealing with this data – which in many cases can be personal in nature. Ultimately, participatory sensing involves a complex socio-technical system in which people and sensors support and complement each other in gathering and responding to data. This thesis addresses one of the key challenges in this system, focussing on the relationship between people and the sensors they work with, it looks at the dialogue that develops and how to support new and different forms if it for future participatory sensing experiences.

The challenges faced by participatory sensing are shared by the wider pervasive computing community, addressing them will help to provide the basis for building ubiquitous computing infrastructure as ubiquitous and pervasive computing comes to the forefront of modern technology. Pursuing participatory sensing research will help discover new and improved ways to handle the vast amounts of data it is possible to gather with pervasive computing systems, and further understanding of how to present interfaces to the new and complex systems and services that are emerging. These new systems also present challenges to privacy and data security, the development of participatory sensing systems will also explore these.

1.2 Contributions of the Thesis

This thesis is therefore concerned with the dialogue between humans and sensors in participatory sensing experiences. The principal contributions made by this thesis are:

- A review of projects and related research that has made noteworthy contributions to participatory sensing. This review identifies common trends and disparities across the field, looking at kind of sensors used, the range of sensor automation, and areas the work has been applied to.
- A study of a project that uses a combination of handheld sensors and pervasive technology to create a participatory sensing style experience. Taking place as an educational activity in a school environment, it investigates the dialogue between people and sensors looking at how it was formed, what aspects worked smoothly and what was more difficult.
- A second study working with many participants over a shorter time period, again using handheld sensors to collect and collate information and then visualise it in a combined view. The study further investigates dialogue between humans and sensors looking at participatory sensing related aspects.
- A framework to describe key aspects of human-sensor dialogue based on the findings from the two studies. The framework is illustrated using the previous studies, demonstrating it as a tool to analyse participatory sensing experiences.
- A demonstration of the use of the framework to devise new participatory sensing experiences. Using techniques informed by the earlier analyses, and building on the previous work, a demonstration application is created to fulfil requirements drawn out through the use of the framework. This combines handheld and fixed sensors to collect environmental data in a workplace environment, providing both location-centric and person-centric viewpoints.

1.3 Approach to the Research

The work in this thesis was conducted alongside two larger projects that the author was involved with and contributed to. This approach was mutually beneficial, working in collaboration with these projects provided exposure to and involvement with the ongoing research as well as access to a wider range of resources and opportunities for study throughout the development of the thesis. The outcomes of this involvement are evident in Chapter 3 and Chapter 4, and are summarised below:

Chapter 3 was a result of involvement with the SENSE project, a JISC funded investigation into the use of emerging networking technologies to enhance techniques science lessons in schools, promoting the use of hands on methods of learning. The author materially contributed to the design and construction of the sensing equipment used throughout the project, assisted in the design of the programme of activities and with the collection of data for evaluation purposes. The study within this chapter was a result of parallel work, re-using and independently analysing the data collected throughout the project specifically for this thesis.

The Participate project provided the background for Chapter 4. Participate was a large multi-partner research initiative involving the universities of Nottingham and Bath, the BBC, BT, Microsoft and ScienceScope, it was co-funded by both the EPSRC and the Technology Strategy Board (formally known as the Department for Trade and Industry). The three year project explored the convergence of pervasive, online and broadcast media to facilitate mass participatory events based on the theme of the environment. For the first half of the project work was subdivided into three streams, school activities, gaming and community involvement. As with involvement in the SENSE project, the author contributed to the schools related activities, assisting with the design and conduct of the initial design work based in schools involved and assisting with the development and evaluation of prototype technology from which the sensing toolkit used in the study was developed. The fieldwork reported in the study was an independent trial conducted by the author out of the main stream of work of the Participate project.

Both studies featured in this thesis and the consequent development of the framework and demonstration application introduced in Chapter 5 and Chapter 6 take an iterative, user-centred approach to the research. It combines prototyping, studies, technical innovation and theoretical work in a close knit process, allowing each to inform the others throughout. A fundamental part if this is working in real environments or “in the wild” (Crabtree et al., 2006), an approach used in the SENSE Project[1], Participate[2] and the Equator IRC[3]. Appreciating the situated nature of interaction in participatory sensing experiences, naturalistic evaluation techniques were employed based on observation backed with video footage and combined with the use of sensor recordings and system data collected during the events.

1.4 Thesis Structure

Chapter 2 builds a foundation for the work in this thesis by reviewing existing research in participatory sensing and the key fields that feed into it. These include pervasive

[1] SENSE, http://www.informatics.sussex.ac.uk/research/groups/interact/projects/escience-pollution.htm
[2] Participate, http://gow.epsrc.ac.uk/ViewGrant.aspx?GrantRef=EP/D033780/1
[3] The Equator IRC, http://www.equator.ac.uk

computing, observation networks and public engagement with science. Examples of projects illustrative of these wider areas are given before focussing more on the convergence of these fields in participatory sensing. More specific examples are introduced, describing projects and their outcomes from across the range of participatory sensing related fields, these are analysed on the basis of their application areas, whether the sensors used are fixed or mobile and whether the sensors are automatic or manual in operation. This analysis provides motivation to focus on an investigation of dialogue between humans and sensors in participatory sensing experiences.

Next, Chapter 3 provides a study of a participatory sensing style experience, working with groups of school children collecting information about air quality (Carbon Monoxide) levels around their school areas. Using a combination of sensors, both automatic and manual devices, the participants collected data and analysed it back in the classroom using bespoke visualisation software. The analysis focuses on how the participants used the combination of devices to collect their data and reveals a range of aspects related to the human-sensor dialogue. It showed how participants focussed on various points of interest contributing manual readings (photos, written notes, etc) in an episodic manner, resulting in intervals of detailed, targeted sensing over a background of automatically gathered readings.

Chapter 4 continues the work of Chapter 3, conducting a second study of a participatory sensing style experience. Again working with groups of young people, this study takes place at the World Scout Jamboree in 2007, this 'summer camp' style event provided an opportunity to engage with a wide range of participants, taking part in short half-hour activities mapping sound level readings around an activity area then exploring them using a novel 3D interface. Participants gathered sound level readings using a special data-logger, they took photos using a digital camera and plotted position using a GPS unit. As with Chapter 3 the analysis concentrates on how the participants used the equipment to collect readings, particularly how well they managed to match high readings with photographs. The study highlights factors that relate both to the design of individual devices and the visualisation tools, but also to the way in which the experience was designed and conducted. As with the earlier study, participants focussed their attention on points of interest, their success at the exercise was affected by their choice of points of interest, which related to their attention to the sensor, their understanding of the readings and their prioritisation of activities. The process was also influenced by their understanding of the resulting visualisation based on the feedback from the sensors, conversely how the design of the sensors and visualisation corresponded to their usage of the equipment.

Based on the preceding work, Chapter 5 outlines a framework to describe key aspects of human-sensor dialogue in participatory sensing experiences. The framework outlines five general activities to which dialogue can relate, these activities are interleaved throughout an experience, affecting how it takes shape and resulting from the design of the devices and the experience as a whole. The framework is demonstrated using the two earlier studies, analysing the dialogue that took place in a two part process. The first stage identifies what parts of the experience fit into the five activities identified; planning, testing, navigation, capture and reflection. The second stage then considers the way these elements worked together and the transitions of focus from one to another. This process maps out each experience, characterising them by showing the links between activities created by the transitions and what events trigger the change of focus.

The sixth and penultimate chapter of the thesis uses the framework introduced previously as an aid to design a new participatory sensing experience. The chapter outlines a new scenario, shifting focus from closely managed activities over a set period of time to longer term engagement embedded in day-to-day activities. Using a similar approach to the previous analyses, the framework is used to draw out a set of requirements for the new experience. It looks at the individual activities and then how they fit together, generating a proposed structure of the activity that highlights the desired pattern transitions alongside the requirements identified. The chapter moves on to describe the prototype application that was created to implement the experience, outlining the activity setup, the key features resulting from the requirements and then covering the technical details of the application. This application uses PDAs and smartphones as mobile sensors, working wirelessly with fixed sensors to collect and store information about the local environmental conditions.

To conclude the thesis Chapter 7 finally summarises the work presented, reinforcing the key contributions and discussing the potential for further work.

2 Participatory Sensing, Pervasive Computing and Context-Aware Computing

2.1 Introduction

Participatory sensing brings together three areas, pervasive computing, observation networks and public engagement with science. This chapter will give a general outline of participatory sensing and describe these three fields, explaining the terms used and the broad areas of interest throughout the rest of the thesis. The relationships between the fields will be outlined, describing where they converge in areas relevant to participatory sensing and setting it against a backdrop of existing HCI research in sensor-based interfaces. Applications throughout the highlighted areas will be illustrated with a range of examples, highlighting some of the key contributions across each area relevant to participatory sensing. The examples will then be examined to identify common trends and differences.

2.2 Participatory Sensing

Participatory sensing (Burke et al., 2006) is a relatively new field, named from its integration of sensor networks and 'human-in-the-loop' techniques – the ability to take advantage of data gathering opportunities provided by the actions of individual people participating in a larger observation network. The actions may be specifically performed, or occur as a result of everyday activities; for example responding to a call to report on a particular topic, or simply by providing a mobile sensor platform as a consequence of daily travel. New and increasingly pervasive technology (mobile devices, wireless connectivity, internet) provide not only the infrastructure for such networks to be built, but the weight of numbers to make them effective (Abdelzaher et al., 2007). They combine elements of static sensor installations, mobile devices, wireless communications and human interaction to dynamically make observations and record information.

Participatory sensing draws inspiration from the overlap of three areas; pervasive computing, observation networks and public engagement with science. These areas and their converging elements relating to participatory sensing are shown in a Venn diagram (Figure 1), which will be explained and developed further in the following sections. First, the three main areas will be introduced in order, and then the converging sections will be described in order again, as indicated further below.

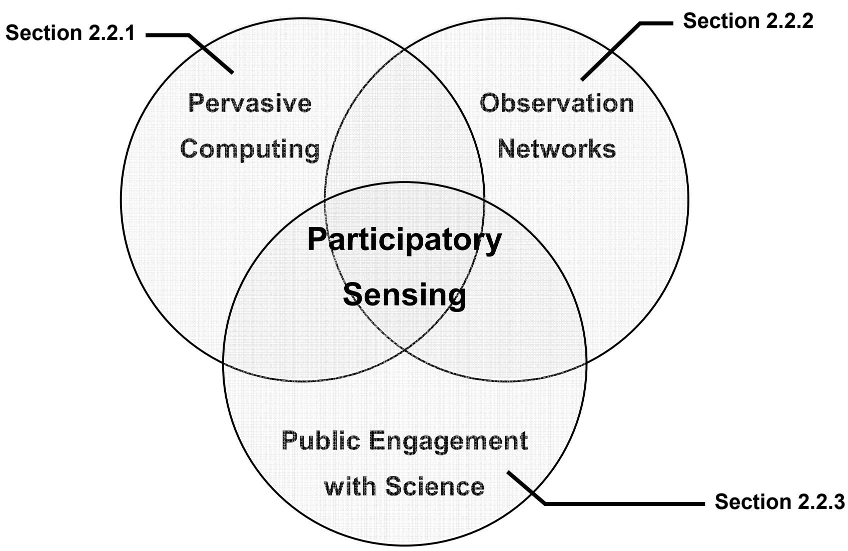


Figure 1: Venn diagram showing participatory sensing at the convergence of pervasive computing, observation networks and public engagement with science.

2.2.1 Pervasive Computing

The first of the major contributing areas to be described is pervasive computing. Improvements in size, cost and power requirements have allowed smaller, more mobile and more capable devices to be combined with advances in communication technology, allowing computing devices to become highly connected, embedded and more personal (Frohlich et al., 1997). Through this technology it is possible to form complex highly interlinked and interoperable systems, and these are increasingly becoming a part of everyday life. As these systems mature, both the complexity of them and potential applications for them increase, the implications of these new systems, both in realising the benefits they can bring and the way in which they may change the environment within which we work and live is an important and active topic for research.

Foreseeing these changes in computing technology, the field of ubiquitous computing was established in the early 1990s (Weiser, 1991), describing a vision of intelligently connected computer systems, closely integrated into the task at hand, allowing their users to concentrate on the end result rather than the device by which it is achieved. Devices of varying scale were envisaged, from personal "inch scale" devices, now realised as mobile phones or PDAs, to "foot scale" devices, such as laptops or tablet PCs, and "yard scale" devices such as the interactive white boards we see now. Ubiquitous computing seeks to assist everyday life rather than overwhelm it, providing information and services when and where desired through the integration of all these different devices.

Ubiquitous computing, particularly the aspects relating to the interconnection of devices of varying scale has also become known as pervasive computing. The two terms are generally interchangeably used and it has been suggested that the term pervasive computing better describes the original, intended vision introduced as Ubiquitous Computing (Satyanarayanan, 2002). As such, throughout this thesis the term pervasive computing will be used to refer to pervasive and ubiquitous computing.

2.2.2 Observation Networks

Throughout the world many things are observed, monitored and reported on and digital communications technology has allowed ever faster and more powerful means of requesting, collecting and publishing this information. Observations can range from human reported, such as eyewitness reports after an earthquake (Wald et al., 2001) to readings from automated sensor networks, such as urban pollution monitoring ('UK Air Quality Archive, Automatic Urban Network (AUN)')[4], and ship location tracking ('Live ship location tracker').

One of the most commonly recognised examples of observation networks are metrological monitoring systems collecting information about weather and atmospheric conditions for reasons including weather forecasting, aviation or shipping safety, and climatological analysis. The UK MET office's land-based observation network is one such as this, combining hourly readings from around 200 fully automated weather stations in the UK, as well as additional daily readings from a range of manned stations ('UK climate: Synoptic and climate stations'; Jebson, 2008). Similarly, another common example of the use of observation networks are for traffic monitoring and reporting, like the UK Highways Agency National Traffic Control Centre ('National Traffic Control Centre'). This operates a traffic observation network, consisting of over 1000 Automated Number Plate Recognition (ANPR) cameras and 1500 electronic loops embedded in the road surface on motorways and A roads throughout the UK. This is complemented by additional reports from CCTV monitors at Regional Control Centres, reports from roadside contractors and information from third party organisations such as the police or airports, sporting venues, etc. This information is analysed and passed on to anyone interested in road conditions through a number of media including TV and radio, variable message road signs, websites, telephone lines and a number of information points located at service stations throughout the country.

The Mass Observation Project of 1937 onwards ('The Mass Observation Project') provides an early example of a observation network collecting human-reported information rather than environmental or natural phenomenon. This London-based project built a national panel of volunteers responding to regular questionnaires to

[4] References to specific websites and online documents are indexed by page title in single quotes and are listed separately in Section 8.2: "Online References".

create what was called an “anthropology of ourselves” – a study of the everyday lives of ordinary people in Britain. Contributing material included personal diaries, day surveys and “directive replies” – a series of open ended questions on a variety of subjects including personal issues. These contributions were made by the volunteers, whilst additional material was provided by paid investigators, adding observations, overheard quotations and ‘ephemera’ (transient material such as theatre tickets, fliers, posters). This project continued for many years though moved more towards the study of consumer behaviour in the late 1940s. In 1981 however, the project was revived along with its original vision, with over 2,800 contributors since then and a current list of 400 correspondents.

2.2.3 Public Engagement with Science

Public engagement with science, also known as science outreach or public awareness of science, covers a wide range of activities, from museums, science education and science literacy campaigns, to involvement in debate over controversial research and participation in scientific processes. Governments and research organisations have undertaken projects to educate the public in issues resulting from scientific research, such as air pollution or the causes of heart disease. Museums, schools and charities also set out to engage the wider world in science issues and foster a greater degree of knowledge, understanding and participation in scientific research.

Museums have played a part in science education; science ‘festivals’ and travelling exhibitions have taken this approach further, bringing a range of exhibits and science activities into communities, providing a unique occasion to stimulate interest and motivate participation. An example of this is the Discovery Dome, a exhibition that toured the UK between 1988 and 1995 (Pizzey, 1988, 1996). The exhibition, housed in a series of interlocking tents contained over 50 individually designed hands-on experiments demonstrating principles of science and engineering based on five main themes; Forces of Nature; Structures, Patterns and Waves; Optics; Technology; and About Ourselves.

The Discovery Dome saw about 80,000 visitors each year, staying at each venue on average 25 days. Visitors included school children (on average 20,000 a year) but activities were broadly aimed at the general public, with exhibition pieces and staff providing information on a number of levels. This project and similar others emerging at the same time, have inspired a range of science workshops, exhibitions and interactive technology ‘museums’ aimed at engaging the public with science and technology.

Public engagement with science is seen as essential in building up trust between science and society, both in order to increase acceptance of scientific developments but also to ensure scientific work reflects the needs and desires of society. This has included encouraging wide participation in debate about new and controversial research and technology, for example debates over new areas such as nanotechnology and stem cell research.

These issues and many others have been the subject of discussion in a range of events in bars and cafés since 1998; called Science Cafés, these informal discussion events demonstrate another area of public engagement. Science cafés are public events, held in casual meeting places such as a bar or coffee shop, at each event a scientist, researcher or other expert introduces a topic to kick off a discussion. The audience is open to, and aimed at the general public; plain language and inclusive conversation are encouraged to create a comfortable atmosphere for the people with no scientific background to become involved. Since the first science café was formed in the UK 1998, many more have sprung up around the world, loosely coordinated through an umbrella organisation “Cafe Scientifique” ('Cafe Scientifique'; Ferris, 2007).

A final example provides a brief insight into the role of mass media and public service broadcasting in bringing science issues to the public. In September 2008 the Large Hadron Collider ('Large Hadron Collider'), a high energy particle accelerator system began operation at CERN, the European Organisation for Nuclear Research ('CERN: The European Organisation for Nuclear Research'). This event was widely publicised in the news media, however the BBC took this a stage further, commissioning a week of special programming on Radio 4 called “Big Bang Week” ('Big Bang Week', 2008). The special programmes during this week not only included factual documentaries and live coverage of the switch on event but also contributions from journalists, comedians, theologians and science fiction writers engaging with the topic from alternative perspectives. These programmes included a piece in the programme “Woman’s Hour” using CERN as a case study to examine efforts made to increase the involvement of woman in science; “Thought for the Day” discussed the reconciliation of science and faith; a special radio edition of the popular science fiction series “Torchwood” used the LHC as a setting and inspiration for its plot; and comedian Steve Punt also took inspiration from the LHC to write the comedy show “Big Bang Day: The Genuine Particle”. The example of Big Bank Week highlights a range of methods through which public engagement with science is developed through broadcasters and the mass media.

2.2.4 Observation Networks and Pervasive Computing

The introduction now moves on to look at three areas of convergence between the fields described above, each also contributing to participatory sensing. First an overall description and some brief examples will give an impression of the areas; the next section in the literature review will then look at specific examples with more detailed descriptions. The first area is from the convergence of pervasive computing and observation networks; in this section the idea of context-aware computing is introduced. The second field is participatory science, where observation networks and public engagement with science combine. Finally the third section looks at e-science and learning – a combination of pervasive computing and public engagement with science.

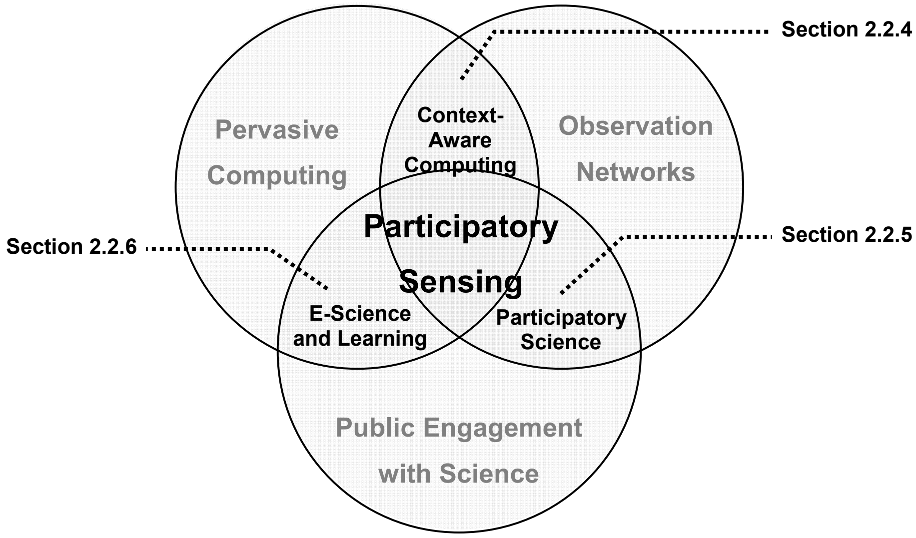


Figure 2: Topics contributing to participatory sensing from convergence of the three main areas

Observation networks fundamentally rely on communication in order not just to pass on and report data but to become established and maintain individual parts of those networks. Pervasive computing technology provides huge potential in this respect, bringing a powerful infrastructure of digital communications as well as new, more capable platforms from which to collect and process data.

Pervasive computing technologies have been used in parallel research, such as UCLs Urban Pollution research ('Urban Pollution research'; Steed et al., 2003), however the appropriation of embedded and networked sensing techniques has been of particular interest in pervasive computing in the area of context-aware computing; this has provided one of the key areas contributing to participatory sensing.

With increasingly complex networks of electronic devices the choice of what configuration to use, what services to offer and what information to process become more and more difficult. Automating these choices provides a means to simplify this, however in order to do so it is necessary for a system to appropriately gather and interpret the correct information upon which to make the decisions. Observation networks constructed from pervasive computing devices can collect information about a user's context which can then be used to configure and coordinate those devices or applications in the most desirable way – this is known as context-aware computing.

In describing context-aware computing Schilit (Schilit, Adams & Want, 1994) give four general functions that context-aware systems can enable:

Proximate Selection: Reducing a list of options to those physically closer to the user.

Reconfiguration: Managing the configuration of hardware and software based upon the user's context.

Contextual Information: Accessing information and sorting information based on users context.

Context-triggered Actions: Automatically initiating actions from contextual triggers.

Contextual information can come from the state of individual devices or applications, such as current activity, past usage, etc, but it is increasingly derived from sensed data gathered about users and their environment. The use of sensed contextual information has been a key focus of work in pervasive computing, and context-aware applications have provided influence in participatory sensing.

2.2.5 Observation Networks and Public Engagement with Science

Second in the list of converging areas is observation networks and public engagement with science. In addition to engaging the public using methods such as those described earlier (museums, exhibitions, broadcasting, and special events) participatory science involves members of the public in the scientific process by soliciting their participation in experiments and investigations. Also known as citizen science, participatory science projects bring together volunteers from the general public; individuals; schools; or communities, to forming networks of observers and operatives to gather data for large scale scientific experiments and enquiries.

Participatory science projects have included projects that observe and document the natural world, particularly spotting and reporting wildlife such as birds and insects. In America, the National Audubon Society (a non-profit environmental conservation organisation) has conducted the Christmas Bird Count ('Christmas Bird Count'), starting as far back as 1900 collecting counts from 25 locations around North America ('Christmas Bird Count History'). In 2007, thousands of observers contributed their bird counts to the project providing information about bird population trends, endangered species and their reaction to changes in climate. In the UK the Butterfly Conservation organisation operates the Butterflies for the New Millennium project ('Butterflies for the New Millennium project'), recruiting volunteers to locate and identify colonies of butterflies throughout the summer and providing government and conservation bodies with important conservation data.

Participatory science experiments have tackled other issues and taken place over shorter durations. During the 1990's as part of the UK's National Science Week, the

Megalab initiative conducted many participatory science experiments, in conjunction with the BBC science and technology show Tomorrow's World and the Daily Telegraph newspaper. One such experiment was the Megalab Truth Test (Wiseman, 1995), which involved participants viewing or reading an interview with a well known political commentator. Two versions of the interview were provided, with the public being asked to call in to dedicated phone lines to choose which version they believed to be lies. Another of the Megalab investigations saw volunteers taking part in weight loss studies for a month (Highfield & Irwin, 1999); different instructions were printed in alternative versions of the Telegraph newspaper evenly dispersed throughout the country. One group were asked to increase non-exercise activities (such as climbing stairs instead of using a lift) whereas the alternative group were asked to "think about being slimmer" by, for example, imagining themselves doing exercise.

These examples highlight the ideas that participatory sensing has adopted from participatory science, where public engagement with science combines with observation networks. The final part of this section looks at the combination of pervasive computing and public engagement with science, in an area described here as e-science and learning.

2.2.6 Pervasive Computing and Public Engagement with Science

As with other areas in science and technology, pervasive computing researchers have sought public engagement to publicise their work and to inform and progress the research itself. Participatory design methods have been used to engage people in pervasive computing research; TeamAwear (Page & Vande Moere, 2007) is a prototype wearable display jersey for basketball teams which was developed in this way. Embedded electroluminescent wires and surfaces are used, sewn into each jersey and illuminated to display information about the individual player (individual fouls and score); their team (winning side or losing side); and the match (1 minute and 10 seconds remaining). The design of the jersey was directed by the participatory design process, where the researchers worked with a group of volunteer sportswomen, coaches, referees and spectators to direct the design; choosing the type of information displayed as well as determining factors in the construction such as location of power packs, fastening mechanisms and durability. Another example, LINC (Neustaedter & Brush, 2006) is a calendar information appliance for a family kitchen, this was developed by researchers alongside a group of 20 mothers with children over the age of three years. The design process involved interviews and design sessions, with the participants' existing calendars used as source material for investigation and paper prototypes were presented as a source for discussion. This work fed into the design of the digital version of the calendar system and again the participants provided a formative evaluation, giving feedback on significant aspects of the design and perceived shortfalls.

As pervasive computing technology becomes more widely available, researchers and practitioners of more varied topics are adopting it for their work. This is the case in e-science, where pervasive computing is providing opportunities to engage with schools and communities in e-science activities using this new technology.

E-Science research initiatives seek to design, build and explore emerging scientific methods which use large scale distributed resources, communications technology and electronic tools as fundamental components. This includes the development of a networked supercomputing and mass data storage resource known as The Grid, as well as tools to harness this capability and assist computer-supported collaboration between researchers. E-Science marries with pervasive computing as laboratories and scientists become equipped with pervasive computing tools, allowing them to automatically capture information, combine it with others' and to document and explore the provenance of such data.

In engaging with the public these concepts are being brought through to the science education community, allowing learners to experience e-science methods and activities using emerging technologies. This combination of public engagement, collaboration and the sharing of resources mediated through pervasive technology falls alongside the ideas of participatory sensing and defines the main focus of the overlapping area in this section; e-science and learning. Two examples of this are given below.

The Schools Malaria Project (Frey et al., 2005) is a project which allowed students to help design potential malaria drugs by linking up their work with high power computer simulations through a web interface. The project was aimed at A-Level students who were asked to design chemical compounds that would form a component of a potential malaria drug. They used a web interface which supported each stage of the process and allowed them to sketch out their compounds and submit for checking on a powerful computer simulation remotely hosted at a university campus. The simulation provided measures of various parameters indicating how well aspects of the molecule performed, and the results included the ability to view a 3D model of their work.

A wider range of pervasive computing technologies have been employed in out-of-classroom science activities, focussing on the use of pervasive technology for data collection and recording, inquiry and collaboration between pupils and teachers. The Ambient Wood project (Rogers et al., 2004) demonstrates this, with handheld computers, specialist electronic tools, location tracking and wireless networking used to communicate with facilitators and collect and access data. The Ambient Wood was a learning experience for 11-12 year olds, it was based upon the idea of a school field trip where, in pairs, participants are given information, asked to collect information, find answers to questions and explore the area. A range of both off the shelf and bespoke devices were used to provide the experience; a PDA and a hand held 'probe tool', provided access to pre-recorded information (over a wireless network) and collection and viewing of light and moisture readings around the area. A mobile listening device called an 'ambient horn' and stand-alone wireless loudspeakers provided location based sounds, either on demand or triggered by their presence. Another stand alone device was a 'periscope' that served as a video playback device located in-situ in the wood. Each pair also carried a two-way radio, though which they could talk with a remote facilitator, to ask questions, describe what they were doing and their plans.

2.3 Sensor-Based Interaction in Pervasive Computing

Pervasive computing has been a major influence in participatory sensing, particularly the use of sensor networks and sensor-based interaction. Having initially detailed key areas feeding in to participatory sensing, this section takes a wider view, looking at a selection of relevant work related to sensor-based interaction from the field of human computer interaction (HCI). As highlighted throughout the start of this chapter participatory sensing draws together a broad spectrum of techniques from context aware computing to more explicit use of sensors and pervasive computing in education and in everyday settings. This section illustrates broader issues in sensor-based interaction, relating participatory sensing to existing HCI research.

In HCI literature that deals with sensor-based interaction authors have often raised concerns involving the need to develop new interaction techniques to account for implicit interactions with sensor-based systems. These concerns have come from both a pure usability standpoint and through highlighting challenges for privacy and trust (Bellotti & Sellen, 1993; Abowd & Mynatt, 2000; Mynatt & Nguyen, 2001; Bellotti et al., 2002; Langheinrich, 2002). Emerging from this work a range of frameworks and guidelines have been developed that provide means to describe and model sensor-based interactions, to inform the analysis and facilitate the design of sensor-based interfaces.

Mynatt and Nguyen discuss concerns with the concepts of "invisible computing" and implicit input in the design of applications (Mynatt & Nguyen, 2001). They discuss the need for feedback and control mechanisms in context-aware and pervasive computing systems, highlighting a number of potential areas to address: dealing with ambiguity and errors in the sensing system, understanding of a system's capabilities (and limitations) and also privacy, trust and security in dealing with sensed data. They propose feedback and control mechanisms integrated into the practices surrounding a system's daily use, using simple affordances, such as visual feedback and the ability to reposition a fixed video camera to provide users with the means to manipulate the content of the information to meet their needs and preferences.

Bellotti and Edwards also explore this area (Bellotti & Edwards, 2001) focussing on the limitations of sensing and the need to involve human initiative in context aware systems. They propose a framework based upon intelligibility and accountability; intelligibility referring to the ability for users to understand what a system knows about, how it knows, and what it is doing about it, accountability referring to the need to link the effects of the actions of a user to other users. Derived from this, their framework is supported with a range of design principles to consider, illustrating ways in which human-salient details can be presented:

- Inform the user of current contextual capabilities and understandings.
- Provide feedback, such as feedforward to indicate possible courses of action, in-process feedback indicating a time consuming task is taking place and feedback about the ownership and availability of elements in a context that may be unintentionally available.
- Enforce identity and action disclosure – providing explicit mechanisms that account for details of presence, identity, arrival, departure status, availability and activity in a given context.
- Provide user control – using strategies to reduce user overload (responding to constant confirmations, etc) but still provide a useful context-aware service. This could include a means to correct system action when there is only slight uncertainty, confirmation when there is significant doubt and a choice of options in other cases.

Imagining more digitally mediated management of privacy concerns in sensor-based systems, Langheinrich presents a set of principles and guidelines based on fair information practices respected in current legal systems (Langheinrich, 2001). He discusses how sensor-based systems should prevent unintentional “spillages” of personal data and focuses guidelines on the collection, storage and transmission of sensed data:

- **Notice:** Announcing what data was being collected –for example preventing sensor embedded artefacts from collecting without those present being aware.
- **Choice and Consent:** Requiring explicit consent to collect and use personal information from sensors, and allowing a reasonable opt-out or compromise choice.
- **Anonymity and pseudonymity:** Anonymity provides less sensitive means to

collect certain types of personal information, and also provides an alternative option for individuals. Similarly allowing pseudonymity allows users to be identifiable within an application but remain unidentifiable externally.

Proximity and locality: Restricting data collection to when the user is within proximity to particular sensor and restricting the sharing of data only to those within a certain distance from the sensors.

Adequate security: In combination with the other elements, this refers to using proportional security measures to the situation, for example high level encryption for financial transactions but not so for short range environmental sensing for example – a user in the vicinity could observe these for themselves.

Access and recourse: Providing a means to reliably review transactions and seeking recourse to correct or enforce penalties for unacceptable behaviour provide essential elements for developing trusted sensor-based systems.

Bellotti and Edwards argue towards human intervention in sensor-based interaction while Langheinrich envisages a more automated mediation of privacy preferences. Both frameworks highlight the need for user notification, choice and accountability in sensor-based interaction, which Bellotti et al. continue in their "five questions" framework, contrasting the design of traditional computer interfaces with that of sensor-based interfaces (Bellotti et al., 2002). While typical computer interfaces rely on a set of expectations and conventions using graphical user interfaces, sensor-based interaction lacks well understood, pre-packaged precedents, requiring designers to continually face the challenges inherent in the use of sensing systems. Their approach is to offer a framework to address these challenges, giving five questions for designers to consider:

Address: How do I address one (or more) of many possible devices?

Attention: How do I know the system is ready and attending to my actions?

Action: How do I effect a meaningful action, control its extent and possibly specify a target or targets for my action?

Alignment: How do I know the system is doing (has done) the right thing?

Accident: How do I avoid mistakes?

Gaver et al. take a different approach altogether, promoting the use of ambiguity to encourage personal engagement with systems (Gaver, Beaver & Benford, 2003). Taking a lead from contemporary art and design practice, three types of ambiguity are identified; ambiguity of information, ambiguity of context and ambiguity of relationship. A series of tactics are suggested in order to emphasise these kinds of ambiguities, such as over-interpretation of data, inviting the user to make an independent assessment of the sensor data and the level of confidence they place on the system. It is argued that ambiguity allows designers to suggest issues and perspectives for consideration without imposing solutions, additionally, that effective use of ambiguity can also help designers go beyond the limits of their technologies, encouraging users to supplement inaccurate sensors and low resolution data with their own interpretations.

Dey and Mankoff also deal with ambiguity, though in contrast to Gaver et al. above, they present a set of design guidelines to allow users to resolve ambiguity rather than create it (Dey & Mankoff, 2005). They also argue that it is necessary for users to be involved in the process of resolving ambiguity, the guidelines focussing on features for designers to consider:

- Applications should provide redundant mediation techniques to support more natural and smooth interactions.
- Applications should provide facilities for providing input and output that are distributed in both space and time to support input and feedback for mobile users.
- Interpretations of ambiguous context should have carefully chosen defaults to minimize user mediation, particularly when users are not directly interacting with a system.
- Ambiguity should be retained until mediation is necessary for an application to proceed.

In another design led approach to sensor-based interaction, Benford et al. present a framework based on a three factor analysis, whether input and interaction is expected, sensed and desired (Benford et al., 2005). The framework focuses on the properties and affordances of sensor-based interfaces, considering expected, sensed and desired movements, and each combination of these (e.g. sensed and desired, desired and expected) as shown in Figure 3. This takes an analytical and inspirational approach, allowing designers to appropriate and exploit mismatches as well as identify potential problems.

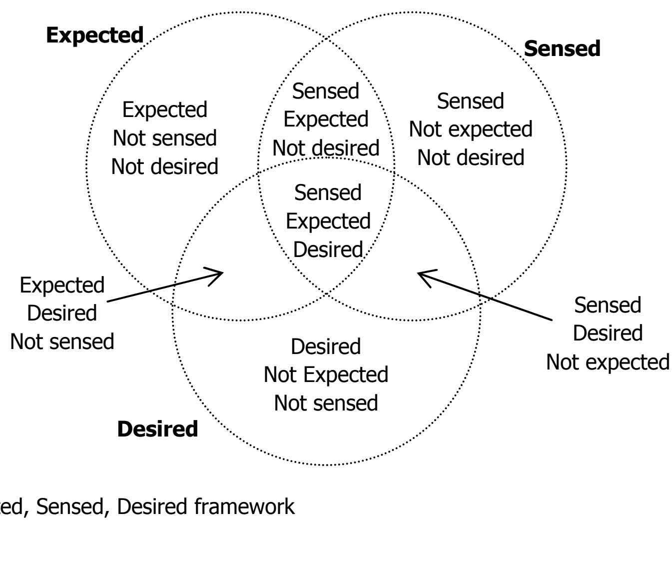


Figure 3: Expected, Sensed, Desired framework

Hinckley et al. also provide some advice for designing sensor-based interfaces, focussing on foreground and background modes of operation in handheld devices (Hinckley et al., 2005). They note that the earlier “five questions” framework considers mainly foreground tasks, and complement this by addressing background issues, commenting on how recognition errors may arise in light of transitions “in the ground” (fore to background and vice versa) and explicitly considering both foreground and background modes, as well as transitions between them should be critical design issues. As design guidance they propose nine lessons learned from their work:

- Use background sensing to assist users in transitions to the foreground.
- Preserve the user’s focus of attention by minimizing disruptions to the ground.
- Provide feedback of transitions between the grounds and awareness of whether user activity will be interpreted as foreground or background.
- Scope foreground interpretation of possible interactions via background sensing.
- Automate blocking steps in the background by sensing and removing unnecessary barriers to interaction.
- Include ground selection mechanisms that help indicate whether activity should be interpreted as foreground or background.
- Prefer background interpretation for typical events.
- Provide explicit ground selection mechanisms that allow foreground techniques to dominate background interpretations.
- Explicitly encode ground transitions between foreground and background and use such encodings to minimize disruptive changes to the current mode of interaction.

The final piece of work consider in this section looks at sensor-based interactions to promote exploration and play (Rogers & Muller, 2006), they argue that the inherent inconsistencies and uncertainties in sensor-based interfaces may be exploited as an integral part of a user experience. In particular they suggest that games, interactive art and public based social activities can use these properties to create engaging interactions, where users are required to discover how to behave to get the desired result. Whilst mastering and understand the uncertainty may present a challenging user experience, they propose emphasising interactions that provoke reflection can help in this respect.

In order to guide the design of sensor-based interfaces, their framework introduces the concept of “transforms” as a way to describe how a person deals with the coupling between actions and effects in physical and digital domains. These involve three key processes:

- **Perceiving:** how does a person detect that the sensor system has done something?
- **Understanding:** how does a person understand the causal links between their

actions and the system's response?

Reflecting: to what extent does a person reflect upon which action caused which effect?

In playful and other user experiences, where control is not important they also stress uncertainty and unexpectedness as key elements in order to generate surprise, and trigger high levels of perception, understanding and reflection. They highlight exploratory and discovery-based interactions as well suited to sensor-based systems and that consideration of how aspects of the experience can be enhanced and how continuous actions can be coupled to different effects.

The third part of the framework highlights a range of sensor properties to consider when mapping sensors to activities; discrete/continuous, level of precision and explicit/implicit couplings between sensors and activities.

These pieces highlight the complexity of, and the need for, the understanding of interaction between humans and sensor-based interfaces that are emerging thorough developments in pervasive computing – participatory sensing being one area of this. This interaction is a fundamental component in the realisation of participatory sensing systems, relying on efficient collaboration of both technical and human aspects to perform well. A key theme throughout the work above has been the relationship between users, sensors and applications, each exploring, advising on or providing a means to describe the dialogue taking place in various ways. This thesis will focus on these issues in particular, exploring and understanding the dialogue between humans and sensors within participatory sensing applications.

2.4 Examples

The first part of this chapter has given a broad outline of the fields of research which are brought together in participatory sensing. Pervasive computing is a key element in this, not only by delivering new and innovative technology but also by offering a vision for the future development and inspiring new ideas. This section focuses on pervasive computing, using examples to illustrate the direction research has taken toward realising these ambitions.

The examples concentrate on instances of sensing technology being employed in pervasive computing applications, highlighting the range of systems that have been developed. These mainly fall within the area of context-aware computing and the central area of participatory sensing. They will be described in order by moving around the space shown in Figure 2, starting with general pervasive computing, then moving clockwise; the first set of examples are placed as shown in Figure 4.

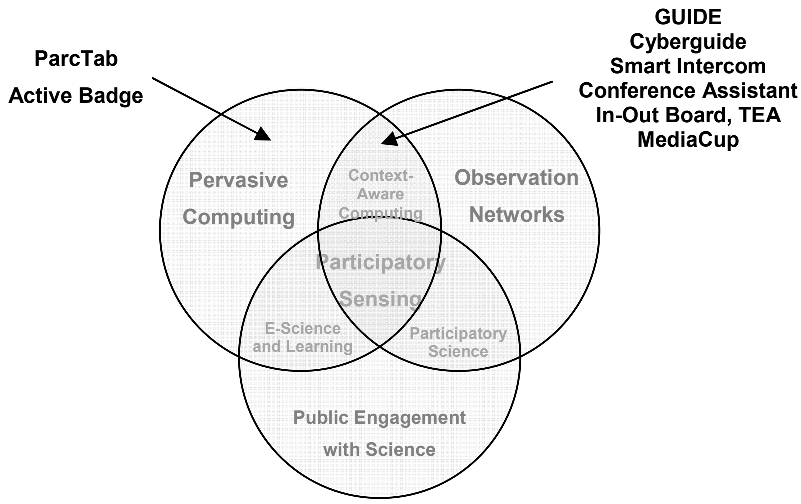


Figure 4: Location of first group of examples within fields

2.4.1 PARCTAB

PARCTAB (Want et al., 1995) is one of the early projects that began to define ubiquitous, context-aware computing. PARCTABs are small handheld devices similar to a PDA, connected to an office network and applications that run on a central server. The PARCTABs are connected to the network using infra-red (IR) signals which also act as a location sensing system. Determining which IR beacon a tab is in communication with allows location to be detected down to a 'room level', where the tab and beacon have a direct line of sight.

The PARCTAB has a number of applications, linking up between each other, the network servers and many additional office items, such as AV systems and whiteboards. The *migration control* application allows windows to be transferred from one display to another or 'hidden' and revealed later. Devices such as Liveboard (Elrod et al., 1992), (an interactive whiteboard system) are linked in so pages can be changed or a pointer controlled via the tab. Through access to local lighting, heating controls and other devices the PARCTAB can be used to allow users to configure their current workspace to their preferences. Equipment such as projectors, TV and audio systems can be controlled via the tabs IR transmitter, using a database of their control signals.

Figure 5: PARCTAB handheld device showing the forget-me-not application.

The tab's infra-red communications system offers 'room' level coverage (as IR light can't penetrate walls and doors). This allows rough location information to be inferred by inspecting which IR beacon each tab is in communication with and so enables a number of context aware functions. As an example of proximate selection an application can highlight the closest free printer and diminish the appearance of inaccessible printers further away. A simple location directory of tab users can also be assembled and is accessed by a 'reverse pager' application called *birddog*. This functionality is extended further with *communicator* an application that combines location information with availability of local videoconferencing equipment, telephone lines or e-mail access to recommend the most convenient way to get in touch with a fellow PARCTAB user.

A final example of context-aware applications on the ParkTab, *forget-me-not* (Lamming & Flynn, 1994) was an application that recorded information about location, who is nearby, workstation activity, documents accessed and phone calls to create a personal biography and memory aid. This application is pictured in Figure 5.

2.4.2 Active Badge

Another one of the initial instances of ubiquitous computing put into practice is the Active Badge system (Want et al., 1992). An Active Badge is an ID badge with an embedded infra-red transmitting device. As with PARCTAB each badge is picked up by receivers located around a building or site, the infra-red cells allow location tracking accurate to within a few metres (where the spaces can be visibly isolated, e.g. between rooms).

The Active Badge is simpler in design than the PARCTAB, serving simply as a beacon to indicate presence to the fixed IR receivers; it does not have two-way communication and so can only transmit pre-defined signals. The badges additionally contain a light sensor that activates a low power mode when the light level drops below a pre-defined level. This extends battery life by reducing the transmitting interval when the badge is left unused, e.g. in a desk drawer or left overnight.

Active Badges are used to provide location information to drive an application for use by staff at a building reception and people looking remotely over a network. The last seen locations of all badge-holders are displayed along with the time of the sighting or a percentage probability (decreased if the sightings have changed recently). This location information is then used to route incoming telephone calls or direct visitors and colleagues to the most probable location of their target. The interface consists of either a complete display of names and their current locations or a set of tools *find*, *with*, *look*, *notify* and *history* which can be used to gain further details about a particular person, a particular location, or watch for an appearance in the future.

Figure 6: Example active badges.

2.4.3 CyberGuide

The CyberGuide (Abowd et al., 1997) consisted of a number of prototype devices designed to provide information to visitors to the GVU Centre at Georgia Tech and the surrounding city area. An indoor version used infra red beacons to provide location information and an outdoor version used GPS. The handheld units acted as central processing devices and relatively simple IR beacons broadcast location identifiers. Wireless communication was achieved using a combination if short range IR and RF in different prototypes to load data where internal storage wasn't sufficient.

The CyberGuide applications consisted of four main modules, mapping, information, navigation and communications. These provided the main features allowing users to locate items of interest in the area, display the user's current location fetch relevant data and send and communicate with other users of the system.

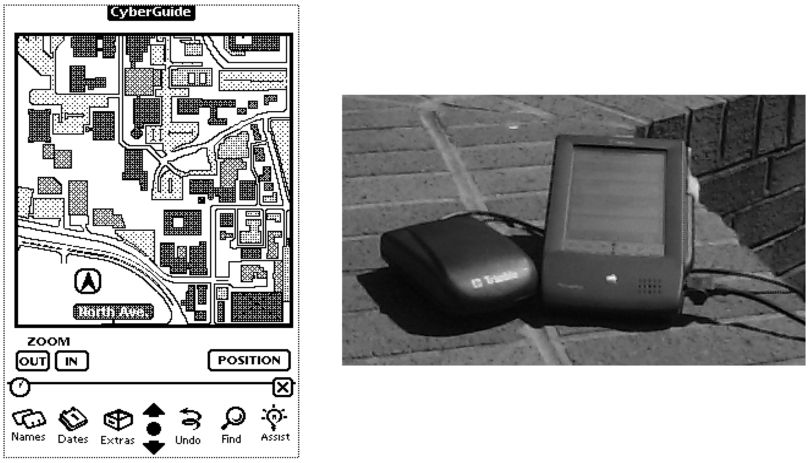


Figure 7: An outdoor version of a CyberGuide, showing the map display and the PDA unit with GPS module.

2.4.4 GUIDE

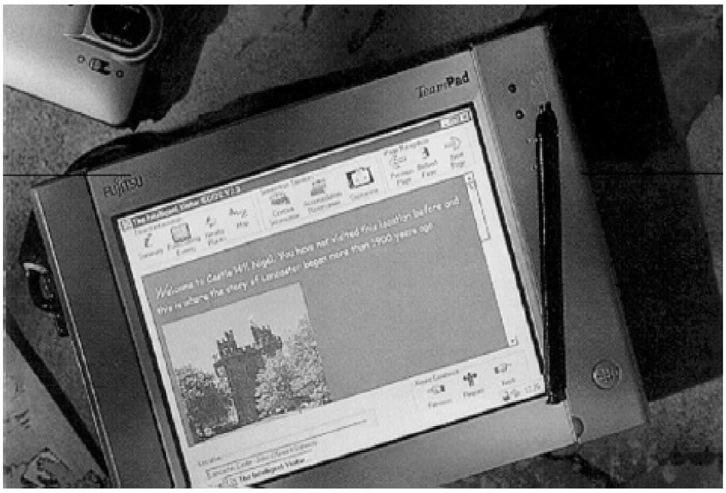


Figure 8: The GUIDE tablet PC

Lancaster GUIDE (Cheverst et al., 2000) directs users on a tour of the city of Lancaster using location determined using a system of wireless network access points positioned at points of interest. The GUIDE provided a internet browser style application coupled with location triggered information to allow users to construct a personalised tour of the city, taking into account the users previous travels with the device and recommendations from a pre-compiled database of attractions. The system can give directions from place to place and takes into account the pace of the user for journey times, adjusting tours for closing times and busy periods at attractions. It has interactive features such as access to café menus, reservations and accommodation booking.

2.4.5 Smart Intercom

The Smart Intercom (Kidd et al., 2000) was a project that was developed within the Aware Home research environment, a specially built house to facilitate the development and evaluation of context-aware technology within a family home setting (Kidd et al., 1999). The system was built into rooms in the house to allow voice activated communication in various ways.

Users are able to address a particular room of the whole house, choose a particular person to talk to or monitor a selected room. When contacting individuals aspects of their context is taken into account, for example if the selected person is not alone the 'caller' is warned.

In the initial version the sound was picked up using radio microphones worn by users, preventing audio feedback in the system, the intercom was controlled using voice commands and a central computer. Members of household also carried radio ID tags that allowed sensors in the house to locate them with a high degree of accuracy. A subsequent version used audio/control points around the house rather than mobile microphones and voice commands, the interface used is shown below.

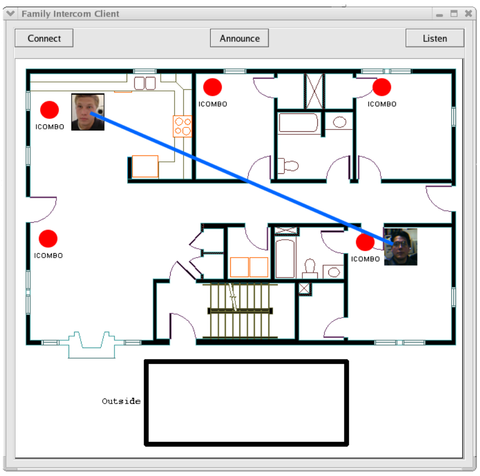


Figure 9: Intercom control screen input

2.4.6 In Out Board

The In/Out Board (Salber et al., 1999) was a context-aware application that automatically displayed whether people were in or out of a particular building, to locate users the In/Out board used a Dallas Semiconductor iButton system (small ID tags that operate when they are touched on to readers) and later radio location tags similar to active badges. As people docked the iButtons or entered or left the range of the radio location system the board would be automatically updated to “In” or “Out” appropriately. The board was viewable at dedicated display points, over the internet or on portable devices, when it was viewed inside the building the display also included the time when users had left.

2.4.7 Conference Assistant

As indicated by the name, Conference Assistant (Dey et al., 1999) was an application aimed at guiding visitors at an academic conference, it was designed for use with a wearable computer however in practice it was implemented on a combination of laptops and PDAs. The application takes account of a number of context types for a number of users and locations (such as lecture theatres). This includes information about not only the attendees of a conference but the presentations that are taking place and who is giving them. A wide variety of context information is extracted from digital schedules and A/V devices including conference and user schedules, personal preferences, presentation details (presenter, current slide, whether video/audio recording is taking place) and the reported activity of colleagues. The main sensed information in the application is location, using a PinPoint Corporation's “3D-iD” radio tag system, as used with the intercom system above. The Conference Assistant application provided recommendations to help support decision making based on preferences and other users’ reports, note taking, and providing information to guide the users to rooms or other people.

2.4.8 TEA: Technology Enabling Awareness

TEA is Technology Enabling Awareness (Gellersen, Schmidt & Beigl, 2002), describing technology aimed at embedding context-awareness into personal devices to automatically control their functions such as ring volume, power consumption or connectivity based on the user's situation. Specifically this project was working with mobile phones, looking at detecting context related to the phone and the activity of its user. A number of sensor devices were tested for recording context, resulting in a demonstration board containing light sensors, two microphones, a dual axis accelerometer, a temperature sensor and a touch sensor. The add-on board used the readings to activate different profiles on the phone (ring tone/volume/vibrate settings), with automatic pre-sets such as "sitting in a pocket", "lying on the desk", "in user's hand".

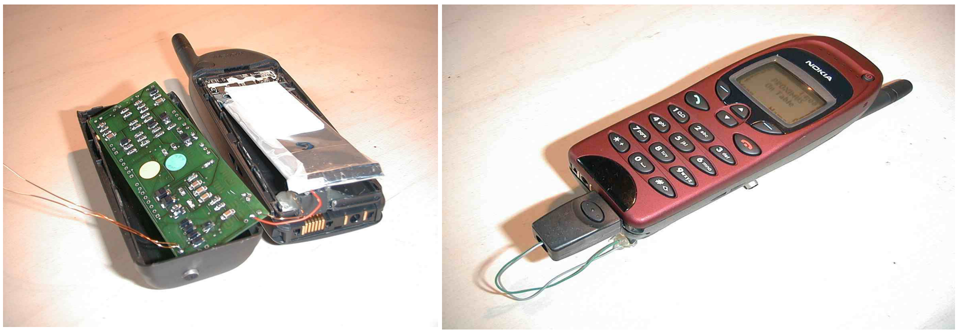


Figure 10: TEA Phone add-on

2.4.9 MediaCup

A project that followed on from TEA was MediaCup, a demonstration set-up for ubiquitous computing in everyday objects (Beigl, Gellersen & Schmidt, 2001). In this case coffee mugs were the main focus, with a coffee machine and watch part of the system too. Each mug contained a temperature sensor, tilt switches and a switch to determine whether the cup was on a surface or being held. They used an IR communication facility to pass on information about how the cup was being used at any particular time, which also acted as a location beacon. It was powered by an inductively charged capacitor, built into a specially designed 'coaster', eliminating the need for changing batteries.

The MediaCups provided information for several applications around the research lab, for individual users it could provide an indication of the temperature of the contents of the mug, the linked-in watch providing a personal readout or warning if necessary. The system could also control the coffee machine so, for example, it could be activated to prepare to top up an empty mug. For general use around the workplace, the mugs reported their location, temperature and current mode of use on a display screen and web page. The modes reflected 3 states of the mug, left standing, being held/drunk from and being 'fiddled with' whilst empty.

Figure 11: A MediaCup and watch display

The areas of convergence identified earlier highlighted the main influences that are drawn into participatory sensing, stepping back from this for a short period, the next three examples take a slightly wider view of the convergence of pervasive computing. The examples concentrate on the more general parallels between pervasive computing and observation networks and public engagement with science. "Duck Island" describes a wireless sensor network system designed to monitor wildlife habitats; this sensor network demonstrates how the technology used in pervasive computing systems is brought to bear in the field to create new types of observation networks. Can You See Me Now? (CYSMN) and "Uncle Roy" are two examples of pervasive computing technology being brought to the public through interactive performances or games. These highlight public engagement with pervasive computing, and both the experiences themselves and the technology employed – they are particularly involved with sensing, observation and the dialogue between these systems and people.

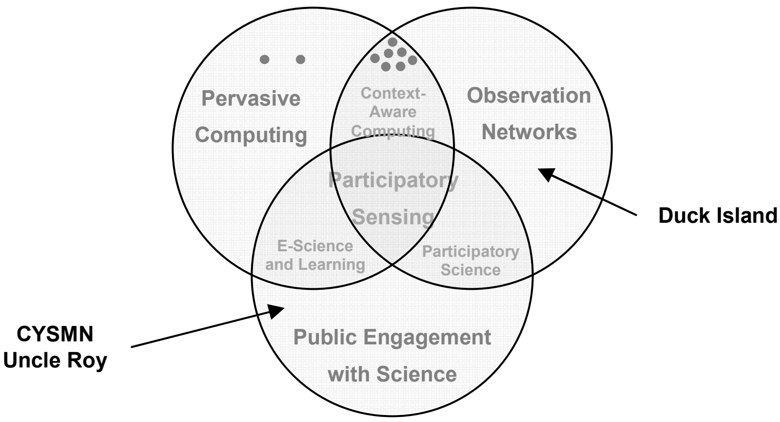


Figure 12: Location of second group of examples within fields, previous examples are shown as dots.

2.4.10 Can You See Me Now?

Can You See Me Now? (CYSMN) (Benford et al., 2006) is a multiplayer game that takes place both in the streets of a city and in a recreation of that city in a web based game. Players take part through a web based application, moving their avatar around the map to avoid 'runners', who are members of the game's cast on the streets of the host city. The locations of the players are relayed to runner's PDAs, which in turn transmit the runners' positions back to the online game. The PDAs are connected via a WiFi wireless network and their positions are determined using GPS units carried by each runner. Players may type messages which can be seen by everyone in the game, the runners use handheld radios which can also be heard by the online players. The objective of the game is to evade the runners, who 'catch' the players by moving to within 5 metres of the corresponding physical location of the player's virtual position.

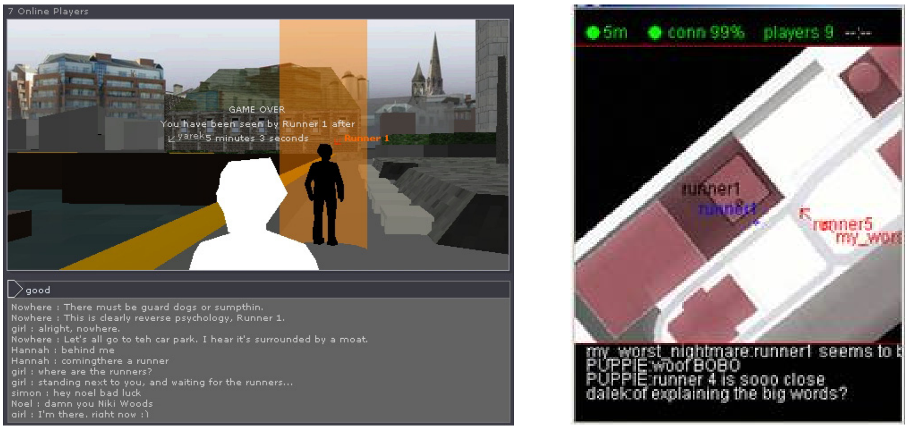


Figure 13: Can You See Me Now? Online screen display (left) and runner's PDA display (right)

2.4.11 Uncle Roy All Around You

Another interactive, pervasive computing inspired game experience is Uncle Roy All Around You (Flintham et al., 2003; Benford et al., 2004a). As with CYSMN this game comprised of a real world setting mirrored in a web based environment though in this game players took part on both sides. The street players, those who were taking part in the game in the 'real world' had to follow a series of clues from the mysterious character “Uncle Roy”, these clues were designed to lead them eventually to Uncle Roy's office and the end of the game. The online players observed this process and provided clues to lead, or mislead them along the way. Communication between online and street players took the form of text and audio messages which were sent both ways via the online interface and PDAs carried by street players.

Unlike the previous two examples, location reporting in this game was manually established via the map interface on the PDA, as street players browsed the map, their general location was inferred from where they were looking. They were also encouraged to specifically declare their location throughout the game, a process which triggered more clues from Uncle Roy (the game engine) and 'beacon' animation in the 3D map alerting online players of the location update.

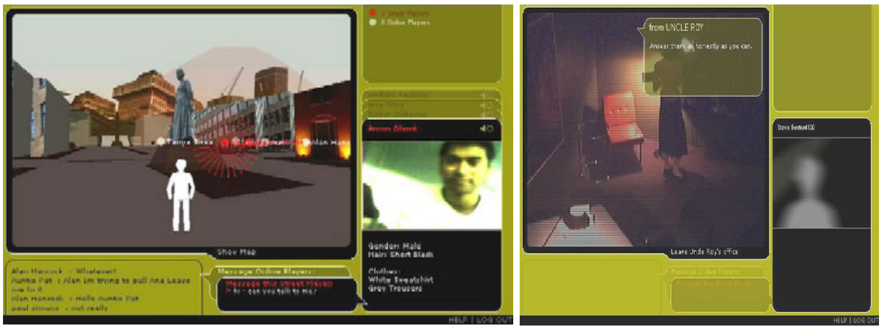


Figure 14: Screenshots from the Uncle Roy All Around You web interface, (left) showing a location update

2.4.12 Great Duck Island Habitat Monitoring

This is an example of a wireless sensor network created to monitor remote habitats in the wild. It was designed for and deployed at two sites in the USA; Great Duck Island in Maine and James San Jacinto Mountain Reserve in California (Mainwaring et al., 2002). At Great Duck Island the aim was to gather data to study the ecology across the varied habitats to be found there. The deployment specifically monitored large colonies of Leach's Storm-Petrels and other sea birds. The focus at the James San Jacinto Mountain Reserve was on enclosed habitats such as nest boxes and bat caves.

The sensor network that was designed and implemented for these locations consisted of a tiered hierarchy of devices; sensor nodes, gateways and base stations with internet/WAN connectivity. Based on UC Berkeley Motes the sensor nodes consist of a microprocessor device with additional sensor modules, registering temperature, light, humidity, and atmospheric pressure. The nodes have a short range radio communications module, allowing them to form small multi-hop networks called patches, centred around gateway devices. These gateways provide a longer range link to a central base station, as well as providing extra processing and data storage facilities to the sensor patch.

Base stations, designed to be located in ranger stations or similar buildings, receive data from the gateways and stores it in a single database. They are connected to the internet and so provide a relay and repository for all the data received, making it available remotely to distant users and services. A further component of the system is a handheld device, a PDA equipped with a RF interface, these allow users to interact with the sensors in situ on site.

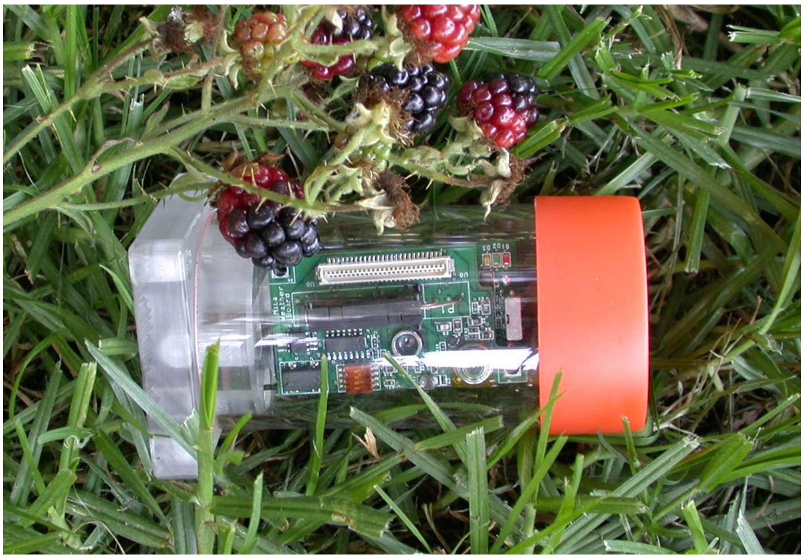


Figure 15: A sensor node consisting of a Mote, sensor module and weatherproof enclosure.

The final group of examples looks at two areas, e-science and learning and the core area of participatory sensing. The first example, "Savannah", describes an interactive educational experience designed for school children learning about lions and lion behaviour. Handheld devices equipped with GPS and wireless communications are used to create a location based "game", which participants play then review their experience in the classroom, adapting their behaviour between rounds as their understanding progresses.

Examples of participatory sensing are given in Campaignr, Bikenet, N-SMARTS and the Urban Pollution Sensing project. These show a range of sensor systems and devices that have been developed from past or current projects that either relate to participatory sensing directly or combine people and devices to collect data in a participatory sensing manner.

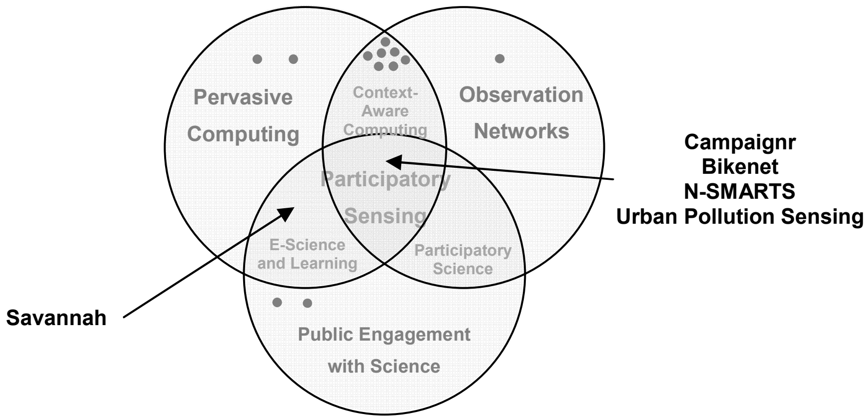


Figure 16: Location final group of examples within fields with earlier examples added as dots.

2.4.13 Savannah

Savannah (Benford et al., 2004b) was an educational game designed for year 7 secondary school students (11-12 years of age), it provided an opportunity for the students to learn about the lives and behaviour of a pride of lions by acting out their lives on the school field with an interactive environment using PDAs and a classroom computer setup.

A 'virtual savannah' was mapped out on the school field, defining various areas such as a spring, short grass or marsh. The participants carried a PDA with a GPS receiver fitted to it, their movements around the field triggered images and sounds on the PDA, illustrating their movement through the savannah, displaying what they could see (and smell) and playing authentic noises to set the scene. Each player took on the role of a lion and as the game developed new aspects were added, such as hunting and indicating the need to eat and drink. Only by adopting the strategies used by lions in the wild (stealth, co-operation, etc) could the payers succeed and live through the game.

Figure 17: Savannah PDA display (left) and overview map display (right)

The PDAs were linked to a central game server using a wireless network, which allowed players to interact with each other (to hunt in a group for example) and allowed their experience to be recorded for analysis (both their own and the researchers). Between sessions the players reviewed their game, and facilitated by the teacher considered the choices they made, allowing the gameplay to develop along with their learning.

2.4.14 Campaignr

This example is a project directly in the area of participatory sensing, Campaignr ('Campaignr by Center for Embedded Network Sensing'; Joki, Burke & Estrin, 2007) is part of a suite of applications for Symbian S60 mobile phones to collect, report and visualise data using a distributed person-centric sensor network. Campaignr is part of a framework that has been developed to facilitate data gathering campaigns, it forms the basis of phone applications that allowing data to be manually and automatically captured, stored, and uploaded to a central web server "SensorBase" ('SensorBase').

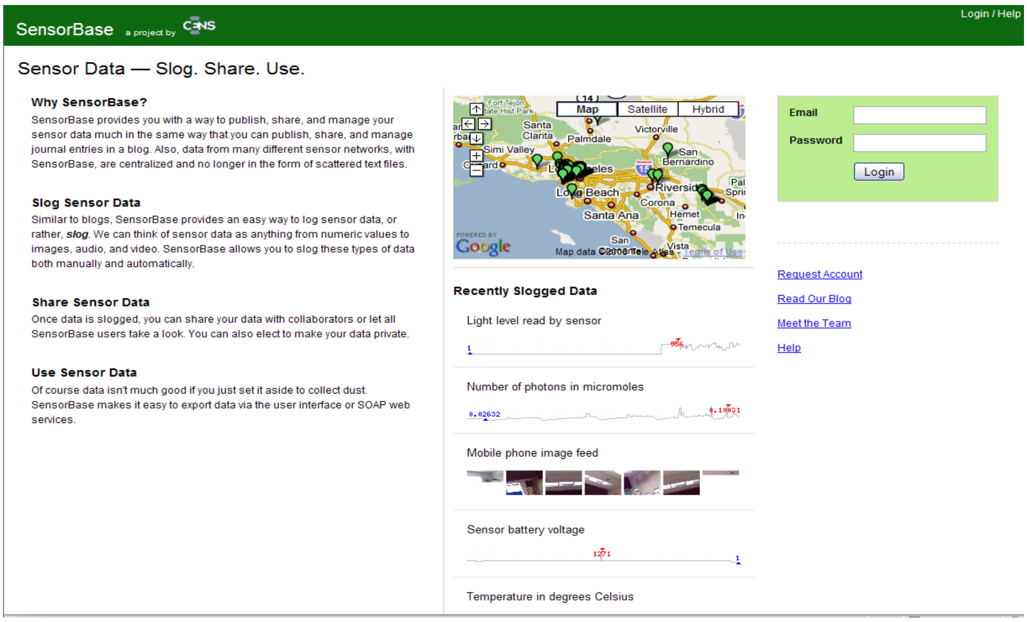


Figure 18: SensorBase.org website, showing data uploaded via the Campaignr

Data captured by Campaignr based applications is chosen according to the campaign, the end user has the option of joining and participating in each Campaign through the phone interface. The data is collected via the mobile phone and could consist any of a number of parameters, based upon the target phone's built in capability; text, sound, stills, video, cell id, Bluetooth, WiFi networks. Readings can be specifically reported or collected in the background automatically without the user's intervention.

2.4.15 Metrosense: BikeNet

MetroSense ('MetroSense') is a project studying large scale sensor networks with a combination of mobile and static nodes. A hardware and software platform has been created to allow the study of mobile sensors alongside static sensor networks and is being implemented on a campus sized area. The Dartmouth College campus is where the network is being developed; one of the projects that have used this network is BikeNet (Eisenman et al., 2007), which provides the basis of this example.

BikeNet uses the installed infrastructure along with mobile sensors built into a bicycle to collect, report, store and visualise various readings about the bike and it's passenger. This data is displayed on a web based visualisation tool, BikeView ('Bikenet Portal'). BikeView displays the collected data, which can be information related to the bike (e.g. speed, pedal rotation, tilt), the rider (e.g. GSR, heart rate) and the environment (e.g. GPS, Audio, Images, Carbon Monoxide). The portal also allows live queries to be sent to users, requesting location, audio or image data.

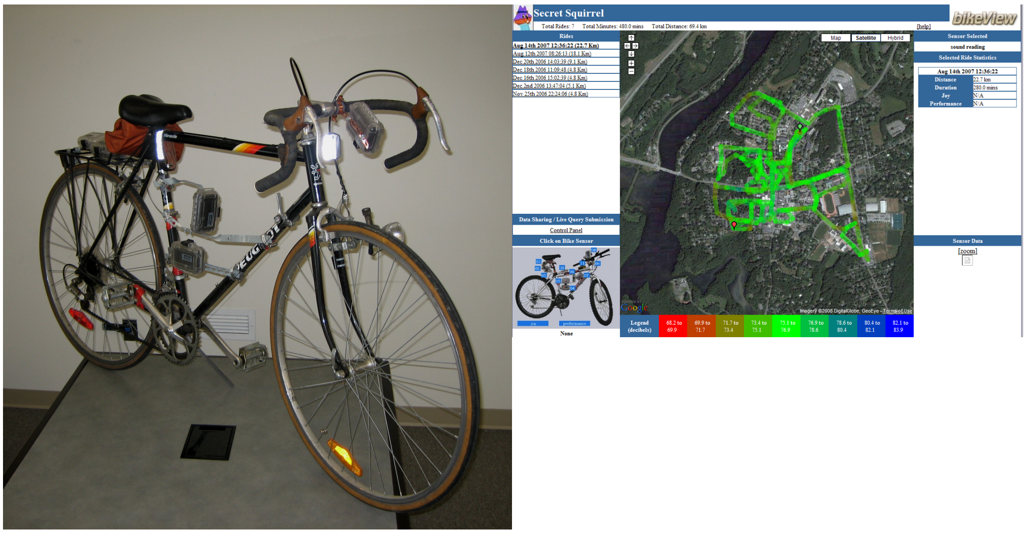


Figure 19: BikeNet – an instrumented bike (left) and the BikeNet data viewer website (right).

2.4.16 N-SMARTS and Participatory Urbanism

N-SMARTS (Honicky; Honicky et al., 2008) stands for Networked Suite of Mobile Atmospheric Real-Time Sensors, this is a hardware and software platform for mobile sensing of environmental data (air quality in particular). The system consists of three main elements, a prototype personal collection platform, an integrated platform and an automotive platform.

The personal collection platform is mainly for experimentation, consisting of a number of separate data loggers collecting GPS, Carbon Monoxide, Nitrogen Dioxide, Sulphur Dioxide and/or Ozone. These are attached to a belt so they can be carried around together and take their readings in the same location, allowing for various loggers to be trialled before being built into the integrated version. The automotive device similarly uses the same loggers in a capsule that can be carried by vehicles to collect readings along its travels. The capsule is vented at both ends and mounted inside the car near to the window/vents for good airflow.

Figure 20: N-SMARTS Personal collection platform (left), automotive platform (right)

The integrated platform is more specialised and is designed to be a more practical version of the personal collection system. It uses a small microprocessor based unit with air quality sensors (as above), a temperature sensor and an accelerometer. This is designed to be embedded into a mobile phone to allow synchronised data collection and reporting through the phone's cell network. Location sensing features on the phone (e.g. Assisted-GPS) also provides position information which is relayed along with the sensor readings.

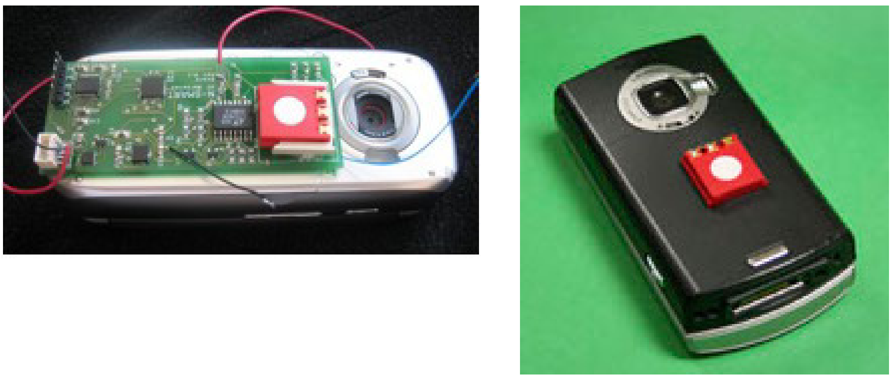


Figure 21: N-SMARTS Integrated platform, circuit board (left) in the complete package (right)

The Participatory Urbanism (Paulos, Smith & Honicky; Paulos, Honicky & Goodman, 2007) strand of the Urban Atmospheres research collaboration uses the N-SMARTS platform within their work, looking at *"networked mobile personal measurement instruments"*. This focuses on the open authoring, sharing and remixing of urban technologies for citizens to participate and express themselves. In this project, four personal sensing platforms and a number of the automotive units were used to collect two weeks worth of data about the pollution in the down-town area of Accra, Ghana.

2.4.17 Urban Pollution Monitoring: CO Mapping

Within a larger strand of work investigating urban pollution, one particular project (Steed et al., 2004) used mobile Carbon Monoxide (CO) loggers and GPS units to map pollution around a city area. The monitoring devices were designed to fit on the back of bicycles and allow a number of people to simultaneously record data, this data was then aggregated into a single map at the end of the study period.

The logging devices consisted of a specialised CO sensor box that was connected to a PDA, the PDA also had a GPS connected to it, and coordinated the logging, sorting the data in its internal memory.

Figure 22: 'Tea-tray' CO Logger installed on a bike

2.5 Analysis of Examples

This chapter started by identifying the key areas contributing to participatory sensing. Having outlined these, pervasive computing was highlighted as a key component, bringing new technology and ideas that enables participatory sensing applications to be realised. In the first section, the issues related to human-sensor dialogue were introduced, directing the focus for the rest of the thesis.

A range of examples have been given focussing on sensor-based applications from pervasive computing and the fields it has influenced. This part of the chapter will now examine the examples, providing an overview of sensors used, application domains and the characteristics of the applications seen. The analysis of the examples falls into two parts, the first is a side by side comparison of the features of each example and the application areas of the systems developed. The second part places each example on axes, measuring the balance between fixed and mobile sensors, and the balance between automatic and manual sensing techniques.

2.5.1 Comparison of Application's Features and Purpose

Comparing these two aspects of the examples will help to give a broad view of any similarities and differences; the first aspect comparing what sensor information each application deals with (location, air pollution, etc), then the overall purpose of the application (navigation, communication, etc). The examples will be listed side by side in a table with a mark under one or more general headings which group together broadly similar aspects. The first table will show sensed data, grouped into the headings below:

Table 1: Description of groupings of sensed data

Location	Location sensors include any method of determining the location of an object or person, such as GPS, infra-red beacon systems, WiFi cell location systems and mobile phone cell-id systems. It also includes more explicit location determining systems, such as the use of iButton docking and user declared location.
Light	This is for devices with sensors that report the ambient light level.
Sound	Sound sensors can be one of two kinds, those that give an indication of sound level (as measured in decibels) and sensors that actually pick up the actual sounds using microphones.
Orientation	Orientation sensing includes anything that measures orientation of an object (i.e. right way up, upside down) and if it's being moved around. This could be through the use of accelerometers, tilt sensors, or pressure sensors on the device, anything where the resulting reading indicates orientation.
Temperature	Air temperature or temperature of an object to which the sensor is attached.
Video	Moving video and sound.
Stills	Still photographs.
Air Quality	Air quality data, which includes measures of pollutants like Carbon Monoxide and Sulphur Dioxide.
Physiological Data	Physiological data groups anything about a person's body, such as heart rate, or galvanic skin response (GSR).
Atmospheric Conditions	Sensors that collect information about the atmospheric conditions, this includes measurements of air pressure and humidity.
Nearby WiFi / Bluetooth Devices	Many devices use their built in wireless receivers to detect other devices within range, this is often used to determine if there are other people nearby as well as an estimate of location (when used for location alone it is only included in this location).
Vehicle Data	Used in cars, bicycles or other forms of transport these sensors give information about speed, gear and wheel rotations, etc.

Table 2: Type of data used in applications

	Location	Light	Sound	Orientation	Temperature	Video	Stills	Air Quality	Physiological Data	Atmospheric Conditions	Nearby WiFi / Bluetooth Devices	Vehicle Data
PARCTAB	X											
Active Badge	X	X										
CyberGuide	X											
Lancaster GUIDE	X											
Smart Intercom	X		X									
In Out Board	X											
Conference Assistant	X											
TEA		X	X	X								
MediaCup	X			X	X							
Duck Island		X			X					X		
CYSMN	X		X									
Savannah	X											
Uncle Roy	X		X			X						
Campaignr	X		X				X				X	
Metrosense BikeNet	X			X	X		X	X	X			X
Urban Pollution Monitoring	X				X			X				
N-SMARTS Participatory Urbanism	X						X	X				

The comparison of sensing in the examples (Table 2) indicates that location has been the most popular type of information used in applications, often in conjunction with other things. Apart from that there is a general spread across a range of the data types used.

Table 3: Description of application area groups

'Buddy' Tracking	These applications deal with tracking and monitoring the location and status of friends, co-workers, etc.
Location Guide	Location guides give information about a particular area, for example for tourist and visitor information.
Communication	This groups applications that deal with direct person to person communication e.g. audio and video intercoms.
Games / Entertainment	This includes games and interactive entertainment involving the public, or in schools.
Research	Some applications were created as investigation tools for research projects (for example 'TEA'), so are added to this category.
Remote Monitoring	This refers to applications that specifically collect and report data from remote locations, for example datalogging and networked sensors.

The second comparison (Table 3) looks at the application areas of the examples given. The stated intent for, and the features provided by, each example system was considered by looking at the literature. These were generalised into higher level headings by identifying common themes and differences in their focus area. The spread of examples through each heading is fairly even, showing no strong bias toward a particular area and no area obviously standing out as unique.

The two tables show the spread of sensing and of applications in the examples taken from the areas outlined earlier. This can be taken a step further by comparing sensing and application area – effectively cross referencing the two tables. This will help to show any tendencies toward particular types of sensor data for particular activities.

Table 4: Comparison of application domain for the examples

	'Buddy' Tracking	Location Guide	Communication	Games / Entertainment	Research	Remote Monitoring
PARCTAB	X					
Active Badge	X		X			
CyberGuide		X				
Lancaster GUIDE		X				
Smart Intercom			X			
In/Out Board	X					
Conference Assistant	X	X				
TEA					X	
MediaCup	X				X	
Duck Island					X	X
CYSMN				X		
Savannah				X		
Uncle Roy				X		
Campaignr					X	X
Metrosense BikeNet						X
Urban Pollution Monitoring						X
N-SMARTS Participatory Urbanism						X

Table 5: Cross reference of sensor data used and application categories

	Location (15)	Light (3)	Sound (5)	Orientation (3)	Temperature (4)	Video (1)	Stills (3)	Air Quality (3)	Physiological Data (1)	Atmospheric Conditions (1)	Nearby WiFi / Bluetooth Devices (1)	Vehicle Data (1)
'Buddy' Tracking (5)	XX XXX	X	X	X	X							
Location Guide (3)	XXX											
Communication (2)	XX	X	X									
Games / Entertainment (3)	XXX		XX			X						
Research (4)	XX	XX	XX	XX	XX		X			X	X	
Remote Monitoring (5)	XX XX	X	X	X	XX X		XX X	XX X	X	X	X	X

In the columns on the table sensor data used has been listed and in the rows the application areas identified have been given. In brackets after each heading the total available for the row or column has been given; "Location (15)" indicates that there are in total 15 examples using location data, "Communication (2)" indicates there are 2 communication applications in the examples.

On the table itself the combined count for each cross reference is given by a number of Xs. A comparison of individual counts with the totals in each heading gives an indication of the possible maximum count available. For example, by looking at both "Communication" and "Sound" it can be seen that 1 of 2 communication applications use sound, and that 1 out of 5 examples that sense sound are used for communication.

The results of this comparison generally echo the previous two, in that it can be seen that the range of sensor data used by individual applications is fairly well spread, though location remains one of the most often used. The table does however highlight the more specialised sensor types are more limited to research and remote monitoring applications – though it shows also that research and remote monitoring applications use a wider combination of sensors in general, so it would be within expectation that sensors less popular elsewhere to be included in this mix.

2.5.2 Further Classification of the Examples According to Sensor Automation and Positioning

The comparison tables above have given an overview of the range of sensor data used, the application areas and the degree of spread within the examples. This section takes a different approach – rather than categorising the examples, they are placed along a continuum to indicate the balance between particular factors in their design. Two factors have been chosen to assess the examples by, first the axes will be introduced individually, then as with the combined table earlier, they will be joined to form axes on a graph, illustrating the relative correlation between them both.

2.5.2.1 Sensor Automation

One of the most important aspects of participatory sensing is the role that people play in data collection, whether it is in actuating the sensors (by moving them around an area, or by specifically taking readings, for example), or by contributing data directly (such as reporting observations, or reviewing existing data). Rather than classifying sensors as either “automatic” or “manual” sensors, this introduces a scale indicating the level of automation – from operating fully independently of user intervention to requiring fully manual operation where the user has to operate every step of the gathering and recording process.

Taking a photograph with a digital camera would be considered mostly manual and part-automated, as the user is required to point the camera and press the button at the correct moment – however the image is automatically created and recorded. A video camera on the other hand is constantly recording, and so provides an opposite mostly automated, part-manual sensor. Examples of sensors placed further toward each end of the scale would include an almost fully-automated GPS logger (simply requires the user to carry it with them), and note taking – almost fully-manual (requiring the user to observe, take notes and enter them into the system).

In looking at the examples an overall view is taken considering all the sensor components and weighting them according to the level of use and influence on the function of the application. For example, many examples are placed far toward the automated end of the scale as these are fundamentally based on automatically gathered and reported location data: generated as a consequence of the users’ movement with other more manually gathered data being related back to it.

2.5.2.2 Sensor Positioning

Another factor for participatory sensing is the combined use of data from both mobile and static sensors, municipal sensor networks combined with mobile phone based readings for example. The second factor in this section of the analysis will therefore be to consider the use of mobile and fixed sensors in each application. This will act as the vertical axis, examples that use only fixed sensors will be placed at the bottom, and examples that use only mobile sensors will be at the top.

As with the horizontal axis, a spread across the range would show that a variety of combinations is being used. This results in applications that equally use both fixed and mobile sensors, and a combination of automatic and manual sensing, being placed toward the centre of the graph – in the middle of both axes.

When placing examples on the scale, the positioning of some needs to be justified more clearly. Some sensing systems use a combination of fixed and mobile components, in particular this applies to location sensing systems that track objects (like badges) or receive specific signals (like IR beacons). In these cases the emphasis is placed on the part of the system that actually gathers the readings; the receiving component rather than the beacons or radio tags. Two examples help explain this:

Active Badges use a system of fixed IR receivers to pick up ID signals transmitted by the badges (which move around with the people wearing them). In this case it is a fixed system, the sensors are in fixed locations picking up signals from the badges – there is no location information available to the badge itself.

The GUIDE system uses the identity of WiFi access points as a reference to its location. WiFi signals are picked up by the GUIDE handheld device, so the sensor is mobile.

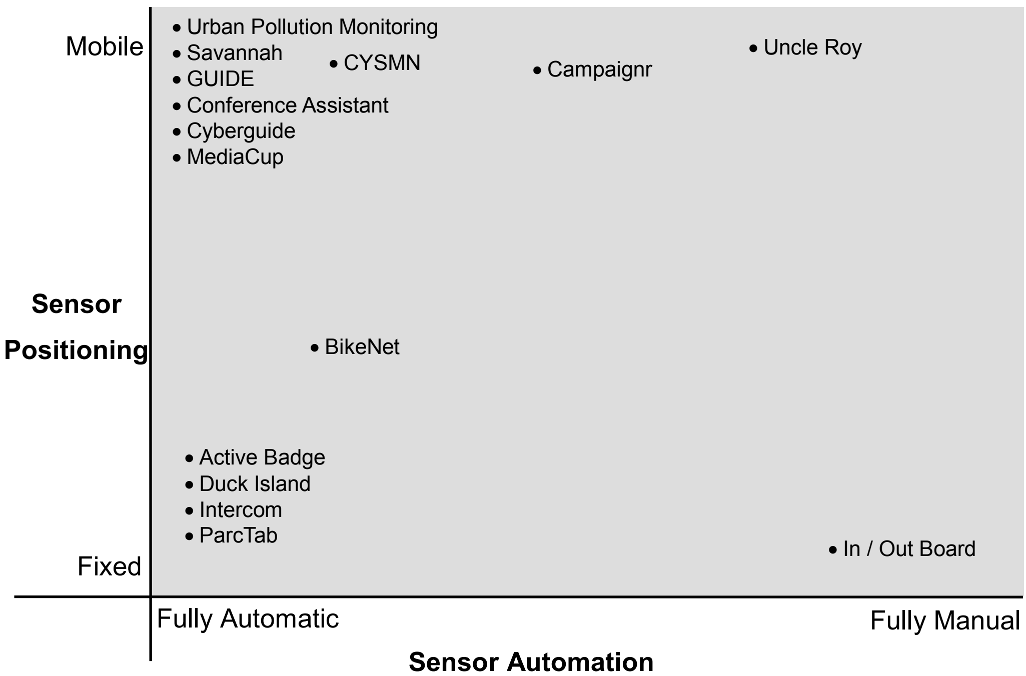


Figure 23: Distribution of examples with respect to fixed/mobile sensors and automatic/manual

The examples tend toward automatic sensing and there is a clear split between fixed and mobile. There are very few examples of combined or manual sensing with just two at the far right hand end of the graph and a two toward the centre of the scale. The examples that fall closest to the centre of the scales are those from intentionally designed participatory sensing projects. Their positioning represents use of a limited mix of fixed and mobile and manual and automatic sensing, though there is nothing that falls obviously in the centre still.

This graph provides a reference point for the range of possible combinations of sensor setups in sensor-based applications, in participatory sensing and related pervasive computing applications. Both axes represent different aspects of human interaction with those applications, the position of an example characterises part of the human-sensor dialogue in the experience. The placement of the examples therefore indicates the characteristics of research so far, highlighting two main trends.

First it can be seen that most of the examples tend toward the fully automatic end of the scale, with only a few towards the centre (adopting a combined approach) or the fully manual end. Second, there is a degree of polarisation on the sensor positioning axis, with examples tending to be either fixed or mobile and not integrating both kinds of sensors.

These trends highlight the narrow spread across the range of possibilities; earlier in this chapter human-sensor dialogue was established as a focus for the thesis, the analysis of the examples refines this further, revealing a range of possibilities for this dialogue that has so far received attention in a limited area.

2.6 Conclusion

This chapter started by introducing participatory sensing – a concept that combines sensor networks, people and mobile devices to create a new form of sensing systems. Participatory sensing is characterised by the use of human-in-the-loop sensor techniques, with person-centric sensors collecting data either through the everyday actions of participants (e.g. moving around a city providing an opportunity to measure pollution levels), or specific reporting and gathering of information (for example taking photos or sending text messages to report traffic congestion).

Three general areas that come together in participatory sensing were introduced; pervasive computing, observation networks and public engagement with science. These areas were outlined and then their convergence was examined, describing three further areas relevant to participatory sensing that fall within combinations of those first general areas; context-aware computing, participatory science and e-science and learning.

Looking more closely at HCI research in sensor-based systems in this area revealed concerns and issues raised regarding human interaction with sensor driven technology, particularly highlighting the need for feedback and control over the data collected and the behaviour of the application(s) linked to it. These issues included dealing with ambiguity and errors in sensor data, understanding a system's capabilities and limitations, and privacy, trust and security regarding the data collected. It was seen that the dialogue between humans and sensor-based systems is complex and multi-faceted, and the need for further exploration in this area was highlighted as a means to understand it and develop new techniques and conventions in this domain.

Exploring this dialogue between humans and sensors in participatory sensing provides the focus for this thesis. The second part of the chapter began by describing a range of sensor-based interfaces and technology relevant to participatory sensing and pervasive computing. The examples showed a range of sensor types being used across a variety of application domains. The examples were classified using two scales, one of sensor automation (automatic to manual) and sensor positioning (fixed to mobile). They were plotted on a two axis graph, showing the distribution of the examples throughout the possible combinations of automation and positioning. This revealed two trends; that the applications mostly employed automated sensing techniques, and that there was a polarisation in sensor positioning, between fixed and mobile; few examples employed combinations in either category.

This analysis highlights the potential for further forms of human-sensor dialogue across the area shown in Figure 23. This further refines the focus of the thesis to explore the potential more directly; inspired by the approach of the "Expected, Sensed, Desired" framework (Benford et al., 2005), this thesis will develop an understanding of the human-sensor sensor dialogue in participatory sensing experiences, informing a framework to serve as both an analytical tool and a generative tool to uncover and inspire new forms of dialogue.

The first stage of this process will involve the use of combinations of sensing techniques in practical studies of data collection applications, providing direct experience and a starting point to investigate the dialogue further.

3 SENSE – Schools E-science Network for Study of the Environment

3.1 Introduction

The previous chapter showed how the field of participatory sensing applications is being shaped by the technologies of pervasive and context aware computing. Looking through a selection of applications indicated that there was a bias toward automatic sensing techniques and that they were generally either mobile or fixed sensors, with little use of combinations of the two.

This chapter presents a study of a participatory sensing style application, primarily concentrating on the use of different kinds of automatic and manual sensing techniques. The aim of the study was to compliment the literature review by gaining some direct experience of the issues involved with manual sensing techniques and combining their use with automatic sensors.

The sections in this chapter contain an introduction to the SENSE project and the study conducted alongside it and a description of the observations made. The chapter concludes with a consolidation of the findings and puts them in context with the objectives developed so far.

3.2 The SENSE Project

SENSE was a project undertaken by researchers from the universities of Nottingham and Sussex, working with groups of children from two local schools (one nearby each institution). It was funded by JISC[5] with a contribution from the EPSRC[6] funded Equator IRC[7].

The title SENSE stands for Schools E-science Network for the Study of the Environment, and this describes part of what the project was about. The overall aim of the project was to explore the use of modern computing techniques in school science lessons, using the technology to facilitate collaboration both between different schools and between pupils in the same school. A key part of the study was to look at how to deal with remotely collected data which is shared between users, particularly using contextual information such as video alongside sensor readings. As such, this project lent itself well to an additional study of participatory sensing applications using a range of both automatic and manual sensing techniques. This section will outline

[5] JISC: Joint Information Systems Committee, http://www.jisc.ac.uk
[6] EPSRC: Engineering and Physical Sciences Research Council, http://www.epsrc.ac.uk
[7] The Equator IRC, http://www.equator.ac.uk

the activities undertaken in the whole project, and then focus on the specific analysis conducted for this work.

3.2.1 Overview

The project was carried out in conjunction with two schools, in Nottingham this was Glenbrook primary school and involved a class of year 6 children (aged 10-11). The team in Sussex worked with Varndean Secondary school, working with year 9 pupils (aged 13-14) and an after school club with members ages ranging from 10 to 14 years. As the needs of both classes varied, the setup differed slightly between the sites and each programme of activities will be described below. The differences were mainly in the activities surrounding the sensing experiments but also some of the equipment used varied as well. The main objectives and methods during the sensing experiments were consistent across the sites, so the differences aren't that significant in the later analysis.

3.2.2 Activities at Nottingham

At Glenbrook primary school in Nottingham the year six class took part in activities in two terms. The series of sessions consisted of a number of exercises in preparation for the practical work that followed and then some more time in the classroom to look over the results.

3.2.2.1 Background Material

The first few sessions covered background material in order to familiarise the children with pollution and the problems that it can cause. They also served to gauge what existing knowledge they had, not only to monitor progress but also to aid in planning the following sessions. After learning about the general issues of pollution the class was encouraged to think about pollution with a local perspective, in groups they were asked to highlight places on a map of the local area that they thought might have especially high or low amounts of pollution. They did this by sticking coloured dots on to the map and adding notes to describe potential causes. Another activity encouraged thinking about changes throughout the day or week using images taken from traffic cameras to count the number of vehicles on the road at different times.

Following the introductory sessions the work then narrowed down to air pollution, with some more specific background information and the first practical experiment that the class would undertake. The children used small DIY particle collectors in and around the school grounds. These consisted of a square of clear acetate with a thin coating of Vaseline on it. This caused airborne particles to stick to it so that deposits could be captured over a 24 hour period and subsequently inspected using a microscope enabling different locations to be compared. This exercise introduced the idea of invisible airborne pollution, leading on to gasses such as carbon monoxide and so the experiments to measure this kind of pollution were introduced with the use of electronic sensors to detect CO.

3.2.2.2 CO Sensing Exercises

The groups took part in practical exercises to record the level of Carbon Monoxide around their school, monitoring the CO levels as they were moving between chosen locations as well as for a few minutes at those particular locations. This gave them the opportunity to observe changes in readings based on their position as well as how it varied over time in particular areas. The locations they chose to observe were partly based on the earlier preparatory work, i.e. choosing targets in a classroom session, but also affected by events during the experiment that they reacted to. In addition of CO levels, they also recorded the wind direction and strength, written observations and video footage.

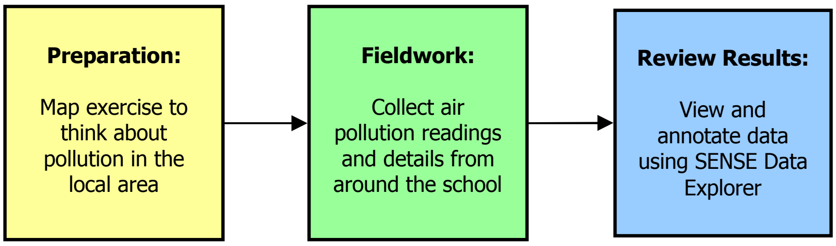


Figure 24: Stages of the sensing activities

Each recording session lasted between 15 and 30 minutes and was assisted by the researchers who provided advice about the equipment along the way. When the data had been collected they reviewed it in following lessons using software on their classroom PCs. This software provided a specially designed interface which displayed all the information they had collected and allowed them to review and comment on their results.

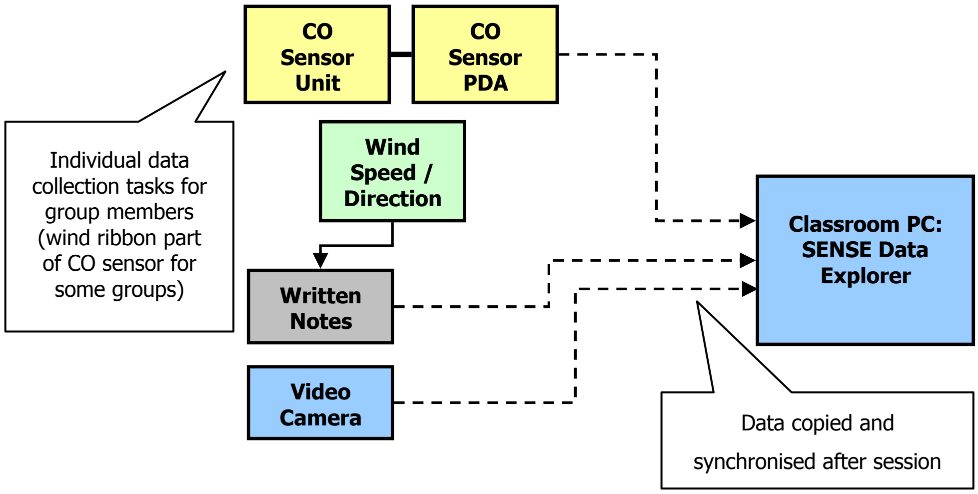


Figure 25: Use of equipment during data collection sessions

The groups of consisted of up to four members, each assigned a specific task such as taking CO readings or keeping notes. They were given the equipment necessary to perform their roles and during the experiment the participants occasionally swapped roles and swapped equipment to do so. The tasks each group had to perform were:

- Positioning the CO sensor
- Operating CO sensor PDA
- Videoing the experiment (using a DV camera)
- Taking notes and recording measurements

The CO sensor that the children used was built specifically by the SENSE team in Nottingham for the year 6 children. Named the 'sensor stick', the CO sensor consisted of the CO sensor unit at the end of a long stick, with a reading shown on a PDA separately. This design allowed the children to safely hold it higher up or lower down as well as in positions such as at the edge of roads and near exhaust vents without getting too close themselves. The main version of the sensor stick used a separate handheld PDA linked to the sensor by a Bluetooth serial module. A second version was also created to allow two groups to work at the same time, this had the PDA readout mounted on the stick itself and was wired to the sensor directly as a second Bluetooth serial module wasn't available.

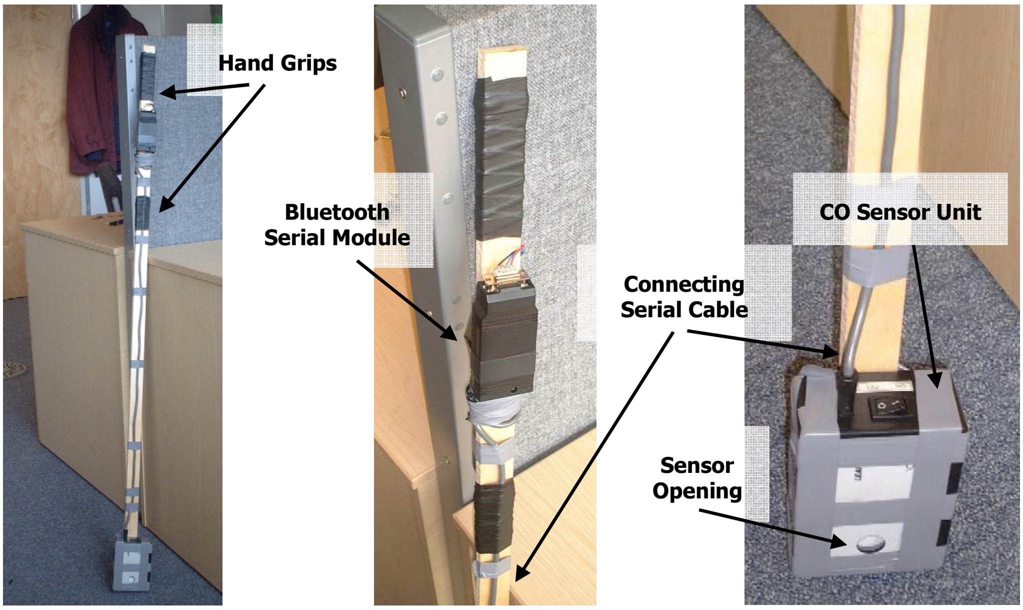


Figure 26: CO Sensor on a stick design during construction

The CO sensors performed two functions, recording a continuous log of CO readings and providing the ability to mark particular times in the log with marker points. The marker points were given individual numbers which were added to both the CO log and written notes made at the time, this meant that the CO data could then be matched with the notes after the experiment when they were compiled for review. The marker points also allowed interesting moments to be noted and referred back to later, for example a particularly high reading when a bus passed.

In order to help the children judge wind speed and direction, a wind ribbon was attached to the end of the sensor stick, this provided a clearer representation of which direction the wind was blowing in reference to the CO detecting unit. This was visible on the video footage as well as being observed and noted in the written notes. As the orientation of the sensor was also relevant to this, the sensors were coloured differently on each side, providing a means to easily determine the orientation of the sensor on the video footage. The finished unit can be seen in use in Figure 27.

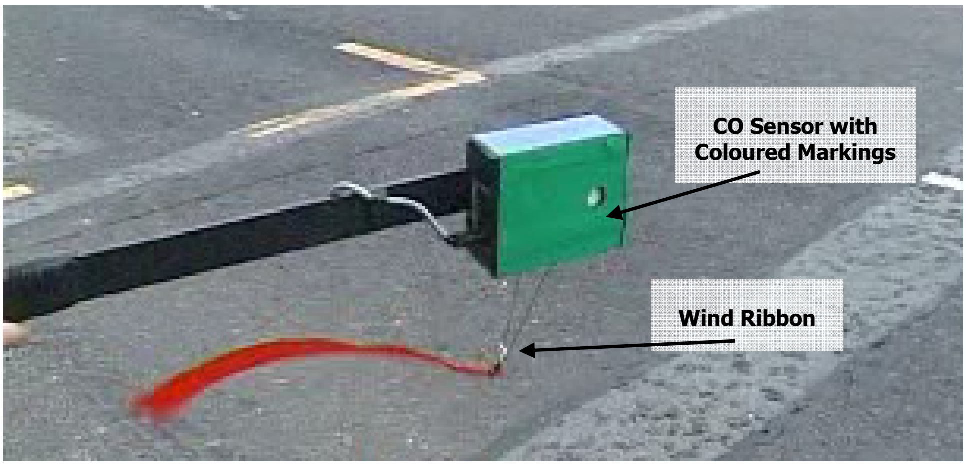


Figure 27: Sensor unit with coloured markings and wind ribbon

Some screenshots of the PDA application are also included in Figure 28 to demonstrate the display that the member of the group monitoring the readings saw. One image shows the standard display screen when readings are being collected and the other shows the message shown when marker points were set. As can be seen, each marker point is numbered so the notes recorded on paper can be linked to it during the fieldwork.

Each group had to take notes and record video footage of the practical work and so whilst two members of the group were working with the CO sensor, the other two members were concentrating on making other observations. One writing notes using a clipboard and a pre-prepared notes sheet, the other with the video camera.

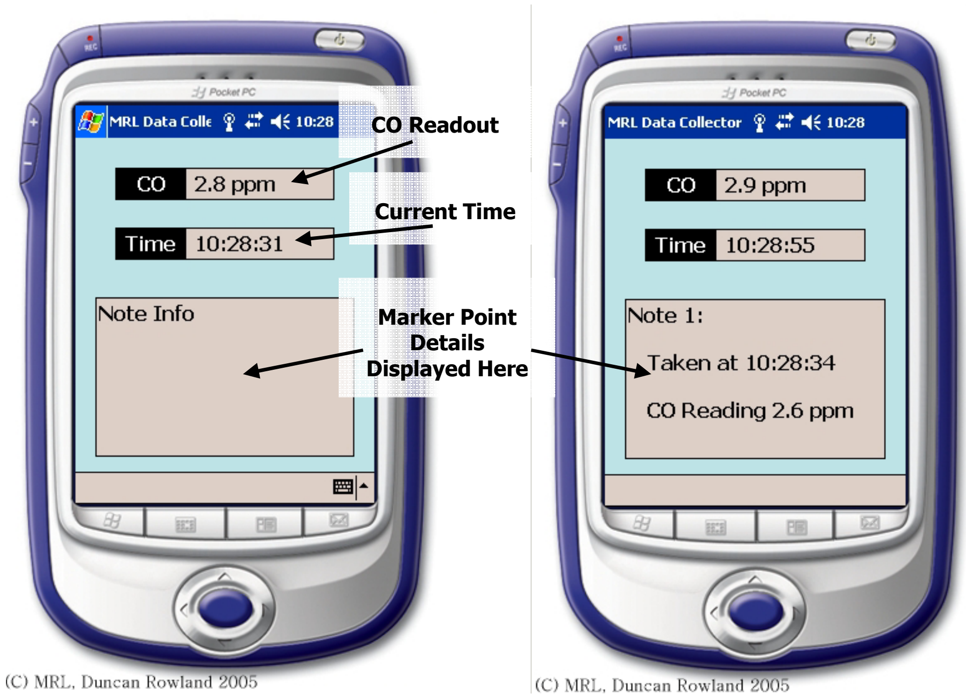


Figure 28: Screenshots of PDA software, normal (left) and after setting a marker point (right)

3.2.2.3 SENSE Data Explorer

The data collected by the group members in their experiments included continuous video footage, CO readings every second, marker points and the notes that were made along the way. After the data had been collected, the data was imported into the custom viewing application called SENSE Data Explorer (SDE), this brought all the data together using a graph of the CO readings as a timeline linked to the video footage with a moving cursor. The video data and the CO readings needed to be processed before they were viewable in SDE and this was done by the researchers in the days between the experiment lesson and the following analysis lessons. The marker points added to the CO log during the experiments were overlaid onto the graph with a space for further written comments to be added by the group as they reviewed their data. These points could also be supplemented with extra markers and annotations during the analysis session. Figure 29 shows a screenshot of the SDE application, showing the CO graph, video window and marker points.

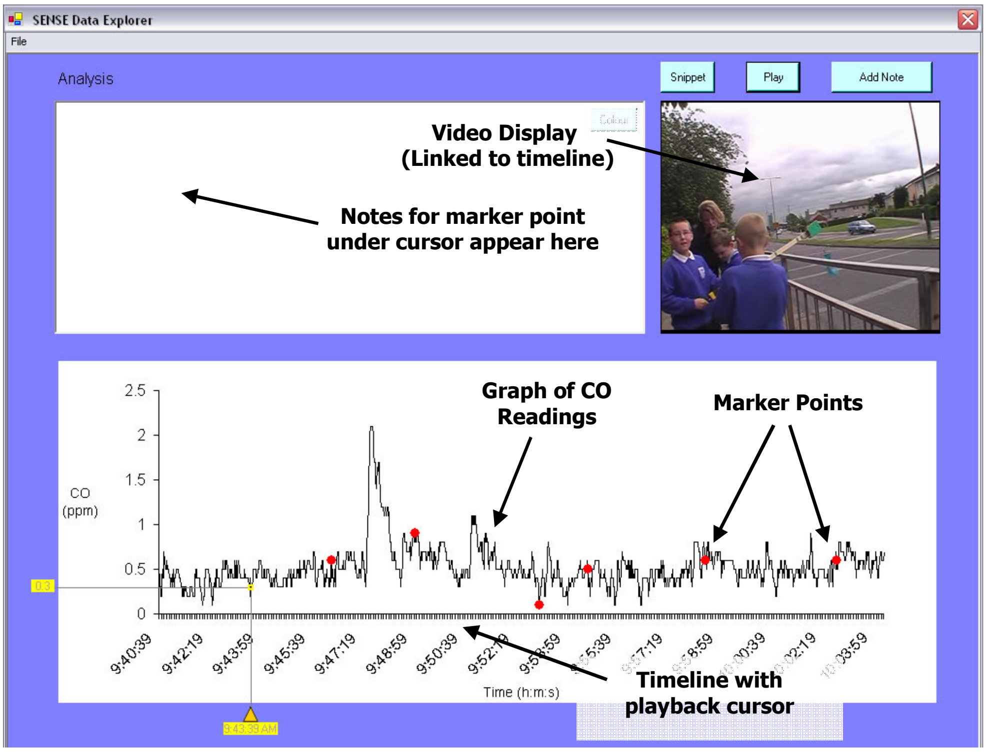


Figure 29: Sense Data Explorer screenshot

Using this software the children were able to see peaks and dips in the readings more readily than when out in the field and were able to compare them in context with the rest of the readings. The synchronised video allowed more of the context of the readings to be represented enabling a more detailed exploration of what caused the readings. Another feature of the application is to allow two sets of sensor data taken at the same time to be overlaid over each other, this is demonstrated in Figure 30, the video window indicates the relative positions of the two sensors to each other and show events surrounding the sensors.

Figure 30: Sense Data Explorer screenshot showing two concurrent datasets.

3.2.3 Activities in Sussex

In Sussex the team worked with two groups at Varndean secondary school. The first group was the environment club, a group ranging from 10 to 14 years of age that met out of lesson time. The second group was a class of year 9 students taking part in their science lessons. The environment club helped trial different techniques that would be refined and used by the year nines later on, acting as a test-bed for ideas.

The environment club undertook a map exercise similar to that in Nottingham where they were asked to place stickers predicting areas of pollution. They also trialled the particle collector experiment in different locations around the school. In preparation for work with CO detectors the group conducted some preliminary experiments with CO detectors whilst recording temperature, wind direction and strength. Different measurement devices were tested for example wind was measured with an anemometer and wind ribbon.

The sessions with the science class started with background work about pollution, using photos and some scientific theory about Carbon Monoxide to establish the knowledge for the rest of the work, this was at a higher level than Nottingham as the class were three years older. The lessons then went on to hypothesis planning and devising the experiments that would be conducted in the next stage.

The pupils in the class conducted two data collection and analysis sessions, giving them a chance to incorporate any improvements and knowledge they had gained from first time round. As part of the analysis of the second experiment the groups contacted an expert scientist helping them to prepare presentations to explain their findings and conclusions.

3.2.3.1 Differences in Equipment

There were two main differences in the Sussex data collection experiments, they used a different CO sensor configuration and they also they used an anemometer to record more accurate wind speed measurements.

The CO sensor was initially designed for research at UCL (mentioned in the examples in the literature review) and was designed to be mounted on the back of a bike. As opposed to the sensor sticks the units were fixed in place on a board and so couldn't be as easily pointed and positioned as the sensor stick design. The orientation was more or less fixed (due to the need to be able to read the display) so it was not as important to keep as close track of them as the sensor sticks. As the participants were older so sensor positioning was less of an issue (in terms of both safety and accuracy) as they were more experienced in using measuring instruments. The type of CO sensor (ICOM by Learian) was used by both Sussex and Nottingham which allowed data to be compared relatively accurately.

Figure 31: CO Sensor used by Sussex group

3.3 Study of Sensor Use in SENSE

The SENSE project itself was focussed on investigating the use of e-science techniques in schools, so the main body of the work was aimed at evaluating the educational aspects of the activities, however the project leant itself to conducting a study into the use of the sensing equipment alongside that work.

The CO measuring experiments combined the predominantly automatic sensors, the CO logger and the video camera with manual sensors – written notes, marker points and wind readings. The objective of the study was therefore to observe and document the ways in which the participants used these sensors to collect and report data and how their data served to document the conditions they experienced to others.

3.3.1 Methodology

The study consisted of naturalistic observation of the participants, recalling observations made when assisting with the preparation and fieldwork, combined with the video footage taken by the participants as they conducted their activities. The use of "in-the-wild" case studies, as described by Rogers, et al. (Rogers et al., 2007), provides the opportunity to obtain rich and varied data about how novel pervasive technologies are appropriated in their intended settings. In order to provide a more complete record of the experience involving the role of the sensing devices the observations were supplemented with the sensor readings, notes and comments entered into the SDE application as part of the work. This provided a view of what the sensors were reading throughout the experiments, as well as the information participants added during and after the fieldwork. This data was particularly necessary in addition to the video footage and observations because, as Crabtree, et al. highlight (Crabtree et al., 2006), in these kinds of systems participants work with multiple handheld devices on which readings are not easily observable from afar, and were frequently changing.

The analysis was data driven, taking an informal participant observation (Jorgensen, 1989) and grounded theory approach (Glaser & Strauss, 1973), (Fernández, Lehmann & Underwood, 2002). In the initial stage the video data was reviewed to gain a general first pass impression of the events that took place and the different ways in which the participants used the sensors were noted. Following this, each session was studied in more detail by reviewing the video alongside the CO readings and additional data, using the SDE application to replay the events and correlate them with the sensor readings. Over an iterative process the ways the participants interacted with the sensors were documented and consolidated into a set of observations, from which illustrative excerpts have been chosen and transcribed for inclusion in the write up. The final stage was to reflect on these observations, as documented in the final section of this chapter which discusses their implications about the use of automatic and manual sensors.

3.3.2 Data Sources

From Varndean School in Sussex data and video were available from three of the sessions that took place. Two groups feature in the sessions, one group complete two successive trips a couple of weeks apart, the next group one trip on the day of the other's second. Each group consisted of four members of the class and two facilitators from the team at Sussex to help with equipment and to record the sessions. In the two trip group one of the group members changed on the second session but everyone else was present. One member of each group carried the CO sensor, another carried a clipboard and a sheet to make notes, the third carried the anemometer and the final group member videoed the events. The length of the first session was about 20 minutes, during which notes and wind measurements were taken six times and marker points were set a total of 16 times. The second session lasted about 16 minutes and again six sets of notes were taken and this time six marker points were set. The session the other group made was 18 minutes and they marked 19 points in the data.

The data available from Nottingham consisted of video and data from three sessions, two groups separately on the first day and a simultaneous session from the second day were recoded. Those two sessions were split into two sections each, the first group had a total of 26 minutes with 9 marker points set, the second group had two 20 minute halves with 8 and 16 marker points respectively.

Table 6: Summary of data collected in school sessions

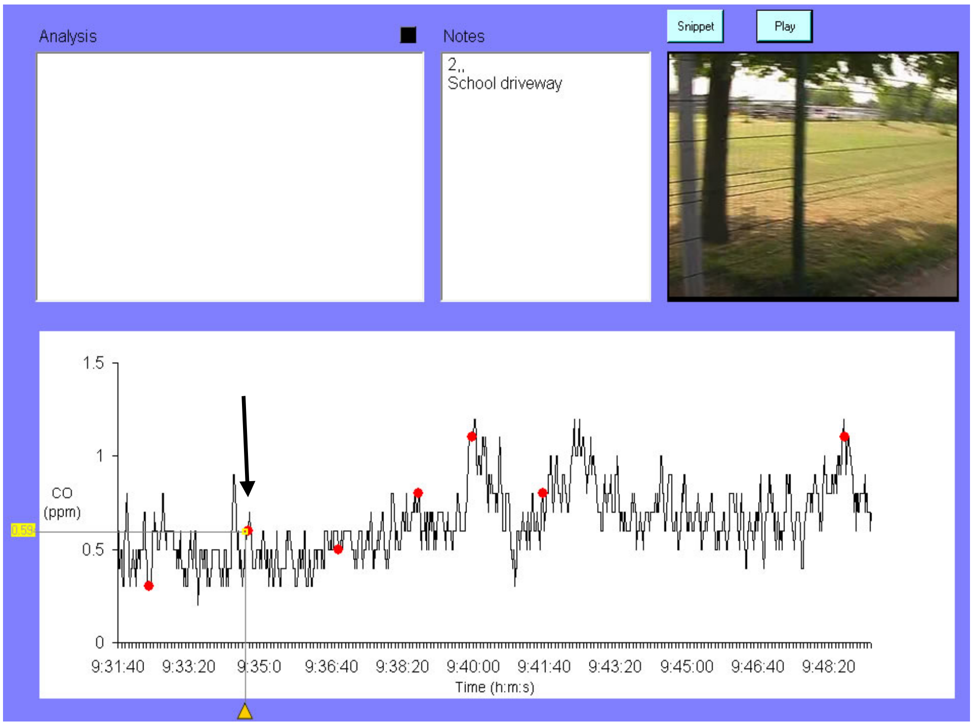
Session	Length	Marker Points
Sussex 1	20 minutes	16
Sussex 2	16 minutes	6
Sussex 3	18 minutes	19
Nottingham 1a	26 minutes	9
Nottingham 2a	20 minutes	8
Nottingham 2b	20 minutes	16

Excerpts from the video, sensor data and other information recorded during the sessions, along with the audio commentary taken from the video will be given to show the observations made. These will be described in the next section before being summarised at in the final part.

3.3.3 Observations

The initial step was to look at how the groups took readings and recorded data during the sessions. Watching the videos made it obvious that there were two main modes of data collection. Through all of the sessions the CO logging sensor was running and the video camera was recording but they were not focussed on anything in particular, at various times the members of the group would stop and work together to take readings, make notes and set a marker point using the PDA software. At this time the users of the CO sensor and the video camera would also pay particular attention to collecting data, for example holding the sensor out toward the edge of a road and panning the camera around the area to record the surroundings.

Sequence 1



A is holding PDA, C is writing, E is filming. T1 and T2 are members of the Nottingham team,
The group are walking down the school driveway near the start of a session.

A: "Stop!"

The group stop walking.

T1: "What's that?"

Marker point set as shown on graph.

A: "It's taken a note, it's getting higher."

T1: "Ok"

A: "Taken at 9:34:44, CO reading 0.6"

C begins to write down details whilst E points camera at clipboard

C: "0.6 and its now at number 2."

T2: "You need to put where it is"

C: "School driveway"

E: "I can see the school car park"

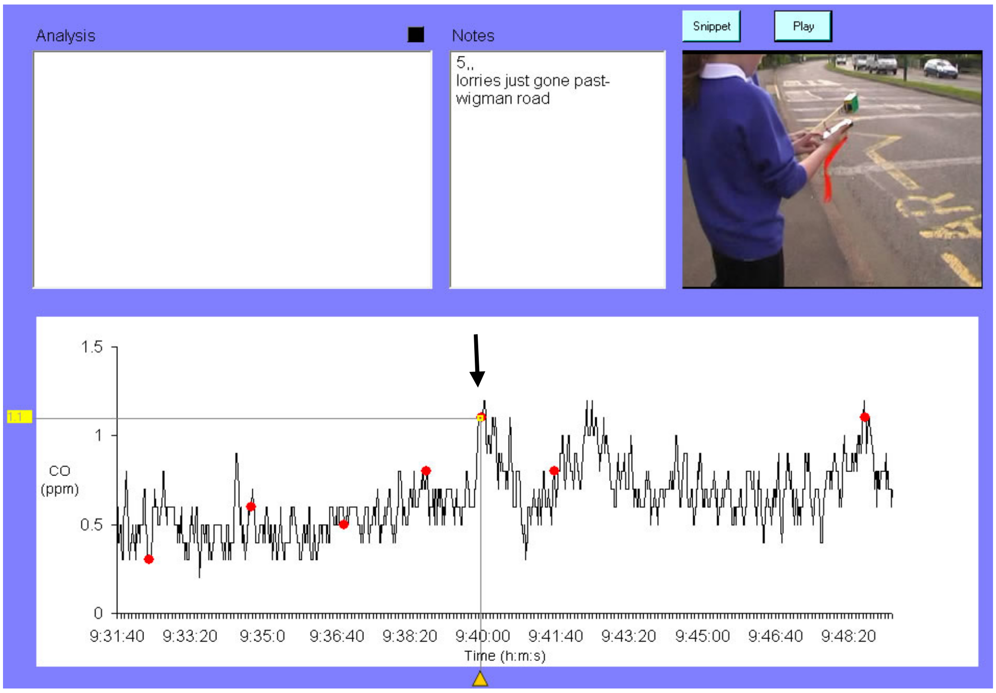
C: "It's blowing still towards it…right, carry on, let's go."

The group turn and continue down the drive, E points camera ahead

Sequence 1 shows a typical example the groups working together to collect data. The group member with the CO readout watches the reading rise, so calls to the others to get them to record details of what is happening at the time. He sets a marker point in the data using the PDA, allowing the notes and data to be referenced together later. The excerpts from the session are shown with the data screen on the left hand side and the transcript from the video given on the right. This shows the video image at the time referred to, and the data can be seen with a playback marker on the time axis.

A second example, Sequence 2, is later in the same session, this shows another incident taking place, in this instance it was triggered by some large vehicles approaching along the road and not the sensor readings. One of the group noticed the trucks coming, realising they are a potential source of Carbon Monoxide they get the group members to orient the sensor into a position to get a good reading.

Sequence 2



A Is holding PDA, B is holding Sensor stick, C is filming, D is writing notes

The group is stood by the side of the main road outside the school.

A: “We need to get the lorry…”

B: “Lorries!”

B: “Shall I hold it that way or the other way around.”

B: “I’m holding it out to the wind”

C: “The wind is blowing confusedly!”

A series of large vehicles pass on the other side of the road, **marker point set** as shown on graph.

A: “1.1”

B: “1.1”

D: “1.1”

C: “It’s blowing north! I think.”

The group continue to stand by the side of the road whilst the notes are completed and then begin to

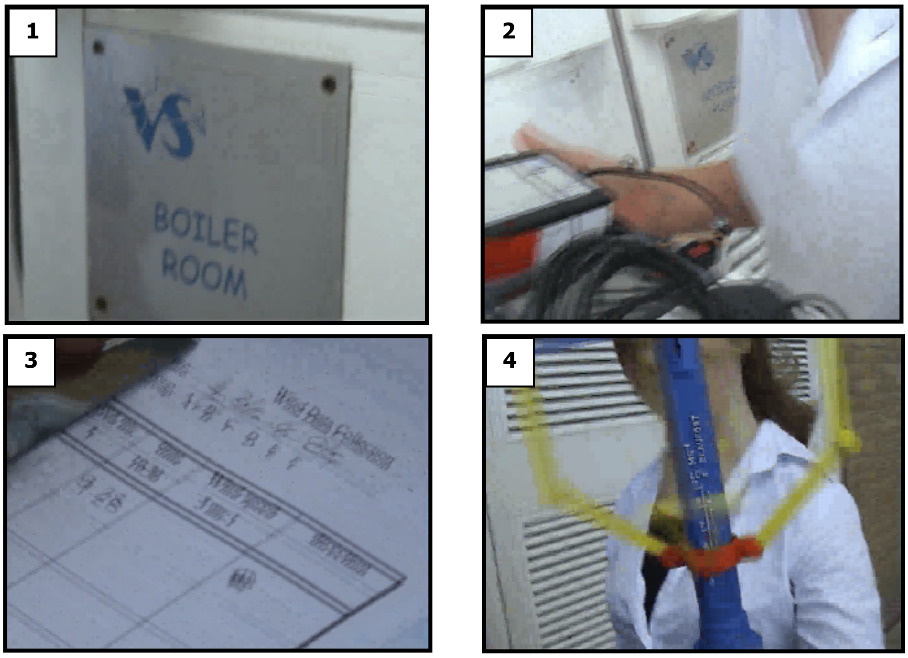
These examples reflect how numerous readings and observations are collected throughout the sessions, either based on a sharp rise in readings, or due to an event taking place that the members of the group think is significant to their experiment.

The next set of sequences show in more detail what happens during these episodes where the groups are taking detailed readings. The excerpts show a number of frames from the video and the transcript of what the members of the group were saying at the time.

When they decide to take readings, they begin to use the more manual methods of sensing, that is they write down observations and record the wind speed and also pay more attention to the automatic sensors, pointing the CO sensor and video camera at more specific things and commenting on them at the same time. This reinforces the idea of contributions being formed into episodes, building up the additional information around a trigger event, and trying to identify the most significant factors that affect the readings.

In Sequence 3 the year 9 participants filmed themselves taking a reading, showing a location sign, the items of equipment as readings were taken and their notes. This provided a useful aid for their analysis (to remind them exactly what happened) and was also useful when sharing the data; providing a geographical reference point for their location at the time, and showing how their readings were taken. Sequence 4 follows a similar pattern where they identify changes in the readings as cars go past.

Sequence 3



A holds anemometer, B holds camera, D holds CO sensor, E is writing.

The group cross a courtyard and approach the doors to the boiler room.

A: "That was like up to 9"

D: "Lots of wind"

The group arrive and stand in front of the doors, B points camera at boiler room sign. **[IMAGE 1]**

D: "Nothing's happened"

E: "The reading please"

D: "Err...it doesn't tell me, oh wait here…"

B moves over to D and points camera at CO sensor. **[IMAGE 2]**

D: "Err nought point nought five, err, 0.5…0.6 now ... 0.5"

B points camera towards and approaches E, who has moved away from the doors.

E: "We don't have a sheet, no Brad really there's no a sheet"

B points camera at clipboard whilst E writes the readings down, struggling to keep the paper in place as a gust of wind blows it. **[IMAGE 3]**

D: "We should have been out yesterday!"

B moves towards A who is now stood in the courtyard holding up the anemometer **.**

E: "Hey Elinor, did you pick up a sheet, 'cos you kind of gave me this without a sheet."

B points camera at anemometer **[IMAGE 4]**

B: "I caught the reading, it was eight five."

A: "No that's just what was there."

B: "What's the wind, eh?"

A: "The wind went up to 9 a minute ago"

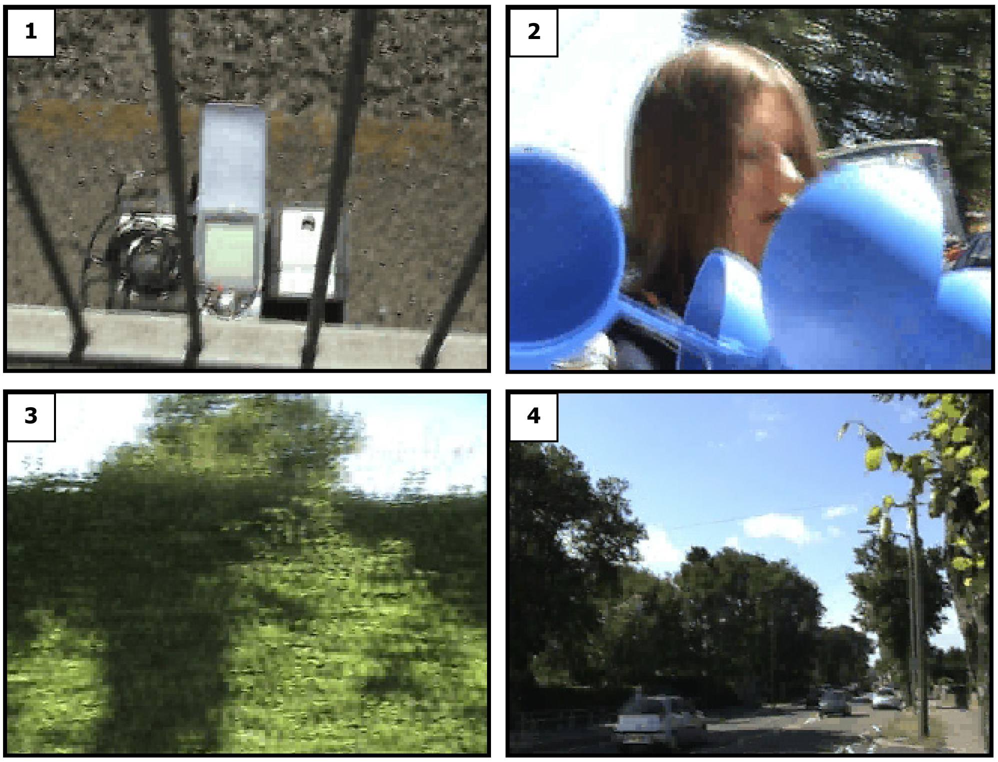
D: "Really? Yeah, we should have brought this out yesterday, god it was windy…something off the scale because yesterday you actually could lean into the wind and not fall over!"

E: "Go, let's go to the tennis courts"

B: "We're going to the tennis courts yeah?"

The group leave the courtyard and move on.

Sequence 4



A holds anemometer, B has the camera, C operates CO sensor, D is writing, T1 is one of the Sussex team. The group have just placed the CO sensor on the floor by the side of the road outside the school. **[IMAGE 1]**

B: "What's the reading now? Chris, go and have a look."

D: "0.8, 0.7… 0.6"

A: "Ah!"

C: "Shall I push it?"

C pushes button on the CO sensor to set a marker point. **B:** "Try the…

C: "It's interesting because it goes up whenever a car goes past…er whatever"

B: "Why could that be?"

B points camera back toward D, the group member who is writing.

T1: "How much does it go up by when a car goes past?"

D: "One or two

C: "Well .1 or .2, up to 0.7"

D: "What's the wind?"

A: "There isn't any wind it's very sheltered."

T1: "Oh really?"

[IMAGE 2] Camera is then panned around the area. **[IMAGE 3]**

B: "Is that because of the hedge?"

A: "It's because of the hedge and those things over there that you can see are very windy."

Camera is pointed toward the top of some trees further down the road. **[IMAGE 4]**

The group then continue to stand at the edge of the road and discuss the effect of the wind and the

Even though the participants performed well when they were focussed on taking readings, one of the difficulties seen was in choosing the good moments to take readings. For example in Sequence 1 the group have only been using the CO sensor for a couple of minutes, as they begin their journey down the school driveway they see the readings increase so take a reading and make notes. In comparison with the readings collected throughout the rest of the session this reading is not particularly significant; however at the time it did appear relevant to the group – one of the highest readings recorded so far, a few seconds after another peak. Reviewing the notes and marker points that were added to the data shows similar patterns are repeated throughout the sessions, either where the highest CO readings are detected but not commented on, or where notes are taken because the readings are misinterpreted as high enough to be significant.

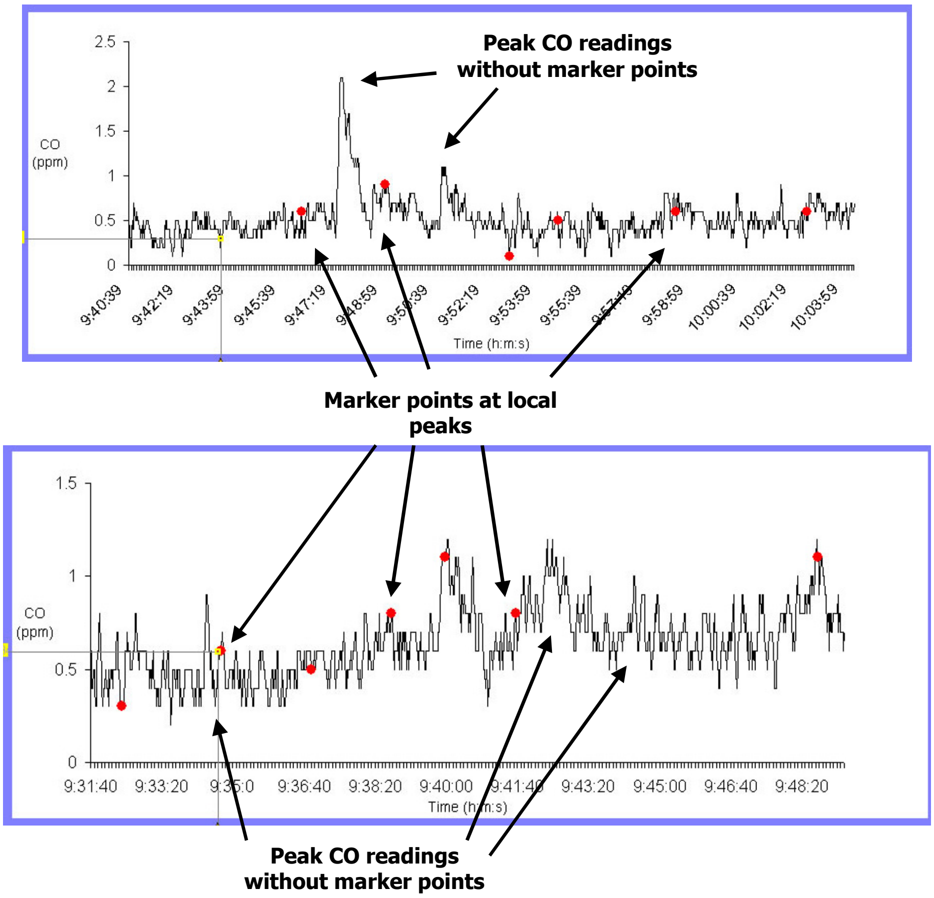
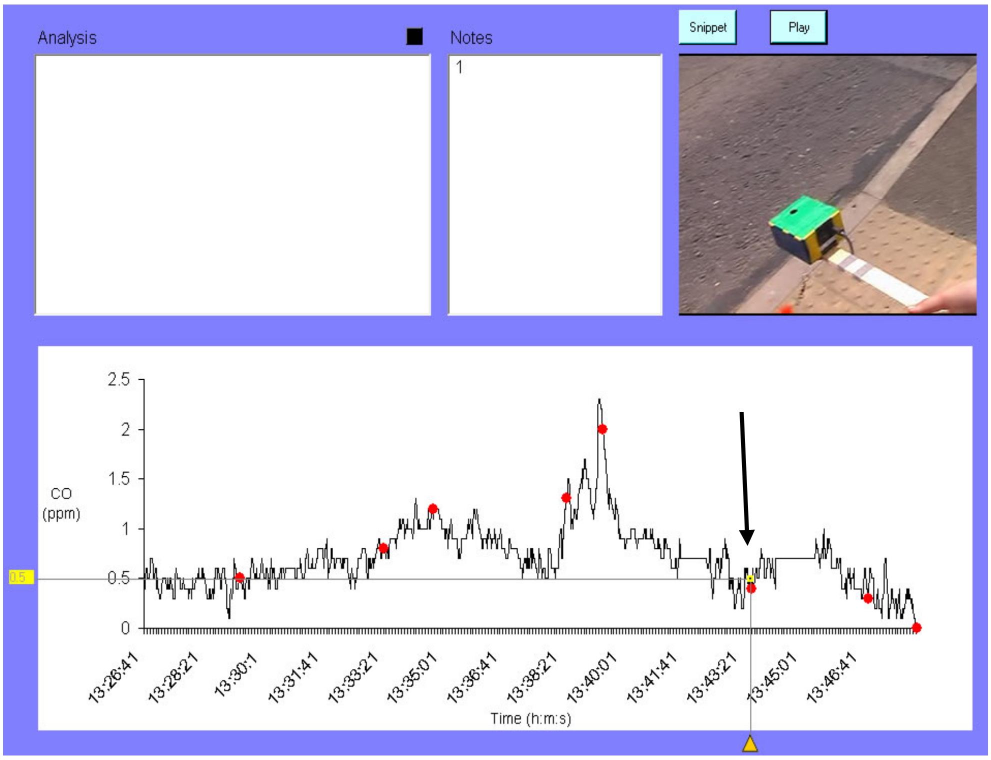


Figure 32: Data excerpts showing where CO levels peaked and where marker points were set

A number of examples can be seen in the two graph excerpts shown in Figure 32, showing how some of the highest readings weren't marked, and some marker points were set to highlight smaller peaks that don't stand out in the full dataset. The differences between significant sensor readings and the moments that the participants reported additional data begin to illustrate a need to involve a more sophisticated dialogue in the process. A greater amount of feedback from the sensor might address this, for example using high readings triggering alerts to draw the users' attention to them, or requiring the user to provide an explicit reason for setting a marker point each time.

Sequence 5



A has the clipboard, B has the CO sensor, C has the camera, T1 is a member of the research team. The group are stood by the side of the road near a crossing, where they have just swapped equipment.

T1: "So basically if you think… if you want to take a reading, you press that, and then you tell Jas, is it Jas, that you've taken a reading and if you [Jas] can write it down."

C: "Oi, how do you… how do you zoom in?"

A: "You turn that thing round, work it out! Turn that thing round."

C: "I know"

T1: "So if you want to take a reading here, you press that button in the middle."

B: "Shall I do it now?"

T1: "Yes just have a go."

Marker point set as shown.

B: "0.5"

The group then note down the readings and wind conditions and continue to stand by the road watching the traffic.

Another source of additional data being recorded is when the participants used the equipment for the purposes of familiarization and testing. They created marker points to confirm the CO sensor PDA was working as expected and to demonstrate it to other members of the group. This was seen a number of times as the participants switched roles throughout the sessions so that every member of the group could try each activity. Sequence 5 shows an example just after switching roles; the group discuss how the equipment works then set a marker point to confirm.

This highlights the importance of the additional contextual information that was collected along with the automatic sensor data, by viewing the video footage it was easy to understand the reasons a marker point had been created. This also has a knock on effect on interpreting the rest of the data collected at that point, for example the CO sensor may pick up disturbed readings as it's being handed over to the next member of the group. Whilst it is easy for a human viewing the video data to understand the situation, this is more is difficult to automatically determine. With a more sophisticated dialogue this process could be enhanced so that it was easier to automatically determine this, i.e. by providing a more explicit means to record the reason for a marker point

The final stage of the analysis looks at additions made to the data during the analysis of their experiments back in the classroom. The additional video and notes provided an opportunity to reflect on what had happened, reminding the members of the group of their experience and helping them draw some conclusions based on a view of all the data that was collected.

Extra comments were added to the graph, allowing the participants to document things that they hadn't noticed at the time, and to revise any annotations. This helped counteract some of the instances of readings that were initially thought as significant at the time, but proved less so in relation to the rest of the data.

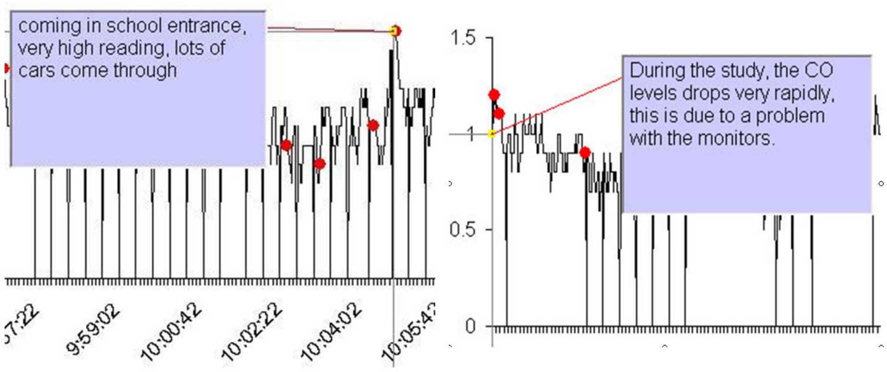


Figure 33: Comments added when reviewing the data using SDE

Figure 33 shows two examples of comments that were added using SDE during the classroom analysis session, the first example shows a comment that was added to provide a description and narrative to the data collection, adding more detail about the area that the video footage showed. The second shows a comment that was added to highlight errors in the data collection, where the readings were inaccurate.

These two points show how the ability to review the data after it has been recorded provides a useful method of counteracting some of the noise and inaccuracies picked up during the data collection sessions.

This review process, which also included looking at classmates' data, can also have positive feedback into the participants' data collection methods. The group that had the time to undertake another data collection session had much more detailed and specific annotations, with members of the group speaking directly to the camera in order to describe their actions and observations. The opportunity for participants to review both their data and that of others helps to improve understanding of the data collected and the data collection techniques and this was something that was borne out in other work (Stanton Fraser et al., 2005).

3.4 Discussion

This study looked at an activity that combined automatic and manual sensors used by a group of young people working together during fieldwork in a series of school science lessons. The observations highlighted characteristics of the dialogue between the participants and the sensors, noting the ways in which it affected the data collected and the potential for developing the dialogue further. These are summarised below describing the observations made in three sections; sensing episodes with continuous background readings; initiating episodes; and review and reflection.

3.4.1 Sensing Episodes with Continuous Background Readings

The data collection activity involved sensors with varying degrees of automation. The CO sensor and video camera provided continuous data recordings but needed the users to point them in the appropriate direction to get a good reading or video shot. The other data was manually recorded, so users had to specifically make readings and write them down.

During the sessions it was seen that the groups would set a marker point and take manual readings as a group at various times. At these times they paid particular attention to the sensors, coordinating the use of all of them to provide as much information as possible; they positioned the automatic devices more carefully as well as adding extra notes and commentary. Outside these data collection episodes the groups didn't make efforts to manually record any information and the members of the group carried the equipment without close attention to its orientation or avoiding interference.

The manual aspects of the sensors used (reporting observations, pointing the camera and CO sensor, etc) supported the episodic pattern of data capture, giving the users the freedom and opportunity to contribute a range of information and tie it back to a moment in the automatic sensor data. Between episodes the continuous automatic readings allowed the participants to monitor and respond to changes in conditions, however as they didn’t pay particular attention to their usage of the devices noise and inconsistencies were introduced, making the data difficult to interpret.

The effect of the episodic patterns of data collection means it is difficult to arbitrarily compare CO readings collected at any time, though it is easier to compare data collected as part of episodes. This is because the additional information gathered, combined with the increased attention paid to the sensors made the readings more consistent and easier to interpret; out of episode readings are more problematic to compare as there is less contextual data and the readings are less reliable.

Implementing ways to recognise and work with the episodic nature of data collection that has been observed may help to better exploit the data that been collected, as well as the opportunities to collect it. This leads toward considering a more involved dialogue between the sensors and their users throughout a sensing experience – negotiating the collection of human and computer interpretable data, and specifically the amount of freedom users have to gather information, versus explicitly reporting data within predefined, machine-interpretable limits.

3.4.2 Initiating Episodes

The next set of observations looked at when and why episodes occurred; this was due to a number of reasons:

- Events occurring in the surroundings
- Responding to peaks in the CO readings
- Testing or demonstrating the equipment

During episodes the participants worked well in collecting data across the range of sensors, but the relative value of each of these were often determined by the focus of the episode and how relevant it was to the CO investigation. When users were responding to a rise in the readings they often reported small scale peaks in CO that were not very significant compared to the overall readings. They set marker points and reported their readings however what they reported did not greatly contribute to the investigation. Conversely, some high readings also went unnoticed with no additional data recorded to explain them.

When users created an episode but no corresponding event was obvious in the CO readings the job of interpreting them became more difficult. The additional data reported by the users was very important in this process making it possible to distinguish between whether it was an event that the CO sensor failed to register, or a test reading that was not related to a significant change in readings. The additional data provided by the group members provided some means to distinguish these types of events, but this was not a particularly strong method of supporting the process as it relied on the users to recognise the need for and volunteer appropriate information. To better separate the different kinds of episodes, the understanding of the connection between the data and annotations need to be developed to a greater degree – allowing the users to use their judgement to provide more appropriate information.

Again this highlights the dialogue with the sensors that takes place during the experience, as this helps determine the users' understanding of how the sensors operate as well as the how they understand the changes in the CO levels. Extending this dialogue provides the opportunity for the users to build their understanding to a greater degree, and so work with the sensors more effectively. Responding to some of the issues seen in the experience, suggested modifications to the CO sensor include adding an indicator to show whether readings were within an expected range or an alert when the levels exceeded a certain threshold. Providing an ongoing comparison with general reference points creates a greater degree of dialogue with the sensor, encouraging the user to reflect on the readings from another viewpoint. The idea of reflection comes from observations made about reviewing the data, which are discussed in more detail in the final part below.

3.4.3 Review and Reflection

This third part covers issues raised by considering the final stage of the activity when the participants reviewed their own, and other groups' data. They did so using the SDE application, which gave them a chance to see the CO, video, marker points and other notes they collected all together in one place. As part of this review process, they were allowed to revise and add additional notes to those made during the outdoors part of the activity, a number of comments were added by the participants at this time.

The notes added during the review process showed that the participants spotted errors or mistakes in the data collection (for example when the CO sensor wasn't working correctly). They also were able to note details they may have not seen during the activity, such as momentary peaks in the CO levels or events going on in the background. The overall viewpoint, especially the graph view allowed them to identify the highest readings and general patterns in the data, details which were less apparent during the fieldwork with only the instantaneous readings given on the PDA screen.

A further result of the review process was to improve participants' data collection techniques, allowing them to reflect upon their methods and respond in further sessions. The amount of feedback provided by the sensors during their use was very limited in the way it supported reviewing the collected data, the CO readout and the video camera viewfinder giving only instantaneous displays of their recordings.

These observations again can be related to the dialogue between the users and the sensors – in particular what feedback the sensors give about the data they collect and when they do so. The contributions made in the review sessions; highlighting errors, adding further detail and improving the data collection methods show the possibilities, though at a cost of timeliness – coming after the main data collection period is over, so missing opportunities for this feedback to directly affect further activities. This therefore demonstrates the potential to developing this dialogue further, integrating those aspects into the data collection process itself as well as being part of the visualisation tools.

3.4.4 Summary

In the study several aspects of human-sensor dialogue have been seen, these relate to:

- The use of automated sensing methods alongside manual contributions from participants.
- Triggers initiating focussed activity from participants above continuous background readings.
- Consolidating human interpretable data with machine interpretable data.
- The effects of review and revision of collected data.

These aspects have shown the potential to both widen and deepen the dialogue by considering the ways to improve on and extend the experience. Issues raised were:

- The freedom given to users to collect data versus the constraints set by the need to provide machine interpretable data.
- The development of users' understanding of the sensing process and the sensor data, for example providing sensor specific feedback to help contextualise readings.
- The integration of review, revision and reflection activities throughout an experience.

In the next chapter, sensor-human dialogue is further explored using another study to further develop and expand on these ideas.

4 Participate and the World Scout Jamboree

4.1 Introduction

The previous chapter began to consider the concept of dialogue between users and sensors, particularly related to automatic and manual sensing tasks and the users' understanding of the sensors. This chapter develops the idea further, building a deeper understanding of human-sensor dialogue derived from a second study. The study takes a closer look at the combination of automatic and manual sensing, it looks again at a collaborative environmental sensing exercise with young people, combining continual sensor readings and reported data from members of the group.

The sensing activity in this study takes a more computerised approach than SENSE, replacing video and written notes with GPS location logging, digital photographs and visualisation using 3D graphics and satellite imagery. The sensing task is simplified, switching from Carbon Monoxide to sound levels. The work in SENSE studied Carbon Monoxide, something that participants had little previous experience of; measuring sound levels exploited pre-existing knowledge of sound and so the focus was more on data collection than discovering the sources. This allowed the study to observe dialogue between the sound sensor and the user in greater detail.

The sensing activity used a sensing toolkit developed within the team as part of the Participate project. This project and the development process within the project will be described in the opening part of this chapter. The setting for the study was the 21st World Scout Jamboree at Hylands Park near Chelmsford, taking place in July and August 2007. After describing the Participate project details of the Jamboree are given, explaining the activity that formed the basis for the study.

The final part of the chapter details the analysis of the activities, taking a similar form to the previous work in SENSE; reviewing the data collected in an iterative approach, refining general impressions into specific observations and examples. The observations provide more evidence of the episodic technique used by the participants when dealing with manual sensors, and the way in which manual reports provide context and surrounding details. The observations highlight understanding issues related to limiting factors in the design of the sensors and the visualisation tools. The analysis identifies difficulties arising from differences in the ways participants expected the sensors to collect and represent data and the way in which the sensors and visualisation actually did so. The observations, specifically the difficulties experienced by the participants are reflected upon in the final part of the chapter, providing some further ideas about the dialogue that takes place between the users and the sensors.

4.2 Participate

The study uses an environmental sensing toolkit that was developed as part of the Participate project. This section describes the background of the project, the sensing technology developed and the design process within the project. The background details cover the overall structure of the project, its aims and the part of the project that the sensing toolkit was developed for. Iterations in the design of the sensing kit will be outlined as well as an overview of the features of the final design.

4.2.1 Funding and Partners

Participate is a multi-partner research project funded by the EPSRC (Engineering and Physical Sciences Research Council) and the Technology Strategy Board (funded by the UK's Department for Innovation, Universities and Skills). Taking part in the project are research partners from academia, industry and the arts; The University of Nottingham (Mixed Reality Lab), The University of Bath (CREATE Group), BT (Broadband Applications Research Centre), BBC New Media and Technology, Microsoft Research, Blast Theory and ScienceScope.

4.2.2 Project Overview

The Participate project is researching the integration of data captured by personal devices and sensors with broadcast and online services. It seeks to develop a new approach for compelling mass participatory campaigns, using a three layered model for participation. The first layer is the mass public, using personal devices, handheld computers and broadband PCs to report and upload data providing a background picture of 'quality of life' throughout the country. The second level of participation brings in schools, communities and environmental groups to focus on individual issues and locations. The final layer takes broadcasters and environmental experts who can study the data, provide feedback and direct the campaign. Figure 34 illustrates this approach. (Oldroyd et al., 2005)

Figure 34: Participate project three-layered approach to mass participatory campaigns.

The project pursues research and involves many aspects associated with participatory sensing, such as using a co-ordinated network of observers, person centric sensors via personal devices, mass scale participation and the integration of diverse devices.

In the summer of 2008 Participate conducted pilot campaign that involved the public, broadcasters and a network of schools. The pilot followed the first phase of the project in which three individual projects were conducted based on specific areas of interest: schools, communities and gaming. The next section describes the schools trial activities, in which the author was closely involved, and from which the rest of this chapter was developed.

4.2.3 Schools Trial

Of the three initial projects that Participate undertook in the project's first stage, this section focuses on the schools trial project. The schools trial undertook the development and testing of an environmental sensing toolkit and surrounding activities, upon which the study is based. The final toolkit was a product of an interactive design process, the details of which will be given below alongside a description of the activities within the initial schools part of Participate.

The activities took place between May and July 2006 and involved members of the Participate team from Nottingham, Bath, ScienceScope, BBC and BT. Two schools were involved; one school located to the North of Bristol, the other in the city of Bath. A teacher at each school worked alongside the team and the trial involved 50 children in total. At the Bristol school a class of year 9 (13-14 years old) pupils took part, in Bath 16 volunteers from year 10 (14-15 years old) took part outside their normal lessons.

The activities in the trial consisted of three stages; initial briefings and familiarisation lessons, experimental sessions, and the analysis and reflection sessions.

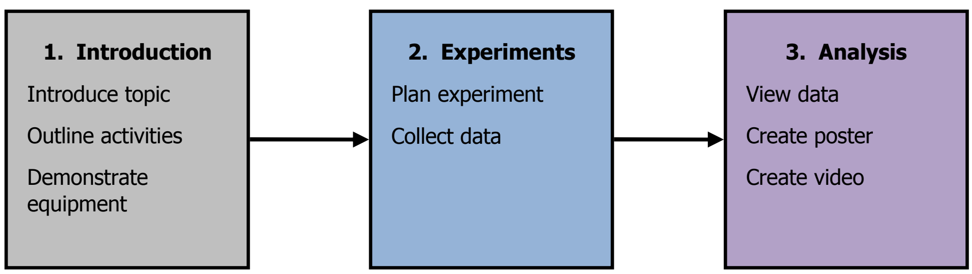


Figure 35: Structure of Participate initial schools trial activities

4.2.3.1 Introductory Sessions

The initial briefings took place in two sessions at each school, one lesson concentrated on the background and introduced the project and the upcoming activities, the second provided a hands-on demo of the equipment they would be using to collect data.

4.2.3.2 Data Collection Experiments

The experiment part of the Participate schools trial consisted of a data collection exercise allowing children to gather readings about the environment (Carbon Monoxide levels, sound levels) on their journey home from school and back again. This took place over a week – individual members of each class took turns to take readings each day. The equipment they used consisted of a mobile phone, and Bluetooth enabled GPS unit, ScienceScope datalogger, disposable camera and notebook. The phone acted as the storage device, allowing location and sensor readings from both devices to be processed and stored in its internal memory, whilst the notebook and camera allowed the recording of additional details. The equipment and the resulting data visualisation provided the prototype design for the second data gathering system, which is used in the main study in this chapter; the following section describes the system in more detail before the main study is introduced.

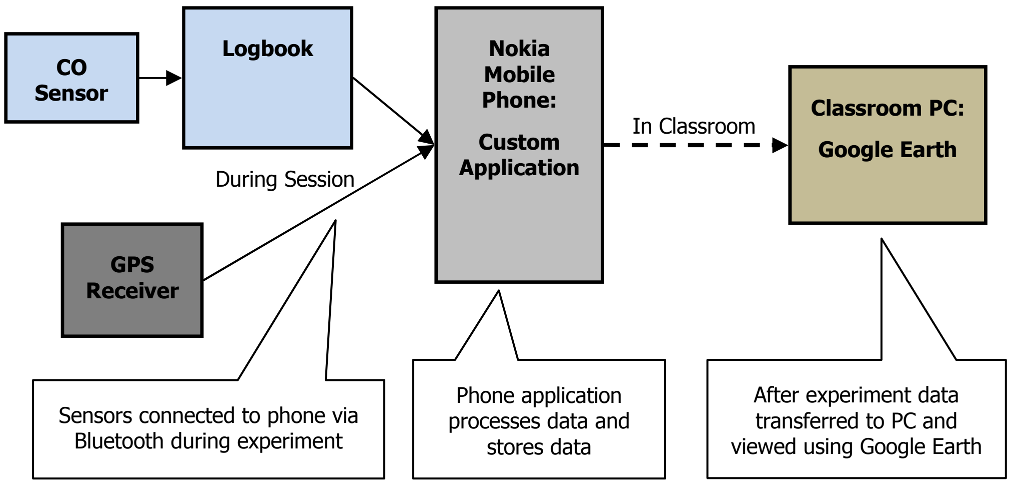


Figure 36: Initial trial configuration using mobile phone application, Logbook datalogger and GPS.

4.2.3.3 Analysis Sessions

The analysis sessions took place in the final stage of the activities, the teachers led three lessons where the children compared and discussed their data and then prepared a group presentation to explain their findings and experiences. They used two software packages to study the data they collected with the phone, GPS and datalogger. One package was called Datadisc – the software supplied with the datalogger, this showed the readings in traditional graph form. The second package, Google Earth, allowed 3D graphs of the data to be plotted and viewed on a map with aerial images using the GPS-recorded position. More details about the Google Earth Visualisation are given in section 4.2.4.2 below. After studying the data, the class created their reports and presented them in either a spoken presentation or a poster (an example is shown in Figure 37. At the end of the project, both classes took part in daylong "60 Second Scientist" workshops led by a team from the BBC. In these workshops, the participants formed groups to create short videos in different styles, reporting their findings and their experiences.

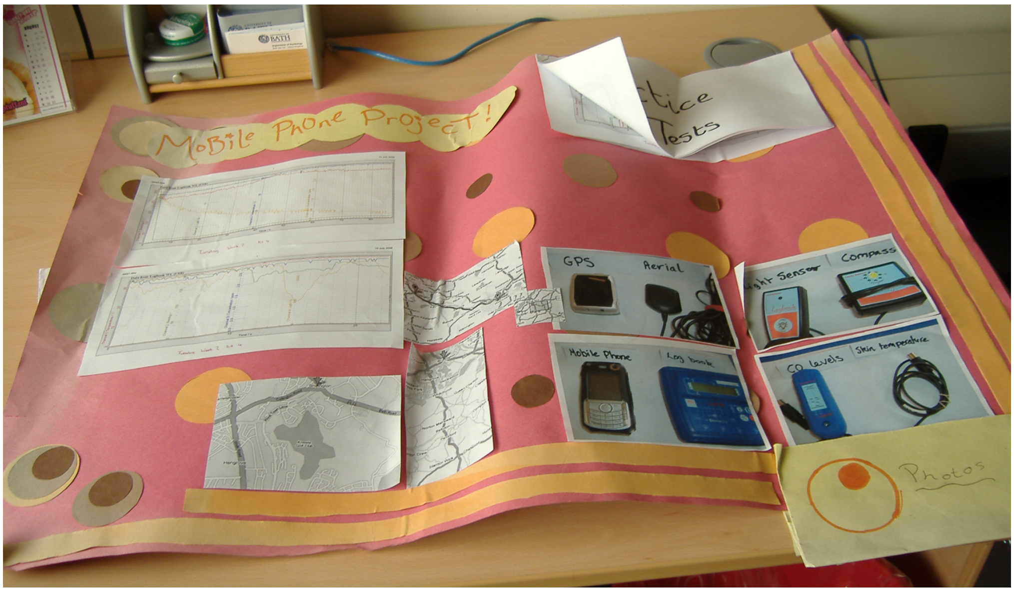


Figure 37: Example of a poster created as part of the initial school trial

4.2.4 GPS Based Datalogging and Visualisation System

This section describes in more detail the phone based datalogging system used in the first part of the Participate schools trial and the visualisation tools for the collected data. Within the project the system was further developed for the second stage of the Participate schools trial, resulting in the JData3D datalogging system used in the study at the World Scout Jamboree. Both systems and the 3D visualisation tool (using Google Earth) are described below.

4.2.4.1 Initial Trial Phone Based System

The schools trial began by investigating the use of mobile phones, GPS units and dataloggers in science lessons. The children in the classes collected data on their way to and from school using a phone based application that collected GPS data and sensor readings via Bluetooth connections to the GPS unit and a ScienceScope

Logbook datalogger. The phone processed the data and stored it in a file to be loaded on to the classroom computer later on, as shown in Figure 36. The data collection kit also included a disposable camera and notebook that would allow them to take notes during their journey as well as collecting the data, though these were little used by the participants in their data collection sessions.

Figure 38 shows the equipment used in the trial, the Logbook has two sensors connected in its sensor ports, one Carbon Monoxide sensor and a light level sensor. The wireless Bluetooth GPS unit is above the Nokia 6600 phone on the right hand side.

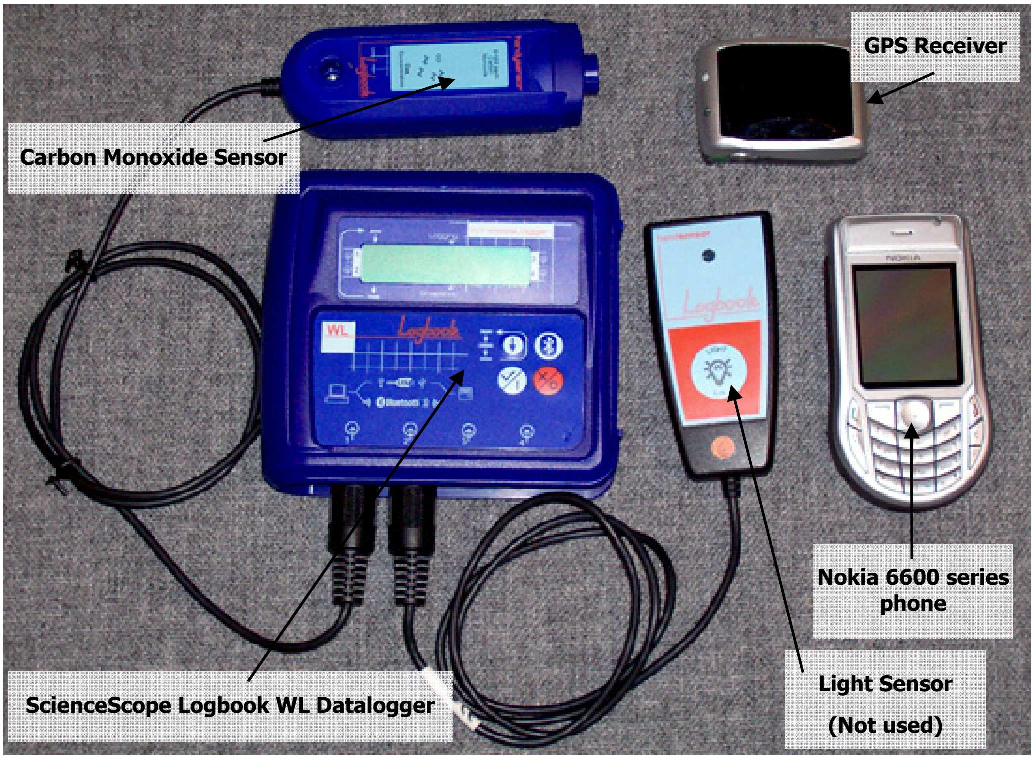


Figure 38: Phone, GPS and Logbook datalogger with sensor modules for light and Carbon Monoxide.

4.2.4.2 Google Earth Visualisation

Google Earth is a free PC application developed by Google that takes satellite and aerial images and renders them on a model of the Earth. Users may then view layers of additional information, such as roads, place names and points of interest, as well as add their own information and 3D models. It has a location search tool, a route-finding function, measurement tools and an increasing amount of other functions. As the user browses, the base information is downloaded from online servers operated by Google, and additional information is added on from the local machine, or through links to additional web servers.

Figure 39 shows an overview of the Google Earth interface, the search tool is in the top left, allowing users to search for particular places (country, city name, post code, etc), when found the main view will zoom into the destination and provide a close up view. The navigation controls (top right) allow the user to change the viewpoint, changing its geographic location as well as rotation, tilt and altitude. The view can also be changed by dragging the main view using the computer's mouse or alternatively using keyboard shortcuts.

The user may create and save points of interest, which are displayed below the search box on the right hand side of the screen. Additional layers of information available though Google can be selected using the layers box below this.

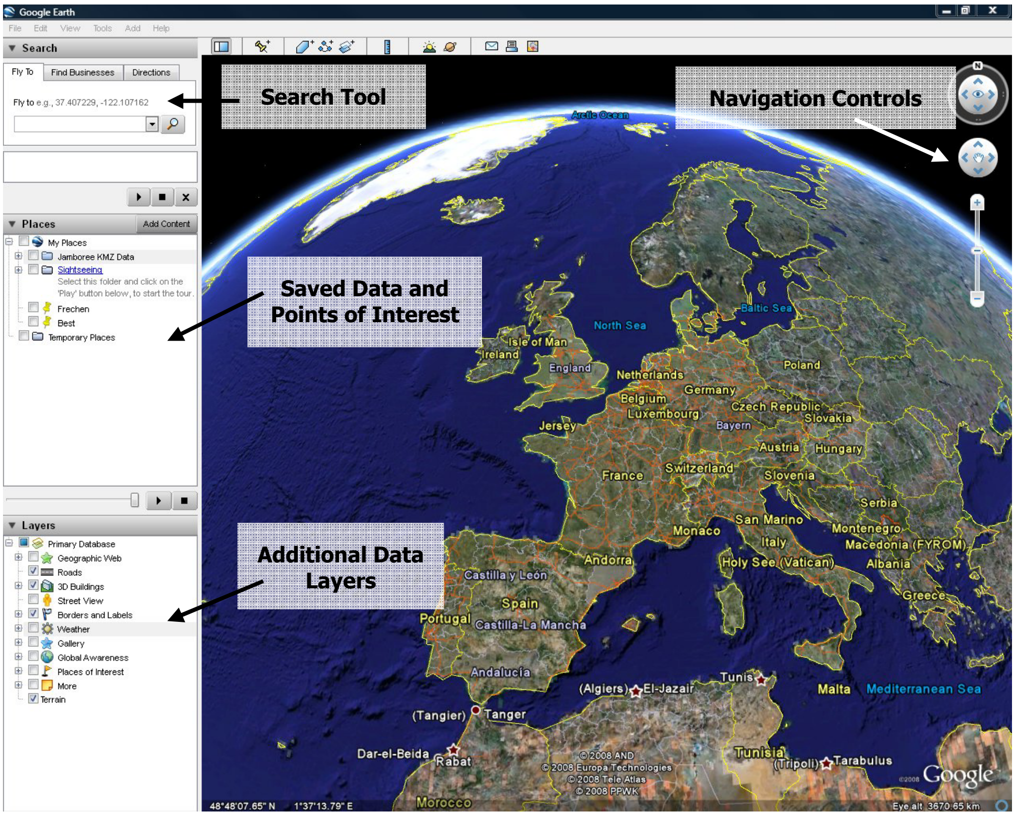


Figure 39: Screenshot of the Google Earth interface demonstrating 3D view

Figure 40 shows a close up view of an area with the view tilted slightly. It has three layers of information visible, roads, place names and borders. As the user zooms in closer to an area, details appear, such as smaller roads (in white) and their names. As the view gets closer, increasingly higher resolution images are used, though the quality of the images available varies from location to location.

Figure 40: Google Earth image showing street maps and overhead images

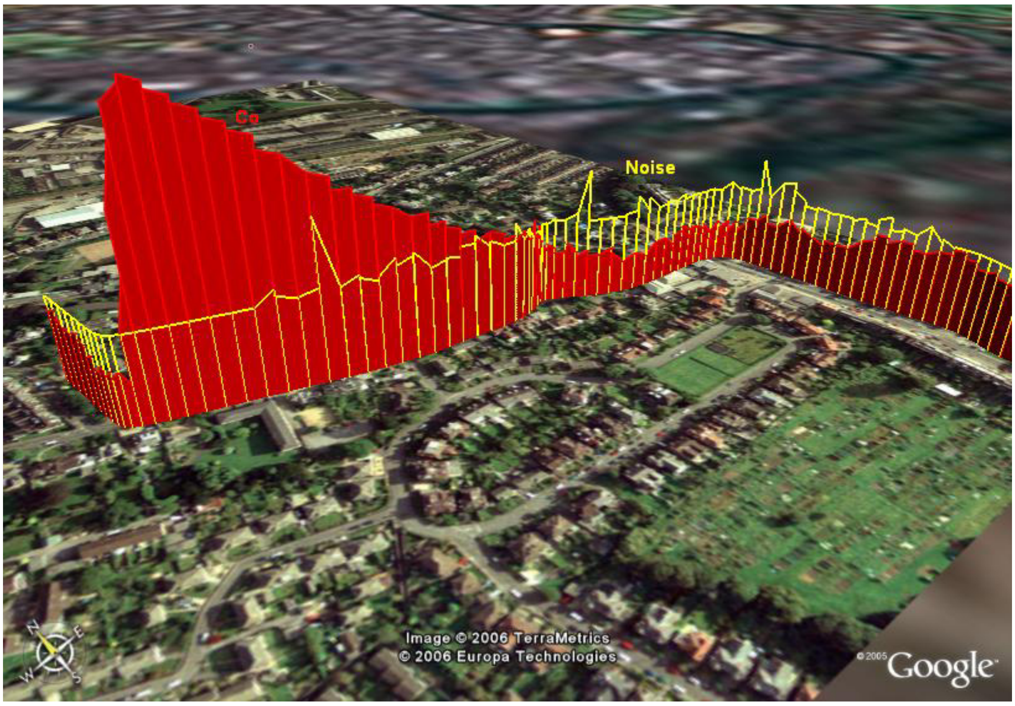


Figure 41: Carbon Monoxide and Sound Level graphs recorded by the phone application

The phone application created a KML (Keyhole Markup Language)[8] file combining GPS and sensor readings, when loaded into Google Earth this file renders a graph representing the sensor readings that followed the route the GPS reported as the children collected their data. KML is a standardised XML language designed for geographic visualisation and map annotation. Figure 41 shows an example of the

[8] Keyhole Markup Language, "KML", http://www.opengeospatial.org/standards/kml

graph created using the KML visualisation of one set of data recorded during the trial with Carbon Monoxide levels in red and sound level readings in yellow.

4.2.4.3 JData3D Datalogging System

Following the initial Participate schools trial, the JData3D system was developed by colleagues within the project at ScienceScope . Its aim was to reduce the complexity of the equipment and more closely integrate the use of photographs into the visualisation. The streamlined toolkit consists of a ScienceScope datalogger, a Garmin handheld GPS unit and a digital camera (Figure 42). It is possible for one person to use the kit, as the Logbook and GPS unit do not need any attention when the logging has started, though it is more suitable for work in small groups (in the school setting this is beneficial as pupils often have to share equipment).

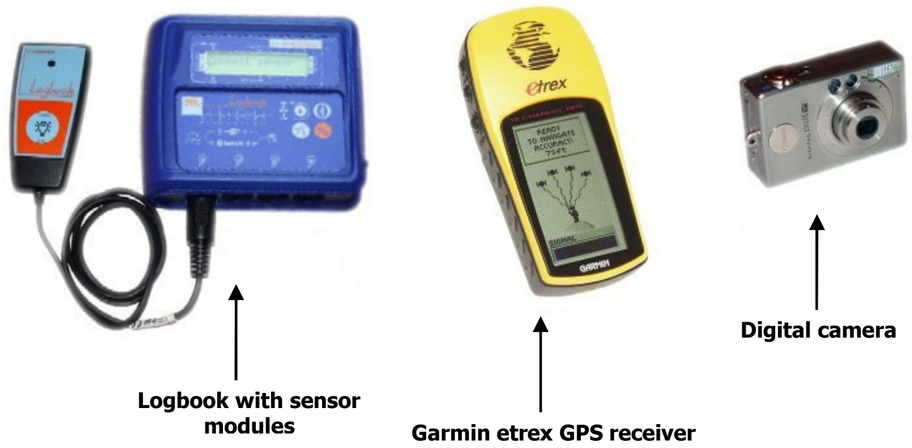


Figure 42: JData3D datalogging equipment

As opposed to the phone application, rather than consolidate the data into one file during the capture process, individual data files are stored on each unit and consolidated at the end of the capture session. The JData3D application downloads the information, synchronises it and generates a KML file for Google Earth on the PC (Figure 43). The digital photos are included as placemarks (points of interest) in the resulting "KMZ" data file (a single compressed archive folder containing KML data and the photograph files).

Data is synchronised to the time data reported by the GPS unit – this time is globally regulated by the GPS satellite system, meaning separate data files may be compared against each other with accurate timing. When retrieving the stored readings JData3D also reads the internal time from both the GPS and Logbook. The time difference between these devices is calculated using the PC system time, allowing the data across the files to be accurately synchronised. It is not possible to read the time directly from the camera, so to synchronise the photos the user must take a reference picture at the same moment the GPS log is reset (at the start of a data collecting session). This method allows time difference to be calculated based on the photograph's created time and the start of the GPS track log (the route information stored in the Garmin GPS). An alternative method allows the time difference to be set manually by reporting the current camera time into JData3D when the photo files are added.

Whilst the GPS data and the sensor readings can be automatically synchronised, the emphasis is placed on the user to take the correct steps to allow photos to be accurately incorporated into the visualisation. Figure 44 shows the JData3D interface used for downloading the data and creating the KMZ files.

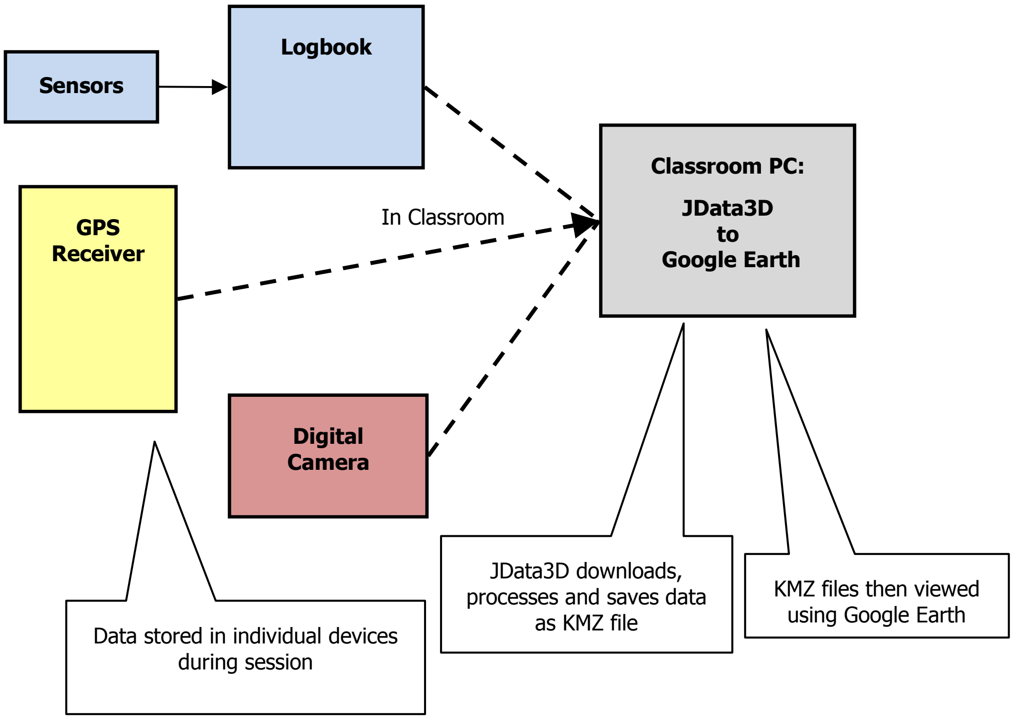


Figure 43: JData3D datalogging process using Logbook, Garmin GPS unit and digital camera

With the new JData3D system, the 3D visualisation is also improved over the files in the initial trials. They not only include photographs, but also individual points of interest with each reading and a timeline showing the readings and route appearing in the order they were taken. Another feature of the JData3D visualisation files is the inclusion of "calibration lines" which act as gridlines, indicating the altitude of various reading levels. Figure 45 shows a labelled diagram of this new format, with examples of placemark information given in Figure 46 showing the details of photos and readings that appear when their corresponding placemarks are clicked.

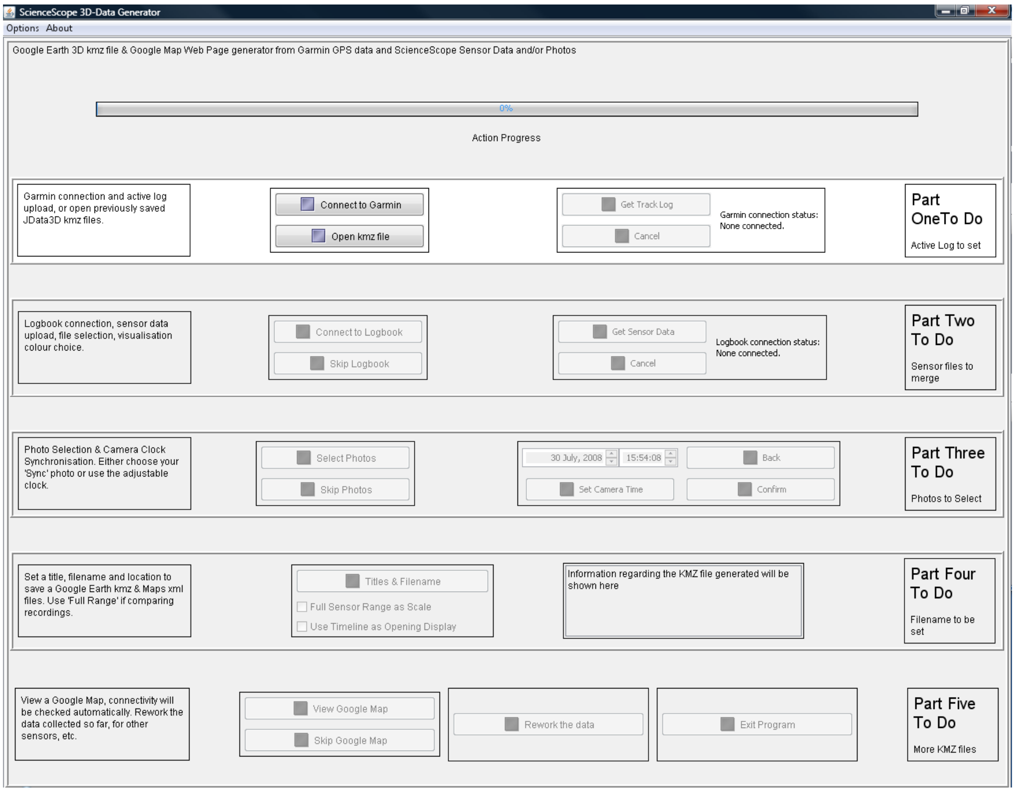


Figure 44: Screenshot of JData3D main window

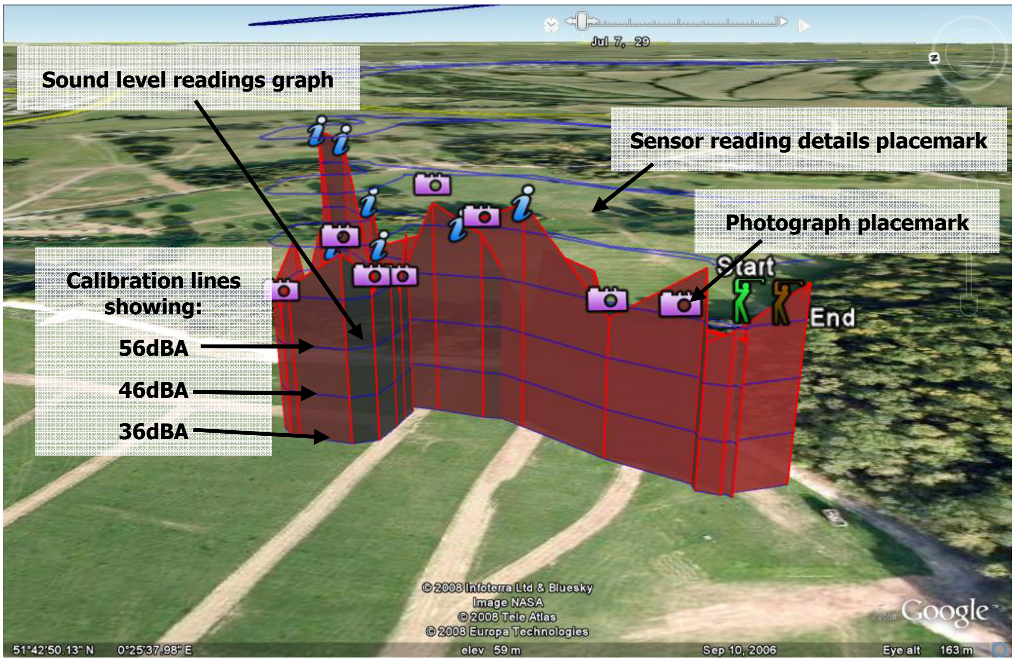


Figure 45: Example of JData3D visualisation

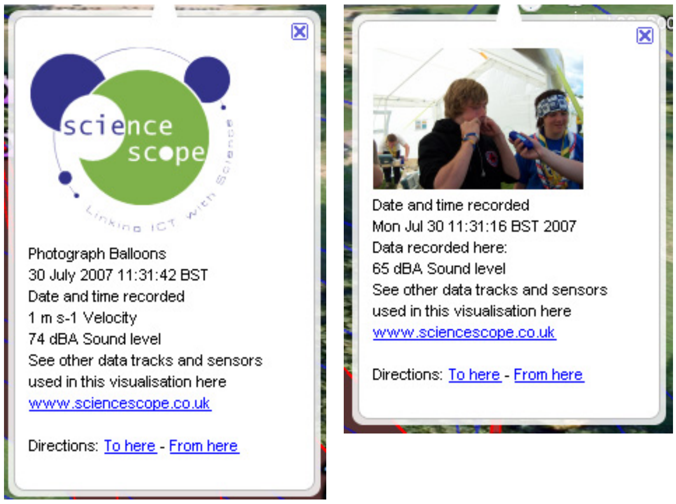


Figure 46: Example information balloons for a reading (left) and a photograph (right)

The JData3D system was used throughout the remaining schools trial in the Participate project and forms part of the school related activities throughout the rest of the project. The datalogging and visualisation toolkit is the system used for the study in the rest of this chapter, providing a system to look at the use of an automatic, mobile sensor (the Logbook) combined with a manual sensor (the camera).

4.3 World Scout Jamboree Study

The first part of this chapter introduced the Participate project and the JData3D datalogging toolkit developed as part of it. It described the development process behind the toolkit, focussing on the Participate schools activities and the earlier versions that fed in to the design. The JData3D system was used as the basis for the second study presented in this thesis, taking place at the 21st World Scout Jamboree, in 2007. The rest of the chapter will describe the study, first giving some background information about the event at which it took place, then explaining the activities that were conducted. As with the previous chapter, the analysis of the study will describe the observations made and give some examples, these are reviewed and the implications considered at the end of the chapter.

4.3.1 Background

The 21st World Scout Jamboree took place between the 27th July and 8th August in 2007. It is a large camping event, with 28,000 scouts and 12,000 adults from all over the world taking part over a 12-day period. World Jamborees take place every 4 years, hosted by a different country each time – previous Jamborees have been in Thailand, Chile and the Netherlands. The 2007 event took place in Hylands Park in Chelmsford celebrating 100 years of Scouting and providing the setting for this study to take place.

Scouts taking part ranged from 14 to 17 years of age, male and female and from over 150 different countries, staying in tents grouped into small ‘villages’ called sub-camps. They participated in a combination of pre-arranged and 'walk-in' activities throughout the event, ranging from adventurous activities like sailing and climbing to arts and crafts. In keeping with the scouting ethos, throughout the Jamboree activities are based on themes of global awareness, changes to the environment and activism. This provided an ideal opportunity for a study to build on the work resulting from the SENSE project, using another sensing system to collect and examine environmental data.

Most of the activities are grouped into specific areas that jamboree participants visit in half-day sessions. Figure 47 shows a plan of the site, the activity areas marked in light blue and camping areas in red, green, yellow and dark blue. One of these areas, called *Elements*, featured science activities grouped around four themes, earth, water, fire and wind. Each of the zones contained many activities set up with a marketplace approach, this meant that participants were free to choose which activity to take part in during their allocated time. Participants visited the zones in large groups of between 100 and 150 and formed small sub groups of friends up to around 10 people whilst they moved around the activities. Running one of these activities allowed the study to engage with a range of these participants, working in groups to conduct a sensing activity.

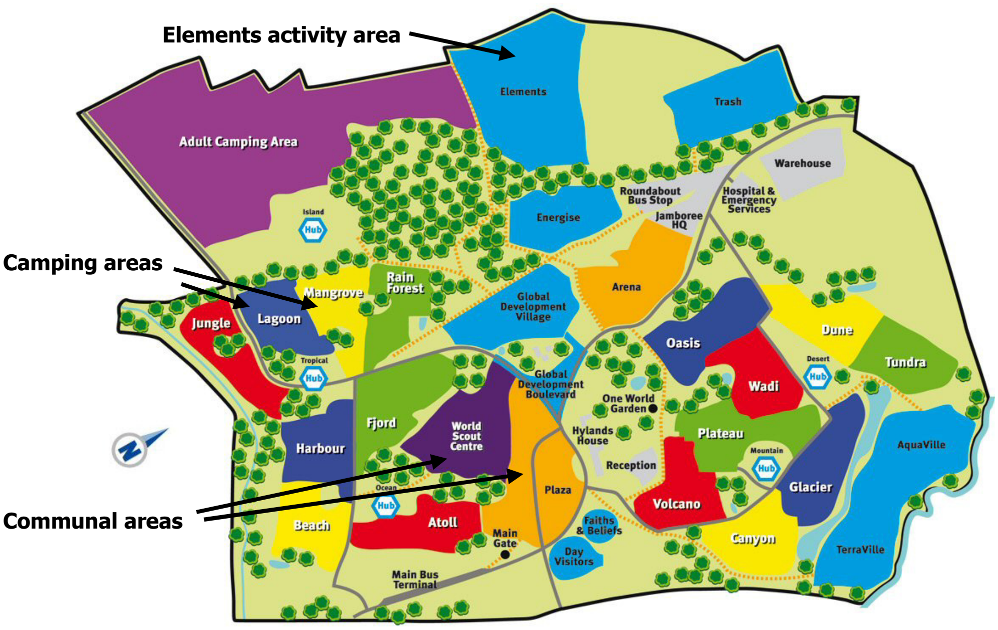


Figure 47: World Scout Jamboree site plan, Hylands Park near Chelmsford

The practical work took place in the wind zone of the Elements area, where an activity was set up to record sound levels around the elements area with the JData3D toolkit. When a group of participants had collected their data it was displayed on a large projection screen on which they could view their graph. A Nintendo 'WiiMote' handheld controller was used in place of the mouse, providing a wireless movement sensitive input device that could be passed around the group.

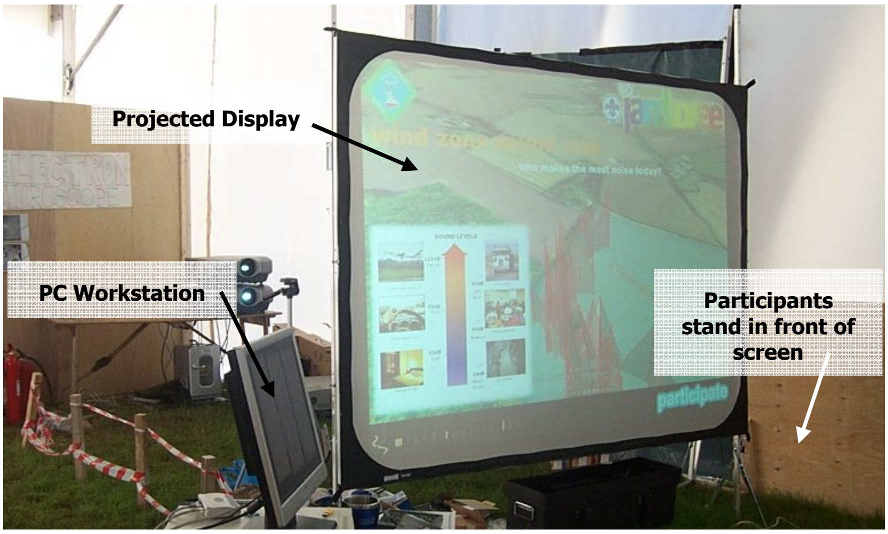


Figure 48: Projector screen setup for the activity in the 'elements' wind zone at the Jamboree

4.3.2 Study Activities

As in the previous chapter, this study is based on observations of a group of young people in an educational setting. They are collecting environmental data, though in this case sound levels rather than Carbon Monoxide, and annotating their readings with the addition of photographs at particular points. The data they collect is mapped using a GPS unit and viewed shortly after the end of the session on a large screen using a wireless controller.

In this study, the GPS unit provides location data, compared with SENSE where location was determined through the video footage. The photos provide additional contextual information instead of video and notes used in SENSE, though the taking of a photo provides a similar reporting purpose of tying contextual information to a moment in time. Sound level readings are much easier to locate and observe than Carbon Monoxide (which is undetectable without specialist sensors) as not only can people hear it but also it is a lot easier to predict the sources of and create on demand.

Again, the activity took place in three stages, an initial briefing, followed by data collection and a review of the data using a visualisation tool. This was supplemented by observations made when groups and individuals watched others taking part while they decided what activity to join or waited for their own turn.

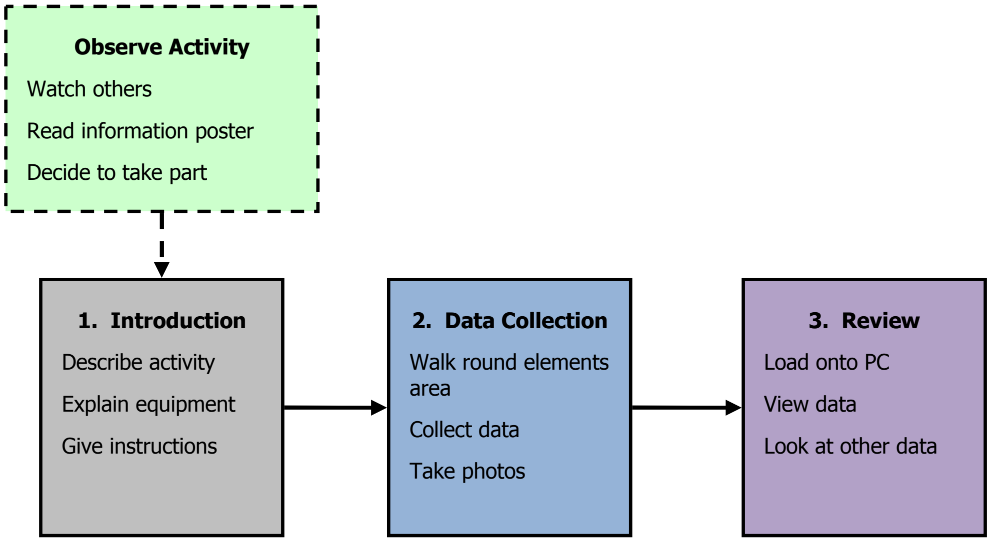


Figure 49: Jamboree study activity process

4.3.2.1 Introduction

Due to the ‘walk-in’ nature of the activities, the initial briefing was very concise, lasting about two minutes, so allowing participants to get on quickly with the main part of activity. The introduction explained the overall objective – to create a map of the sound levels throughout the activity zone during each day. The equipment was introduced and what they needed to do with it was explained, particularly mentioning that they should keep the GPS and Logbook close together for as accurate position information as possible. They were given a time span of about 10-20 minutes within which to search for and record the noisiest places and activities they could find. After this they could come back and view the data on the large screen, and compare it with other readings made during the Jamboree.

The briefing was supported by the observations made by people deciding to take part as they could watch others who were reviewing their data, or were out collecting readings around the zone. When the screen was not being used to view data, a ‘poster backdrop’ was shown, providing additional supporting material (as can be seen in the activity setup in Figure 48).

4.3.2.2 Data Collection

The groups of participants collected the sound level readings using the JData3D kit as described above. The devices were handed to members of the group so that one person took the camera, one the GPS, and one the Logbook. As they took their readings, a helper from the Jamboree’s International Service Team (volunteer Scout leaders) supervised the group. They ensured that the scouts returned within an appropriate timescale and did not wander out of the activity zone. The IST helpers, and on occasion individual members of the group, also helped collect data for the analysis, taking a video camera and recording the session.

4.3.2.3 Reviewing Data

During the final stage of the activity, the members of the group were invited to view their data on the screen and compare it with data from other sessions. The process of copying the data to the PC and loading the graph up took about three to four minutes and was accompanied by an explanation, which helped keep the participants involved whilst they waited to see their results.

The graph display on Google Earth overlaid the readings and photos on to the aerial images of Hylands Park. The Jamboree campsite was specifically constructed shortly before the event, this meant that none of the temporary structures (tents, stages, trackways, etc) appeared in the corresponding aerial images, showing empty fields instead. In order to provide a more accurate representation the map of the campsite (as seen in Figure 47) was added to the view as a translucent overlay. This allowed the participants to readily identify where they had been in relation to the boundaries of the elements area, as well as understand their location in respect to the entire site. Figure 50 shows the site map added to Google Earth, the layer transparency setting allowing the aerial photos to show though the graphics, resulting in a combined representation of the Jamboree site. When the data was added they could then view their graph in situ, with reference points from the map, Google imagery and their own photos – see Figure 51 for an example.

Figure 50: Jamboree site map as an image overlay on Google Earth

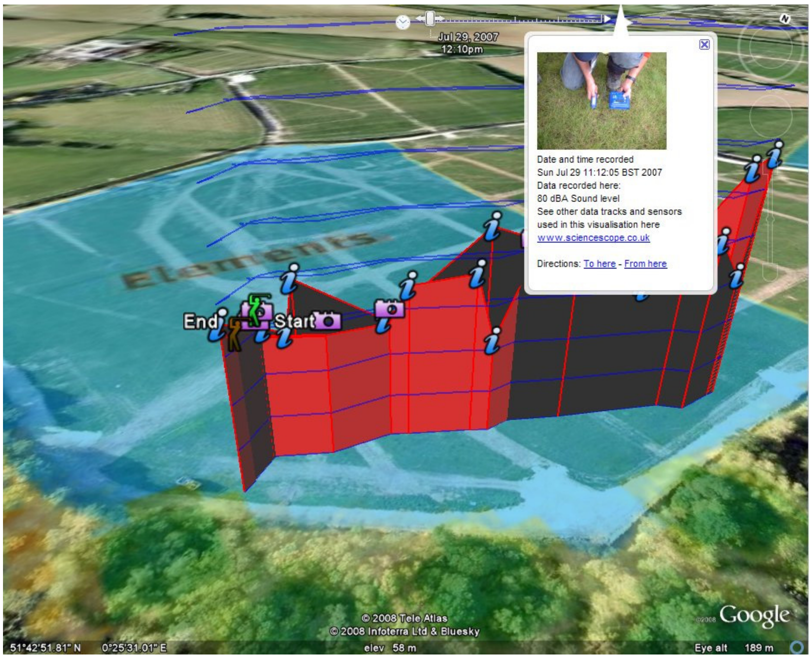


Figure 51: Example of data visualisation as seen by participants

A Nintendo WiiMote wireless controller connected to the PC using a USB Bluetooth adapter allowed the participants to move the map around and look at the data that they had collected. This was achieved using a freely available program called 'GlovePIE' (Kenner, 2007) which allows movement and button presses on the controller to be mapped to keyboard and mouse movement on the PC. A script was written mapping the movements and buttons to Google Earth keyboard commands as shown in Figure 52. Movements were mapped to controls changing the view location and direction. The direction pad and 'A' button were mapped to mouse buttons, allowing the user to click on the placemarks and see their photos and readings.

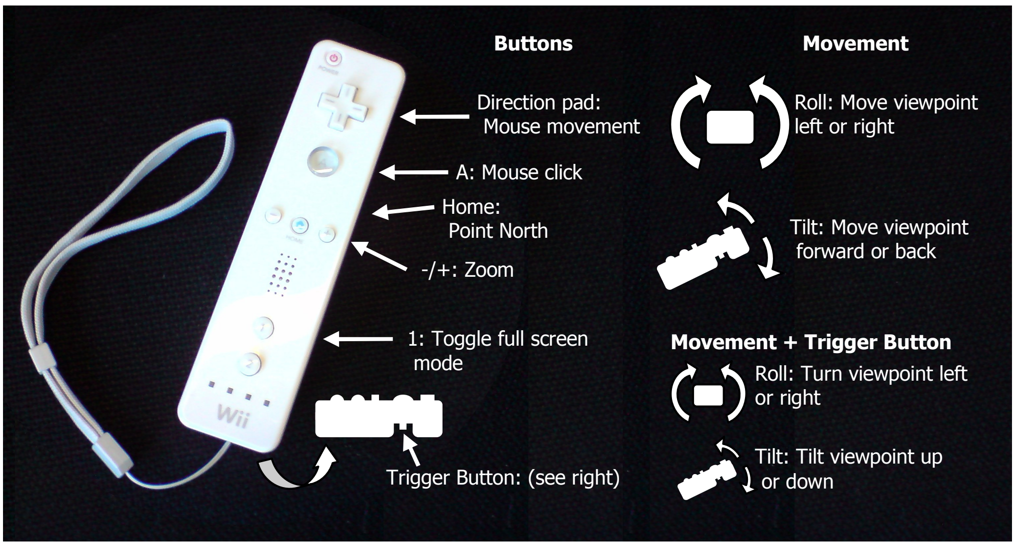


Figure 52: Nintendo WiiMote controller mappings to Google Earth

4.3.3 Methodology

Taking the same in-the-wild approach as the previous study of the SENSE project, the study of the Jamboree activity was based on naturalistic observation. As referenced in Section 3.3.1, the analysis continued the data-driven approach informed by grounded theory and participant observation methods. The observations made during the activities were complemented by specifically recorded video footage taken during the event and the data logs created by the participants.

The study builds on and extends the experiences with SENSE, continuing to explore the ongoing dialogue between humans and sensors. The focus of the observations was to document how participants used the sensors to collect data and worked with them through the activity, both when the sound sensor and the GPS recorded information automatically and when participants specifically captured the details of sound sources they encountered. A key feature of this was how photos were used to record contextual data in combination with marking notable moments during the fieldwork session.

Direct observations were made whist conducting the activity as described above – briefing the participants on the tasks, providing them with the equipment and preparing and demonstrating the visualisations. To back this up and provide additional data video footage was collected from the activity table (the beginning and end of each session) and from around the site during the activity. Jamboree participants or volunteer site crew collected the video footage of the activities around the site, using a camera equipped with a radio microphone attached to the Logbook. This setup allowed the discussions between the members of the group and noises near the sound sensor to be recorded.

As with the SENSE study, the data recorded by the participants was used in addition to the video footage. Many groups took part in the activity over the course of the Jamboree and though it was not possible to record video footage of them, all the data files were available. This provided an additional set of information to study, showing the route taken by the participants, the photographs taken during the session and the sound level readings throughout.

The data files provided a broad view of participants' activities across all the sessions that took place allowing overall features of the activities to be observed. The video footage, synchronised with the data files provided a detailed record of individual sessions, though it was limited in its coverage of participants, provided an opportunity to review and document particular interactions and to closely inspect some features identified from the full set of data files.

The first step in analysing the data comprised of viewing the recorded video, synchronising tapes from two or three different cameras as well as identifying the data files related to the participants seen. The full set of data logs were also reviewed in Google Earth, sorting them into chronological order in order to build up a sense of individual features and general patterns in the data recorded. Each set of video data was then reviewed in more detail alongside the data recordings they made, this involved viewing the video and switching between playback and inspecting the timeline in Google Earth. As with the previous study, the ways in which the participants worked with the sensors and recorded data were noted and correlated with the more general impressions gained from looking at the full series of data files. Individual sequences were identified and transcribed, along with sections of the data file, in order to document the observations.

4.3.4 Data Sources

The data collected during the activities consisted of 58 individual Google Earth visualisation files, recording sessions of an average of 9 minutes and 23 seconds (with a standard deviation of 4m 57s). This provided a total of 9 hours and 4 minutes of sound level logs to view. The jamboree was an international event so many of the participants did not speak to each other in English during their activities, as it was not possible to translate those sessions the video analysis concentrates on English speaking groups, three videos were used for this which provided 41 minutes of video footage.

4.4 Observations

This section presents the main observations and looks into some of the things that influenced the activities. This forms the basis for the discussion and general conclusions in the final section.

The first excerpt (Sequence 6) shows an example of the way the groups approached the collection of readings and taking photos alongside them. As with the experiences with the CO sensors in SENSE, when taking sound level readings with the Logbook sensor the participants moved between episodes of focussed data collection, collecting readings around an individual event or point of interest and then continuing along their way paying little attention to the use of the automatic sensors. In the example shown, the groups come across an activity involving a signal generator and speaker that they can hear being used to generate tones of different frequencies. They first try to find the source of the sound then home in on it, holding the sensor in front of it for a number of seconds whilst they read out the readings and take a picture. The picture then matches up with the high point in the sensor readings, as shown in Figure 53 and Figure 54.

Sequence 6

A has Logbook, B has camera, C has GPS. On approaching the activity they hear the noise coming from the equipment, A addresses the activity demonstrator. **[IMAGE 1]**

A: "Where's the sound coming from? Where's the speaker?"

The demonstrator shows them the controls for the sound source.

A: "It's high pitch, but it's not registering any decibels...not particularly high."

B: "Where's it coming from?"

They search the equipment on the desk to locate the sound source. **[IMAGE 2]**

C: "...it's coming out of here!"

A Points sensor at the speaker as B adjusts the controls, increasing the frequency. **[IMAGE 3]**

A: "Now it's going into ultrasound!"

B turns frequency control again, reducing the frequency this time.

A: "85, I've got a very good pitch. 85's the highest..87.2.. 90.6..keep going. I've got 90.6, the highest so far."

B takes the picture as shown in Figure 53 and Figure 54.

C: "Cool, that's all right, we leave it"

Figure 53: Sensor reading with photo annotation

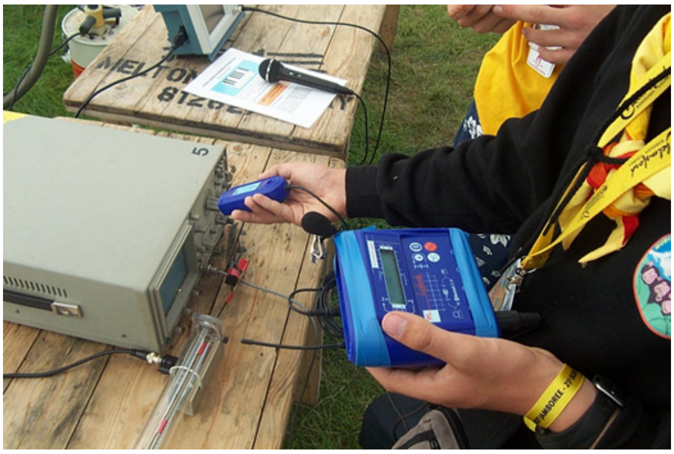
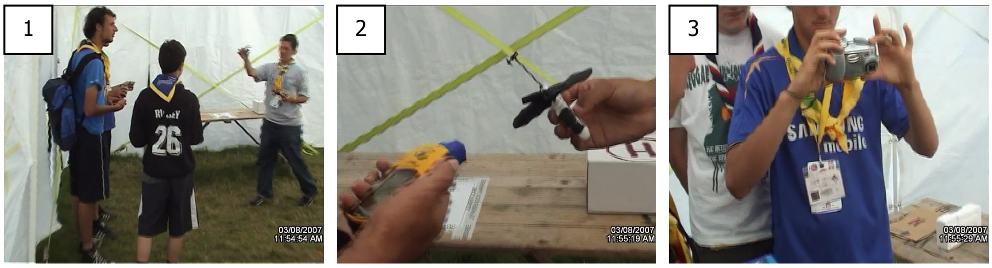


Figure 54: Image of tone generator from Figure 53

This kind of activity occurred throughout the video footage however, the results did not always represent what the participants were trying to record as successfully. Sequence 7 alongside Figure 55 and Figure 56 illustrate where a group of participants try to mark a high reading with a photograph but, despite careful attention, they did not manage to match the peak reading with the photograph. In the example, the group find an activity with a small model helicopter from which they take sound readings. A member of the group reads out the sound levels in excess of 80dBA as the helicopter runs. These do not translate will in the visualisation, where the levels are well below this. The reading when the photo is taken at only 61dBA with a peak of 69dB occurring nearby.

Sequence 7



A carries the sound sensor, B the GPS tracker and C operates the camera. The group enter a tent where a small model helicopter being demonstrated and approach the demonstrator.

A: "Can you just hold it whilst I take a sound reading?"

The helicopter is held in front of sensor briefly **[IMAGE 1]**, the demonstrator lets go and it flies away.

A: "We almost reached 80."

B: "You don't need to let it fly."

Helicopter is held by sensor again **[IMAGE 2]**

A: "81.8...82.1...83.8... and that's about it, thank you."

C reviews the picture (Figure 56) he has just taken. **[IMAGE 3]**

C: "Thankyou"

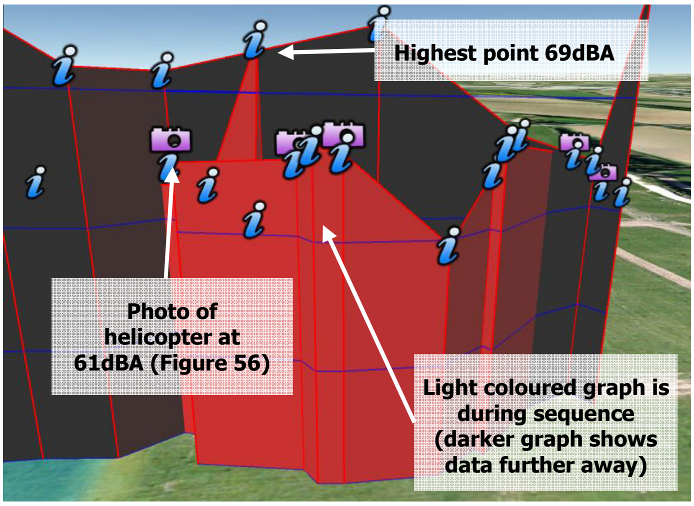


Figure 55: Example of sound levels on map different to sensor readout

Figure 56: Photo of helicopter shown in visualisation

In order to add a photo to the graph, the picture must be taken whilst the desired reading is shown on the datalogger. This obviously requires some co-ordination between the person holding the Logbook and the person with the camera, so it is expected that the photos may be a few seconds before or after the best moment. The visualisation should account for this to some extent, as the readings are linked to the physical location – the design of the graph ensures that they will be at least close to the high point if not right at the peak. This introduced some problems however, as participants were seen to take a number of photographs at the same location in quick succession, using a series of photos to narrate readings. Sequence 8 shows an example of this highlighting the problems participants encountered. In this example, they spot a fan in one of the tents, they switch it on and run through the speed settings on the fan, recording the noise level as they go. As the participants go through the fan settings they take a picture at each point, creating a series of images illustrating the increasing sound levels as the fan speeds up, as shown in Figure 58.

While their intention was to create this series of images, this was not well represented in the visualisation. In order to prevent the graph becoming overloaded the JData3D application reduces the resolution of the data, dropping images close together in time and location. In this case it displayed only a single image in the series (Figure 58, image F), missing off the previous photos taken by the participants and showing only the last image alongside the lowest reading. In the earlier example, a similar process also explains how the 80dBA reading seen by the person holding the sensor was not shown on the map, where the momentary high peak was smoothed out to 69bBA following a series of readings in one location.

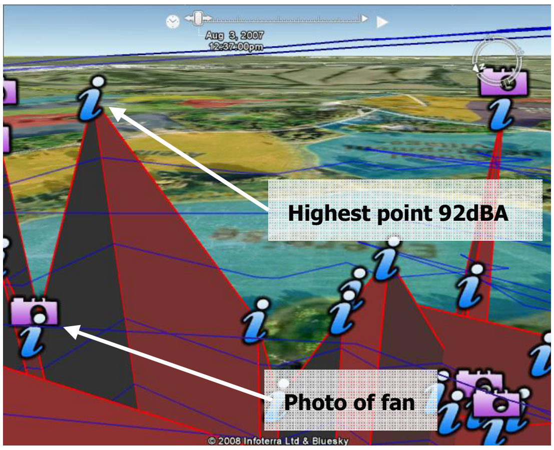


Figure 57: Multiple nearby photos not displayed

Sequence 8

A has Logbook, B has camera, C has GPS. They approach the next activity tent. **[IMAGE 1]**

A: "Err, what about here, what's this... this is energy efficiency... so unless this television explodes I don't think there'll be any loud noises."

The group walk into the tent and see the other equipment inside.

B: "We could turn that fan on..." (to person in the tent) "Can we turn the fan on?"

The group walk over to the table with the fan. [IMAGE 2]

C: "It's not plugged in."

A: "It's not plugged in."

A and B pick up plugs from the desk next to the fan.

A: "It's the white one."

C points to the white plug, then look at the GPS unit. B has the correct power cable, so puts the plug into the socket nearby.

C: "So what do I do with this then?"

A: "You just turn it on."

C switches the fan on to the lowest speed setting, then looks back to the GPS.

B: "Wait to see if we've got anything first."

A: "Oh, yes… definitely, 88..."

B switches the fan to the highest speed setting

A: "..91.7..."

B: "Let's go from 0, then we go 1, 2, 3, 4 up."

B takes photos, Figure 58A, B **[IMAGE 3]**

A: "Ok, step one – level 1... 80.8, 83. Ok, 83's the highest we've got."

B takes photos, Figure 58C, D

B: "Two"

B takes another photo: Figure 58E

A: "Two, immediate increase, 86.9, 87"

B: "And three"

B takes another photo: Figure 58F

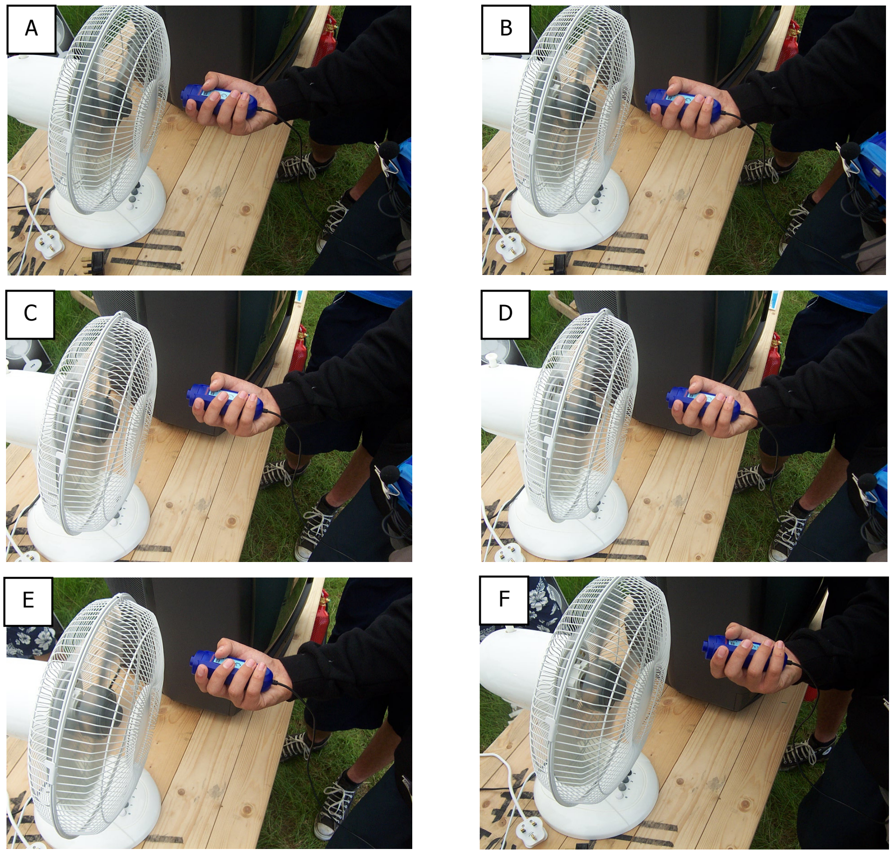


Figure 58: Series of images of fan taken by participants, only image F appears in visualisation

In other examples, high sound level readings were shown on the visualisation, but participants did not attempt to mark them in any way, and conversely, they focussed on events and activities that did not produce high readings. Figure 59 shows a group who record some high readings as they visit three different tents, however they did not focus on this high readings instead concentrating on a piece of equipment in one of the tents.

The video frames included show what the participants were doing at the corresponding positions on the map as they moved down the field from point 1 to point 3. The readings indicate the sound level moving up and down as they pass a noisy group of people and approach noisy electrical generator. Rather than follow up on those things, the participants take readings in a tent with a tone generator in it, which registers a lower sound level reading.

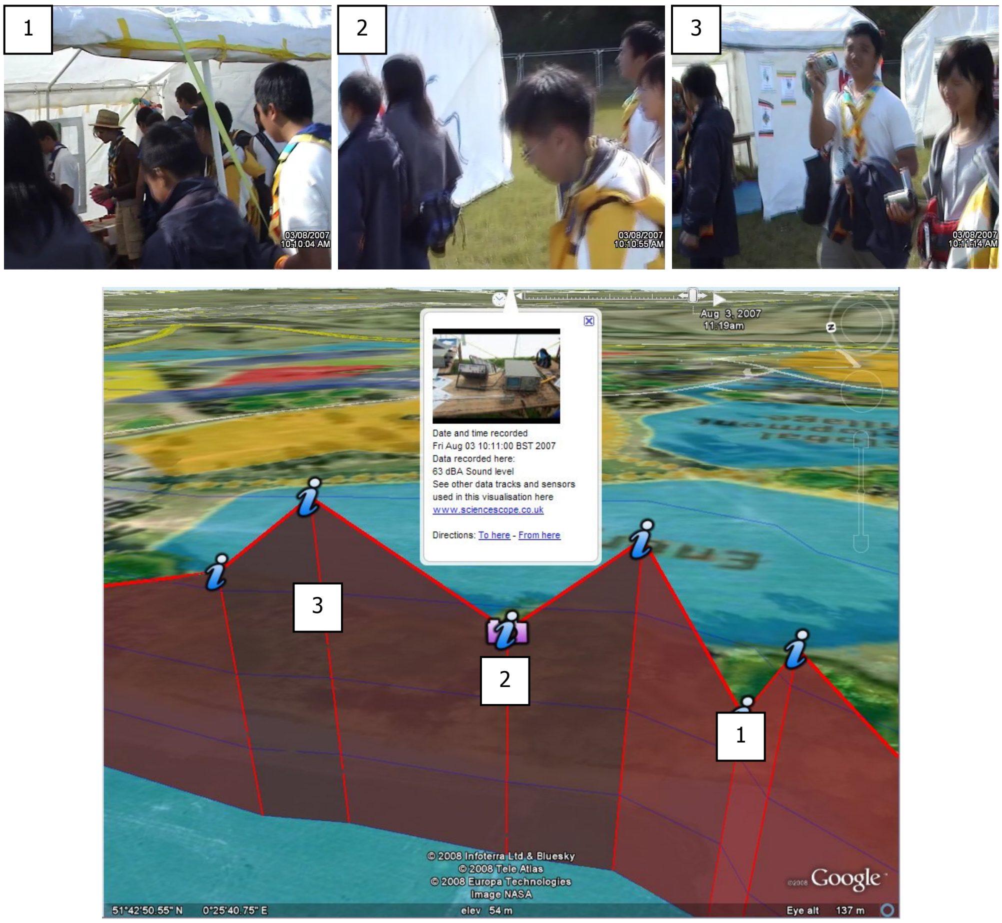


Figure 59: Participants taking readings at lower sound levels

These observations show participants did not always succeed in taking photos alongside high readings or indeed aim to do so on all occasions. As mentioned above, photos were occasionally dropped from the visualisation files, so this potentially clouds this assessment when looking for photos linked to high readings. Looking at the complete set of photo files that were taken using images stored directly from the cameras provided another means to judge this, giving an impression of the range of pictures taken – whether they were showing events that created sound or for other reasons. Having reviewed these images, noting what they were showing let to three main groupings, with roughly equal numbers:

- Photos of activities / things they were recording (Figure 60)
- General scenery – the activity area, etc with no specific focus (Figure 61)
- Photos of themselves, friends or other people they met (Figure 62)

The first group showed participants taking pictures of things they were recording. Comprising only of a third of the total this highlighted that photos were taken for other reasons and not exclusively related to taking measurements.

The other photos were more generally associated with casual photography, taking pictures of the scenery and people they met. These extra photos provided additional context to use alongside the sound level readings, for example showing views of the activity area, how busy it was and who was involved.

Figure 60: Photos participants took to illustrate readings

Figure 61: Photos taken showing the activity area

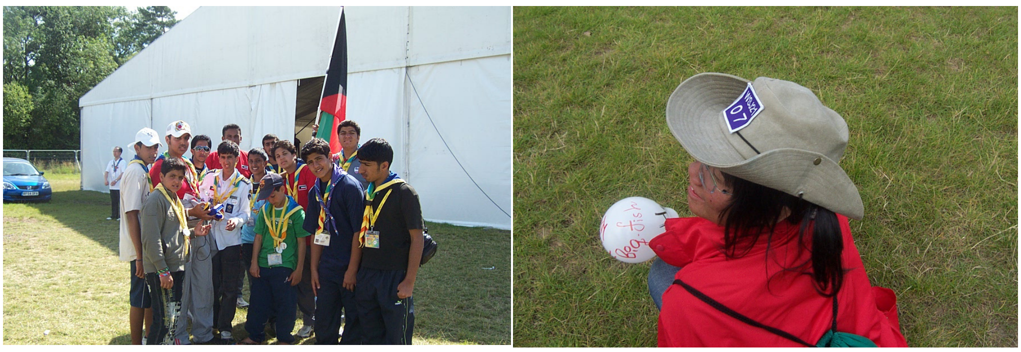


Figure 62: Photos showing friends and other people encountered during the sessions.

4.5 Discussion

In some respects, the observations mirrored those from the previous study, as with the activities in SENSE the participants had focussed periods of data collection along with a background of automatic readings. The participants used the photos to mark points of interest, but also used the photos to collect contextual data and illustrate the process of taking readings in some situations. Along the way they encountered some difficulties in their tasks, in linking the sensor readings up to the photos and also in linking the photos to what information they were trying to capture. Below, the observations are discussed in relation to three key points: episodic data collection, difficulties with equipment and visualisation, and combining automatic sensor data with photos.

4.5.1 Episodic Data Collection

Participants focussed their efforts on recording details of specific points of interest around the activity area, when they did so they took pictures to highlight points, providing contextual information and implicitly marking that location in the resulting visualisation. In between these episodes, the participants did not pay close attention to their use of the sound level logger or to the GPS, resulting in more noisy readings. Between groups techniques also varied, for example whether they held the sensor module at arm's length or near to them when they were walking around. This contributed to variances in the readings that make it difficult to compare sessions like for like. This echoes the observations from SENSE, the additional annotations proving useful again in providing information about how readings were made, though the periodic photographs did not illustrate as clearly as the video recordings in the SENSE experiments.

In SENSE it was seen how episodes focussed on events, sensor readings or aspects of the equipment (testing it, familiarisation, etc). In this study, episodes primarily focussed on events rather than sensor readings, and the degree to which test data was captured was limited as participants could delete photos from the camera as they went along. Events also tended to be set up by the participants, rather than capturing something in the vicinity as it unfolded, such as in Sequence 7 for example, participants asked someone to hold up a helicopter for them to record, compared with recording a lorry passing in the previous chapter's examples.

Unlike SENSE, contextual data consisted of GPS location and photos, the photos especially were important in establishing the focus of an episode. GPS data separated events from one another (as participants moved from one location to another through the activity), but the photos both marked a point of interest and provided some narrative details – in SENSE marker points, notes and video were recorded separately. Along with the unanticipated ways in which the sensors worked, this introduced difficulties when participants tried to link sensor readings to their experiences. Both these aspects are discussed in the next two sections.

4.5.2 Difficulties with Equipment and Visualisation

The observations showed that participants had difficulty synchronising their photos with high readings shown in the visualisation. Whereas in SENSE the observations focussed on how the participants identified points of interest in their surroundings and the CO readings, in this study they were more linked to features of the sensors themselves. Though attention to the sensor and understanding the readings still plays a part, these other contributory factors highlight further aspects of the dialogue between the user and the sensors.

In the sound mapping activity, the groups were recording details of sound sources; this reduced the amount of attention participants had to pay to the sensor display to gauge the level of nearby noise. They could hear and home in on sound sources or anticipate noisy activities, rather than with CO readings where participants had to watch the sensor readings or hypothesise about where levels may be higher. What became more apparent was the effect of the users' understanding of how the sensors and the resulting visualisation worked. Two characteristics of the sound sensor and software in particular contributed to how the annotations did not always match up with what they thought they would get:

- Averaging of sensor reading for storage, as opposed to the instantaneous readings displayed on the screen.
- Multiple photos in the same space and close together in time were discarded in the visualisation.

These issues extend the discussion raised in Chapter 3 where an understanding of what is being sensed and the significance of the readings was mentioned. Understanding how the sensor works and how readings are going to be represented adds an additional perspective relating to the equipment, as well understanding the sensed phenomenon. Not only do problems occur from an incomplete understanding of what is to be measured (CO, sound, etc) but also from the way this is translated into data by the sensor system. Sequence 7, Figure 55 and Figure 56 show how the design of the sensing system leads the users to think high readings have been recorded, but they do not appear in the subsequent graph. Sequence 8, Figure 57 and Figure 58 show how data logged by the participants is not shown in the way they expect, resulting in the photos and the sound level peak not occurring in the same place.

The observations show the importance of carefully considering this aspect of the dialogue. Understanding the mechanics of the sensors and the resulting visualisation provides additional motivation to concentrate on the feedback given by the sensor, showing how its design can lend itself to users developing a useful understanding, or not.

4.5.3 Combining Automatic Sensor Data with Photos

The design and features of the sensors were not the only cause of issues when synchronising or correlating the sound level readings and photos. The observations revealed how participants took a number of photos that linked together to describe a single event, or series of related readings. It was also seen that a large proportion of photos that were taken did not obviously feature noise related incidents, concentrating on other things such as people the groups met, or general background shots showing the activity area. Where they encountered issues revealed how the combination of automatic and manual sensors affected the activity; the data was linked together by the GPS logger, using location (and to a minor extent, time) as a means to link and set apart the other readings. The photos were used to illustrate points in the data and to manually mark a location and point in time. This is where problems arose as the sound readings of interest did not always coincide, for example illustrative photos were posed before and after readings of interest, showing the event more clearly, but not at the exact moment required. The previously mentioned resolution issues also played a part but, on a more fundamental level, in can be seen how co-located events were difficult to distinguish. The data was handled in a location-centric way, so similarly, linked elements in the same place, such as a series of photos and readings (e.g. measuring the different speeds of the fan) were difficult to deal with.

Taking photos was not purely intended to mark high readings as was noted a large proportion of photos were taken that weren’t explicitly linked to noise events. In those situations the sensing system failed to register the intent of the interaction in establishing what, if any, relationship the photos had to the sound readings. Whether this relies on the user to be more selective or wiser in their choice of material, or the sensor system needs to be better matched to the way the users work, this highlights another way in which the dialogue between users and sensors takes place. It shows aspects relating to automatic and manual sensors and to sensing taking place in fixed locations compared to constantly moving sensors, returning back to the axes of sensor automation and mobility in Chapter 2.

4.5.4 Summary

This study provided a second opportunity to look at the human-sensor dialogue taking place in a participatory sensing experience. The observations have built on some of the earlier ideas and highlighted new aspects to this dialogue, reinforcing the idea of episodes introduced in the previous chapter. Further aspects of the dialogue were drawn out by the design of the sensing activity and the equipment, the differences in the design highlighting areas that were not as obvious in SENSE.

First were problems introduced by the sensors and visualisation design, where details were lost as the resolution was reduced. This exposed the effect of discrepancies between the users' understanding of an item to be measured and the process of capturing it – how the sensor works. Some misleading or unclear features of the sensor system resulted in problems matching the participants' photos to the relevant sound readings.

The second aspect came about from looking at the way participants used the photos to report information and link contextual data to the ongoing readings. The photos marked a moment in time and position, and added explanatory details, however these aspects were ill suited to be taken together, denying participants the opportunity to carefully compose photos as well as mark the time and location precisely. This led into more issues in linking both individual sound readings and photos as well as a series of sound readings and photos across time or in the same location. Further issues were seen in linking the photos that were not explicitly related to the sound level readings. Whilst the above issues related to linking the data over time, this related to linking the intent of the photos to the data, hinting more at the level of detail needed to be expressed rather than in tying the various items together as such.

A key point that was established was that with combinations of automatically and manually reported data it must be easier to match up significant readings with observations and annotations, both to allow sharing between individuals and to improve the ability for computer systems to process it. This returns to an issue identified earlier, the negotiation between collecting human interpretable information and machine interpretable data. Two approaches present themselves in this process; first, providing improved automatic and technical means to allow sensing systems to understand the information better in the forms it is naturally provided. Alternatively, by enabling and encouraging the users to work within the limits of existing sensors, providing input that is more readily understood by the devices. In pursuing both these approaches an understanding of the dialogue between the sensors and their users plays an important role.

This study and the previous work with SENSE have provided an insight into this dialogue using real-world examples to reveal the factors involved and identify new approaches in forming this dialogue. The next chapter will draw on this to develop a framework for human-sensor dialogue in participatory sensing systems, a framework that can be used to describe and analyse these aspects of the dialogue and be used to shape this dialogue in the design of new participatory sensing experiences.

5 Framework for Human-Sensor Dialogue

5.1 Introduction

The thesis began by introducing participatory sensing and its background in pervasive computing and sensor based interaction. A range of research was shown that identified and focussed on issues associated with sensor based interaction; this highlighted issues that are relevant to a wider audience over and above the field of participatory sensing. In seeking ways to address these challenges, authors tended to focus on aspects such as feedback, control, notice, and affordances: each aspects of the ongoing interaction between users and sensors. This was referred to earlier as the dialogue between the users and sensors, choosing the term 'dialogue' to reflect a wider meaning, encompassing the affordances and ongoing relationships between sensors and users that are created in these applications – not simply the explicit two-way communication that takes place in order to accomplish a task. This moved on to look specifically at examples of sensor based applications in ubiquitous computing, highlighting the range and combinations of automatic and manual sensors in use, as well as fixed and mobile sensors. This provided the basis for two studies that took place, concentrating on sensor based applications with combinations of these sensor types. These studies aimed to observe and document aspects of the human-sensor dialogue taking place, concentrating on how the participants worked with the devices, using them to collect and interpret environmental data.

The initial investigation based on the SENSE project looked at the use of mobile sensors employing a combination of automatic and manual methods to collect information about Carbon Monoxide air pollution. The study described how users structured their data collection process into a series of episodes, combining reporting of contextual data and marking automatic readings at various points of interest. This began to identify some of the factors in the dialogue between the users and the sensors. It was also seen that the participants' understanding of Carbon Monoxide and their attention to, and interpretation of events and the sensor readings affected the data collection process. The subsequent study of the activities at the World Scout Jamboree extended the insights gained from SENSE, further exploring key aspects of human-sensor dialogue by using a new experience to look in more detail at the factors that affected the data collection process. In particular this study highlighted some of the ways that participants linked multiple items of data together and difficulties they encountered.

The studies observed aspects of the human-sensor dialogue that worked well and facilitated the collection of meaningful data. In those cases participants were able to accurately document what they aimed to capture, and to capture sufficient detail to help others to interpret it. They also highlighted areas where the things did not go so well; where there were difficulties in collecting and interpreting the resulting data – it was not recorded as intended, or it was not possible to capture necessary details. In considering these experiences, the complexity of the dialogue became apparent as various needs and tradeoffs were negotiated. These factors involved a range of elements right through the design of the experiences including the individual implementation of the sensing tools, as highlighted in the Jamboree study. This included the ways participants linked manual and automatic sensor readings to events or to each other, as seen in both studies, and similarly the overall format of an activity: for example switching between episodes and 'background' readings, or review periods. Again referring back to Chapter 2, the sensor-based interaction frameworks that were introduced in Section 2.3 described a range of guidelines and exploratory techniques in order to help analyse, and inspire the design of new applications, devices and interfaces. Drawing from the approaches of these frameworks, this chapter generalises these findings into a framework for describing and exploring human-sensor dialogue in participatory sensing experiences. This aims to provide both high level structural and low level implementation guidance, underpinned by the approach used in the Sensed, Expected, Desired framework (Benford et al., 2005): highlighting a range of potential interactions and inviting the designer to consider how, and if, they are reflected in their application.

The framework first lays down a set of activities that dialogue may relate to: planning, testing, navigation, capture and reflection. There is a complex relationship between each of these activities both in terms of how they facilitate or work at odds with each other, but also in the way in which the dialogue develops throughout an experience, focussing on different aspects at different times. Examining these aspects allows the framework to be used to describe an experience from a structural perspective, looking at the overall format of an activity and how the dialogue may be influenced. This follows the approach of the locales framework (Rogers & Muller, 2006), and the high level principles described by Lanheinrich (Langheinrich, 2001).

Carrying the framework through to aspects of implementation, the framework also provides a means to identify and explore the way in which devices and interfaces embody the dialogue at a more hands-on level, bringing in a more feature based approach, as taken by Bellotti, et al's Five Questions (Bellotti et al., 2002) and Dey and Mankoff's ambiguity mediation work (Dey & Mankoff, 2005).

In this chapter, the framework will first be introduced. Then, returning to the experiences in the previous studies, it will be demonstrated in practice: to examine the dialogue that took place, and based on this considering the ways in which the dialogue in the experience influenced, and could be adjusted to overcome, some of the problems observed. The analysis approach considers each of the five aspects of the dialogue individually, how they work together, how the focus changes between each and how this relates to the design of the experience and the tools used. This provides the groundwork for the next chapter which will take the framework and use it as a generative tool to devise a new participatory sensing experience which is implemented with a demo application; this embodies the framework, showing how its explanatory and reflective elements can be carried through from high level to low level design.

5.2 Framework

This section introduces a framework to describe the human-sensor dialogue in a participatory sensing experience. It serves as a basis upon which to reflect or assess potential interaction between the sensor system and its users. The framework structures this dialogue into a combination of five general kinds of activity to which the interaction can relate. These activities planning, testing, navigation, capture, and reflection, are interwoven to create complex participatory sensing experiences.

At any time the dialogue with the sensing system reflects aspects of each of the activities; as the experience progresses the relevance and attention given to each will change. The needs of each activity change at different times and when different tasks are undertaken, so the dialogue can be seen as an overall balance where the main focus shifts from one activity to another. Each activity will be described in isolation below; the following sections will then show how they combine to represent SENSE and the Jamboree experiences.

5.2.1 Planning

Planning activities lay the groundwork for the experience, setting up how it will be conducted and forming objectives, this includes:

- Formulating hypotheses to test, or topics to investigate, using the collected data.
- Determining the locations, routes, times and the frequency at which data is collected.
- Determining what data is to be gathered, including the choice of sensors to be used.
- Selecting the mix of sensing methods, such as fixed or mobile sensors and the degree of automation and manual input.

Planning includes preparatory tasks such as covering background material or the details of the rest of the experience; it also may be part of an iterative process throughout an experience, or part of a cyclic process linking a series of activities

5.2.2 Testing

Testing activities encompass aspects of the dialogue that relate to the maintenance and technicalities of the experience. This involves commissioning of any equipment; installing fixed devices in a location for example; configuring any software and activating it or powering it up. Sensors may also require calibration in order to work accurately or tuning to deal with the environment they are used in (such as setting the gain level on a microphone based sensor). Such tasks are important, but perhaps sometimes not recognised as part of a participatory sensing experience.

Testing activities may not only be necessary for the equipment but also for participants in an experience. The may need to familiarise themselves with any of the devices they will use and also understand what they are required to do, such as what information to report and when, or how to do so. This may require rehearsal in order to verify the results, which may also affect how the devices themselves are tuned or calibrated – for example adjusting the logging speed of a location tracker depending on whether the user mainly travels around slowly on foot, or quickly by bike.

Throughout an experience testing activities may also account for ongoing maintenance; charging the battery on a mobile phone; managing memory capacity on a data logging device; or replacing consumables such as a filter on an air quality sensor. Recognising and dealing with failures would also come under testing, whether this was replacing a failed device, or alternatively with a more human perspective, verifying the status of a participant who hasn't responded or reported in as expected.

5.2.3 Navigation

The navigation aspect of the dialogue is formed from activities when the participants involved are not focussing on the sensing experience as the main task. Participants may be navigating from one location to another, as the name suggests, they might otherwise be involved with interacting with others; collaborators in the activity or just other people the encounter. They might be going about day to day activities between periods of focussed engagement with the sensing system.

During navigation activities sensors and associated equipment might be:

- Active in the background – participants may maintain a peripheral awareness of the sensor and the sensor readings and may be prompted to return their attention to it.
- Switched off and packed away or inaccessible, such as out of range – when participants have completely suspended their direct involvement for a period of time.

- On standby, not working interactively but still active waiting for a trigger to reactivate to fully functioning mode, like a mobile phone waiting for an incoming message or it's user to initiate one.

Devices finally may be re-purposed for other duties, for example a multipurpose device like a PDA or phone might have hosted a sensing application and return to it's initial function – sending an email or making a call. A sensing device might also repurpose itself to support another activity, such a GPS receiver working as wayfinding tool, or a digital camera being used to take personal photos.

5.2.4 Capture

Capture is the most prominent of the five activities described; it includes tasks that are directly related to sensing and collecting information. Examples of this are pointing handheld automatic sensors at targets, operating manual sensors and reporting observations. As well as working with individual sensors the capture process can involve working with other people; synchronising the taking of readings, sharing individual items of data, and collaborating to decide on a target to focus on. In the studies this took place with participants in the same location, however it could also involve cross-site collaboration, coordinating data capture with participants across multiple locations.

Capture activities may include multiple devices and data sources as well as different participants, these may be close at hand, such as an air quality sensor and GPS receiver supplying data, co-located, such as downloading images from a nearby CCTV camera to use in conjunction with personally gathered data, or perhaps more distant sources, such as a wind gauge on one side of a mountain used to compare with one nearby.

All these activities are encompassed by the capture heading, as they are related to the immediate and focussed collection and recording of data.

5.2.5 Reflection

The final heading is reflection, reflection covers a wide range of activities working with previously captured data; reviewing and revising it, analysing it and testing hypotheses; sharing and discussing it. Captured data includes information that was personally gathered and potentially data from other participants or locations.

Reviewing and revising the data includes highlighting additional points of interest or adding additional details that may not have been captured at the time. It also includes noting errors or discrepancies, for example if the time of a reading is out of step or correcting readings if a sensor malfunctioned and logged biased data.

Further processing of captured data and consolidating different sources with dedicated visualisation tools allows captured information to be replayed and analysed in more detail. This is another aspect of reflection, allowing participants to further investigate their results and test hypotheses formed earlier in the experience.

Included in reflection also are sharing and discussion activities such as preparing a commentary on the data or a more selective presentation of it. Discussion might come from feedback from this, but also discussion may come directly from specific comparisons and questions from other participants; the possibilities for sharing and discussion are quite wide, and as with all aspects of the dialogue the examples just give a flavour of how it may take shape.

5.2.6 Relationships Between Activities

So far, this chapter has introduced the five activities that form the framework for human-sensor dialogue. The five types of activities the dialogue fall into have been outlined – planning, testing, navigation, capture, and reflection – each giving an impression of the range of tasks they include. To some degree they resemble the experimental process; forming a hypothesis, designing an experiment, conducting that experiment and analysing the results, however this resemblance suggests a linear progression through the set. As opposed to this, they are more a set of priorities that are balanced throughout an experience; as needs dictate, each activity may take top priority or fall lower and move into the background of the dialogue.

As well as the actual tasks that the activities consist of in an experience, the relationships between them play an important role in shaping the dialogue. The five activities and the relationships between them are illustrated using examples, returning to the SENSE and Jamboree experiences. These will be covered in the next two sections, and show how the framework can be used as an analytical tool to describe the dialogue in the experience and provide insight into the design of the experience and sensors used. This is a two stage process, looking first at the individual activities and how they were implemented in the experience. The second part is examining how the focus of the dialogue changes and how each element worked alongside each other. The examples show some cases where they were well implemented and activities worked harmoniously together, and in other cases they were not so well implemented or activities conflicted with one another.

5.3 SENSE

The first example will describe the SENSE experience from Chapter 3 using the framework. The first stage will individually consider each of the activities involved in the experience and how the activities within SENSE fit into them. The second part will look at how the activities fit together and how each aspect of the dialogue is related to the others.

5.3.1 Planning

In SENSE the planning activities specifically took place over a number of weeks in lessons before the day of the fieldwork. Bearing in mind that it was an educational activity by design, the objectives of the planning activities had to account for introducing new concepts and knowledge in an appropriate way for the age groups and curriculum. This meant that the level of content and the manner it was covered varied between the year 6 groups in the Nottingham school and the year 9s in the Sussex school, but they both followed a similar pattern, starting from a broad view of the subject and narrowing in on the experimental design.

To start with, the types of environmental pollution were introduced, discussing various forms that it might take; litter, water pollution, noise and light pollution and air pollution. Air pollution was highlighted and covered in more detail by showing a documentary video for further background. The lessons moved on, beginning to look at pollution in a local context using a map exercise to highlight areas of potential pollution in their neighbourhood and another activity that used images from traffic web-cams to count vehicles at particular places at different times of day. Using DIY airborne particulate pollution collectors the participants were introduced to experimental work to collect information about less easy to recognise pollution, examining the results with a microscope. This finally led on to Carbon Monoxide and designing an experiment to measure it around their schools and building their hypotheses about the results. This involved influencing where readings would be taken and deciding what other factors would need to be recorded.

As mentioned above, this stage of the experience had to be carefully planned and conducted to a high level of detail. The time allocated to this allowed that to happen and so the participants were well informed and shared an understanding of the objectives for the rest of the experience.

Studying potential locations of interest in advance, discussing which to visit and the information they would be recording was a benefit during the fieldwork, reducing the complexity of the tasks by narrowing down the decisions that needed to be made on the spot and ensuring that they were prepared to record the information they needed.

The way in which the planning activities were carried out also introduced some risk factors, as the time taken to cover the background material, whilst beneficial from one perspective, reduced the amount of time available to conduct the rest of the activities. Similarly the detailed planning in advance did not provide an opportunity for the experiments to be easily adjusted to account for new findings as the experience progressed. One particular example of this was in the way that CO levels were seen to rapidly fall, as soon as the source (a bus or truck for example) moved away. This, to some extent introduced a time related aspect that had not been specifically accounted for.

5.3.2 Testing

Compared with planning activities, testing activities were less well supported in the experience. The design intended that setting up the equipment would be handled by facilitators and close integration of the equipment so the participants wouldn't be required to deal with those elements themselves. Familiarisation was also not specifically supported in favour of facilitators playing an introductory role at the start of the fieldwork session.

The testing activities that were planned took place, though participants were more involved in the process; time constraints and their eagerness to begin the main part of the fieldwork resulted in these parts being conducted more quickly than anticipated. As well as activating the CO sensor and the PDA unit, the video camera had to be synchronised with the readings by videoing the time displayed on the PDA display. Familiarisation tasks were rolled into the commissioning stage and the start of the activity as the participants were keen to start using the devices and move on as soon as they were working; explaining their use ran into the start of the main activity in the session.

In addition to the testing activities described unanticipated situations also occurred; the participants switched roles during the session and then took a moment to work out their new duties. This resulted in 'test readings' being made whilst the participants rehearsed their new role and once more familiarised themselves with the devices. This meant that testing activities took place not just at the start of the experience but interleaved throughout as the participants' roles changed.

Designing the experience to reduce the necessity for testing activities provided some benefits, it reduced the time required for commissioning the sensors on the day of the fieldwork; participants could get underway quickly and also did not have to get to grips with technical details in addition to the other demands on their attention.

One of the main issues resulting from the analysis of the experience was the unanticipated use of sensors for familiarisation purposes. The participants rehearsed the process of collecting readings by setting marker points, adding notes and dealing with other sensors exactly as if they were focussed on a point of interest in the surroundings or current sensor data. This was purely to check they were doing it right and that the devices worked as explained, but it had the affect of interfering with the normal collection of “real” readings. These interleaved testing activities added additional factors to consider when reviewing and interpreting the data and brings into light the relationship of testing activities with the other activities in this experience; this will be discussed further in the later section when considering the relationships between each of the activities.

5.3.3 Navigation

During the fieldwork the participants engaged in navigation activities; in addition to moving from one location to another, navigation tasks include anything when the sensing activity took a background role. In this instance, since the time had been set aside for the fieldwork session, this was limited to waiting for group members to catch up or general chat between the participants.

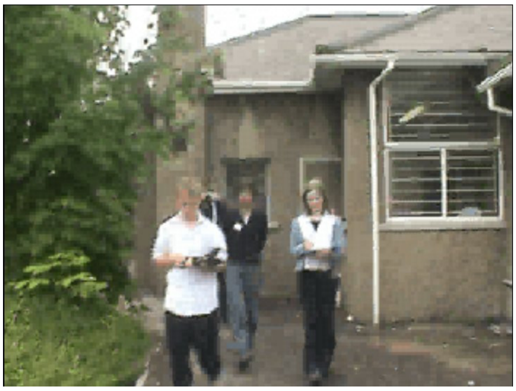


Figure 63: A year 9 group in Sussex walking to the next destination on their route

In moving between locations the participants were supported by the design of the experience and the equipment; as mentioned under the planning heading, the pre-planning locations and use of the very familiar school surroundings reduced the need for route planning and much thought about orientation. The equipment design (lightweight, battery powered, etc) was for portability making moving around relatively hassle-free. As the devices were relatively self-sufficient they did not require any ongoing intervention to work properly, which also allowed them to easily assume a background role, this allowed the participants to focus on other things without distraction.

Had the activity extended out of the dedicated lesson time, such as for use throughout a field trip, this setup may not have performed so well for navigation activities – whilst the equipment does not demand a significant amount of attention to its users it is quite bulky drawing possibly unwanted attention and can’t be carried about a person easily, obstructing other activities the user might engage in.

5.3.4 Capture

During the fieldwork stage of the experience a number of activities were directly related to data capture, these included:

- Pointing and positioning the Carbon Monoxide sensor
- Monitoring and reading out the reading of the CO level from the PDA
- Setting marker points using the PDA
- Writing notes on the worksheet to correlate to the marker points
- Pointing and zooming the video camera
- ‘Narrating’ the activities for the video footage
- Using the anemometer to measure wind speed and noting wind direction

These activities worked with the sensors which were a combination of mostly automatic devices (CO sensor, video camera) and manual reporting (marker points, written notes, wind observations). Whilst the automatic readings provided a baseline level of data, the participants focussed their input on events of interest, highlighting them for reference and reporting additional information. This allowed the recording of both the specific data of interest, i.e. at each location they visited, but also the contextual information related to the readings and details of how they were made. This was particularly important due to the transient nature of CO emissions, which would dissipate quite quickly.

Figure 64: SENSE participants at the Nottingham school collecting readings with the CO Sensor Stick

Another useful element of the sensors was the fact that they were precisely synchronised. The CO readings on the PDA synchronised with the video footage by recording the time display on the PDA at the start of the fieldwork, the written notes on the worksheet also were linked via the PDA, using the number given to each marker point added to the CO log. This design required the participants to work together to share information within the group, this ensured they were all involved and aware of each element of the capture process. This worked well as the members of each group were already classmates and moved around as a group; this may not have worked so well if the participants did not already know each other or the group was more widely dispersed, such as on different sides of the road if the sensors had required them to be further apart.

5.3.5 Reflection

As with the planning activities the reflection activities in the experience were arranged to provide as much educational benefit to the participants as possible. They took place in classroom sessions after the fieldwork and after the research team had processed the video and data logs to be viewable in SDE, the custom visualisation tool developed for the project. The range of activities they engaged in started with replaying the data with SDE, then adding additional notes or highlighting extra points, such as erroneous data and exceptional readings.

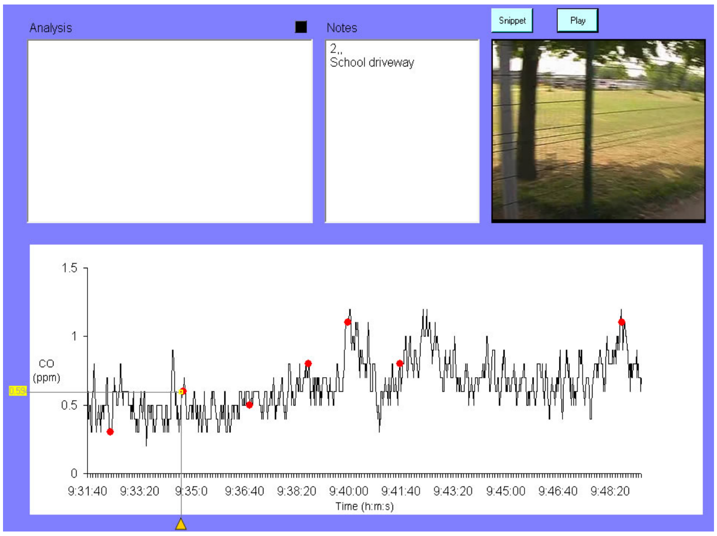


Figure 65: The Sense Data Explorer application used to review and comment on the data.

Following the initial inspection of their data the participants looked in more detail to test the hypotheses they planned at the start of the experiment, preparing presentations of their results to emphasise the outcomes. The analysis was widened to look at the readings collected by other groups, both locally and at the partner school's site. This part of the activity focused on the cooperative nature of the exercise, sharing data to verify results, provide additional information and, when sharing across sites, provide a larger scale comparison (between urban and out-of-town locations). This highlighted how their individual contributions were consolidated into a larger dataset, extending the possible analysis in a number of directions. Going even further, the older groups concluded their activities with an online discussion with an expert scientist to explore the issues further.

Viewing the data using SDE provided a good interface with which to review the data gathered during a single session. It provided the means to identify high and low points in the data and see the smaller variations introduced by sensor noise. A limitation of the visualisation was that it did not reference external sources for comparison, for example the highest readings shown in Figure 65 are between 1ppm (Carbon Monoxide parts per million) and 1.5ppm, the UK Health and Safety Executive gives the safety level as 50ppm – putting the variations shown on the graph into a different perspective. Whist the attention given to the activities in this experience helped set the data in a wider context, as a standalone tool when it can't be explored in such detail this may offer problems.

5.3.6 Negotiation Between Dialogue Focus

The above sections looked at each of the activities in the framework, showing how each part of the experience relates to the different activities and giving the chance to consider aspects of the activities individually. This provided further examples of what each of the five activities involve in practice, and an illustration of how the framework draws out aspects of the experience – considering the extent to which each activity was supported. The second aspect of the framework focuses on the relationships between these activities by looking at how the focus moves from one activity to the next and how the elements of the activities support or conflict with each other. In doing so the observations made in the earlier chapter are recalled, framed in relation to the relationship between the activities.

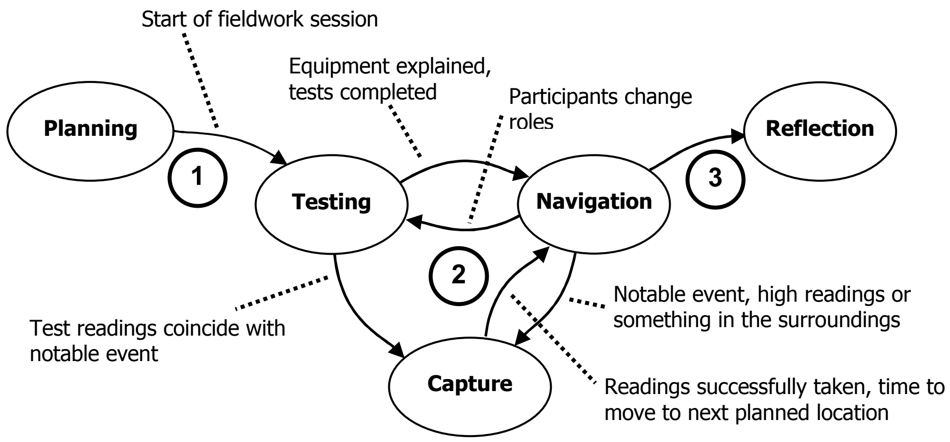


Figure 66: Outline of dialogue focus changes throughout SENSE activities

The first step is to build a picture of how the focus on each activity changes throughout the experience, highlighting the main stages and which activities are involved. This is represented in Figure 66 which shows the five activities connected by arrows, illustrating how the focus changes, each of these changes is annotated, describing what takes place to initiate the change. The diagram follows the structure of the experience with three main parts which are also labelled (1) the initial planning stage; (2) the fieldwork stage; and (3) the reflection stage. Taking each stage in turn, the transitions and interactions between the activities will be examined.

The first part focused entirely on planning activities, taking place over a number of school lessons in the build up to the fieldwork. The fieldwork was scheduled for a particular day and so the first change of focus in the dialogue was dictated by the design of the experience. The focus switched to testing activities at the start of the fieldwork session when the equipment was made ready and handed out to the participants.

The fieldwork stage saw a combination of three activities; testing, navigation and capture, all quite closely interleaved. Testing formed the link from planning, coming as a natural progression in the experience; the participants receive the equipment, get it ready and then move on to navigation as they set off toward the first location on their route. This progression was expected and accounted for in the design by reducing the testing activities required at the start. The tasks were made short and simple so the transition from testing to navigation was a smooth crossover. A more unanticipated element was the return to testing activities during the fieldwork session; this happened when the participants changed roles and rehearsed their new parts by running though the collection process – setting a marker point and writing notes, etc (see Ch. 3 Sequence 5). This introduced a conflict with capture activities adding additional data to the sensor logs that was not specifically related to the CO observations.

Two approaches to address this issue are suggested from this experience; one approach to specifically distinguish testing activities from capture activities through explicit phases – either extending the initial testing period to familiarise all participants with all the devices in advance or distinctly creating exclusive testing periods within the fieldwork session. An alternative approach would be to make test periods more detectable in the collected data; in the activities reviewed the test data was identified by watching the video footage. This could be extended to allow specific marking of test data, allowing the participants to declare at the time whether the readings were "live" or "test" and so filter them in or out in subsequent analysis.

Moving from testing back to navigation activities was again a natural transition, when the readings were taken and the group members satisfied they resumed their previous activity, moving along to the next destination on their route. The issues with testing activities are more complicated though, as occasionally the group went from focussing on testing activities to capture activities. This occurred when rehearsal recordings were combined with events such as high readings or vehicles passing, and so the focus changed from taking test readings to recording the event of interest. This highlights another point to consider; specifically setting aside time for testing activities within a fieldwork period may detract from data capture – or specifically marking test data may present a problem when two priorities overlap.

Looking now at the changes between focussing on navigation and capture activities, it was seen that the change to capture activities was triggered by two kinds of event, related either to observations of the surroundings (vehicles passing, arriving at a significant location) or by changes in the readings from the CO sensor (sharp rises in the CO level). After the readings had been taken, the participants went back to their navigation activities, continuing on their way.

The mix of sensors allowed the users to maintain a balance between navigation and capture, so that data capture could easily take a background role and then become the main priority at opportune moments. This was seen through the episodic nature of the data capture, focussing on changes in the sensor readings and events in the surroundings which were illustrated in Ch. 3 Sequences 1, 2, 3 and 4.

Changing from navigation to capture activities was a relatively simple process as the automatic sensors just needed pointing at a target and a marker point could be set and the notes filled in afterwards. Whilst this had the effect of allowing the participants to respond to changes quickly, it also introduced some more difficulties – as with identifying "test readings" close attention to the video was required to establish the changeover between general navigation readings and more accurate episode/capture readings surrounding the marker points.

This balance between navigation activities and capture was not always optimally negotiated, the observations also showed where the participants missed moments of high readings or responded to small changes of little overall significance (See Ch. 3 Figure 32). As a learning activity this is expected to a certain degree, but as the activity progresses and the users become more experienced it highlights that whilst changing the focus between capture and navigation may be straight forward, doing so at the right time can be more difficult – both in terms of paying attention to the sensor readings and surroundings, and also in recognising significant events.

There are two issues to address here, first, as with the test activities it is difficult to separate out 'navigation' readings from the more accurate 'capture' readings, so again a more explicit change of focus may be required. Direct declaration of this by the users is one solution, though this may make changing focus more difficult and affect the nature of the experience. Using additional information recorded automatically is another potential method, reducing the demand on the participants but perhaps increasing the complexity of the sensing equipment. A third option would be to change the mix of sensors, using something less automatic which is only recording when the participants are focussed on taking readings – this again comes at a cost of a more difficult transition from navigation to capture and back.

The second issue was attention to sensor readings and recognising significant events. One approach to this is to increase the feedback from the sensors, for example, by alerting the user to high readings worthy of note, or an indication of how current readings differ from average. Alternatively, supporting the user's understanding of the causes of readings as a form of ongoing reflection could help improve their ability to recognise moments of interest, introducing additional examples related to their situation during the fieldwork could be one way to implement this.

Reflection activities took priority in a final third phase of the experience, in classroom lessons shortly after the fieldwork session. As with the transition from planning to testing it was dictated by the design of the experience as the fieldwork session came to an end. This acted as the closing stage of the activity, rounding off the fieldwork by exploring the results and comparing with others, though as pointed out above, the potential for more ongoing feedback in the experience was missed, so there was little chance to capitalise on the findings and improve the quality of results as well as participants understanding of the data. The observations also showed how analysis sessions that took place were used as an opportunity to revise the data and highlight errors, Chapter 3 Figure 33 shows examples of two comments added during the review process demonstrating this.

Reviewing the SENSE experience using the framework identified a range of activities within planning, testing, navigation, capture and reflection based dialogue. The range of activities and the complexity of each type varies, for example navigation activities were relatively restricted due to the fieldwork taking place in a dedicated time slot (the participants had little opportunity to engage in unrelated activities), planning activities were in depth and varied in order to provide educational benefit. Looking at each type of activity individually helped recognise some of the choices and trade-offs negotiated in the design, it also highlighted how well supported aspects of each activity were – for example as testing activities initial familiarisation was well managed but later instances were not.

A picture of how the different parts of the dialogue came together was built up, showing the changes of focus within the experience. Some of these were specifically dictated by the experience design, such as moving from planning to testing, or navigation to reflection. Others were negotiated by the participants, such as transitions between navigation and capture. Some of the successful and more difficult aspects of the experience were drawn out at this stage, seen as features of the transitions, for example a simple user negotiated transition from navigation to capture and back allowed the participants to quickly respond to changing conditions, though it introduced difficulty in interpreting the sensor data as the transition was not distinctly recorded. Reflecting on the issues seen, the connections between the activities and the nature of the transitions inspired possible approaches to address the issues seen, these were noted throughout the analysis.

5.4 Jamboree

This section now takes the same approach looking at the Jamboree experience, again using the framework to draw out the aspects of human-sensor dialogue. The first stage reviews the parts of the sensing experience and allocates them under the five activities.

5.4.1 Planning

Figure 67: Planning stage – explaining the object of the activity

In contrast with the activities in SENSE, the Jamboree experience worked with many different people over shorter periods. The aim of the activity was to provide a novel and engaging experience with technology used to gather environmental data and explore it using a new method of visualisation. The set-up was a voluntary experience among a 'marketplace' of other activities within a larger event, this focussed the design of the experience to provide a fast paced and active set of tasks to fit in with the rest of the event and to encourage people to take part. Participants had three hours to explore the range of activities on offer; the sensing activity lasted around 20 minutes, so it was important to offer a rewarding experience to those taking part.

The preparatory stage introduced the object of the activity which was to create an illustrated sound level map of the surrounding area. As potential participants viewed the activity from a distance they saw the visualisation and pre-prepared 'poster' image on the large screen, and saw others taking part interacting with the display or setting out to gather data. When they approached the activity area the experience was explained in more detail, demonstrating the equipment and explaining what the activity involved. If they chose to take part, then the devices were handed out and activities moved on to the testing stage.

Compared with SENSE this planning stage was very brief, covering the bare essentials required to take part. This was motivated by two factors – first to make the activity appealing for people to take part in and second because many of the people at the event were international visitors who did not have a high level of understanding of English, so would have had difficulty with intensive preparatory work. Moving quickly to the more hands-on parts of the experience was one way to address these issues. The planning activities were narrowed to cover some background material and being given some objectives, with most of the other planning work incorporated into the overall design of the experience.

5.4.2 Testing

Testing activities in this experience consisted only of familiarisation with the equipment, which was again very straightforward. The devices were activated in advance so participants did not need to get involved with that aspect, the most complicated device was the digital camera and as they are a common consumer device participants did not find it difficult to use. Unlike the marker points which highlighted readings in SENSE, the photos could be deleted after taking them, meaning that test pictures could be removed from the record.

Figure 68: Testing activities – handing out the equipment and explaining how to use it

The overall design of the experience and the sensing tools used reduced the general role of testing activities. This choice was to provide a quick moving activity to fit in with the environment, as with the planning stage. Where other environments may require more complex sensors greater effort will be needed to set them up and more familiarisation time will be needed, so the role of testing activities would be wider.

5.4.3 Navigation

Navigation activities followed a similar pattern to the previous study as again the participants were taking part in a time period specifically allocated to the data collection activity. This meant they were mostly following the task and navigation activities were limited to moving from one location to the next, regrouping or chatting with each other, people they met or the activity supervisors stationed at the various activity stalls they visited.

Figure 69: Participants pay little attention to sensors whilst walking across the field.

A particular problem with the sound level sensor in this context was that it continually recorded readings – and so picked up handling noise and incidental noise from conversations, etc, as the participants went along. This increased the noise level at the lower end of the scale, so only the particularly loud readings stood out above the background.

In contrast, in this environment the GPS unit worked very well, the experience took place outside in a large field; the only covered areas were tents and marquees. These were ideal conditions to receive satellite signals which can't get through inside buildings and are obstructed by tall structures. The GPS continually logged position to link sound levels to a location, the group members who carried each device therefore had to stay within a short distance of each other so that the location and sound levels would be accurate. As the participants did not always have this in mind during navigation activities this introduced the potential for problems, however these were mitigated by the limited resolution of the visualisation – the participants rarely moved further than 10m apart during their sessions and these small scale movements did not represent a significant change on the map. The visualisation was optimised for measurements along a journey and in order to compensate for the limited accuracy of GPS (which gives a series of readings generally within a radius of 10m) the location readings were smoothed over time (to produce a simpler point to point line on the map). As the GPS conditions were so favourable, this instead compensated for the differences between the locations of the people holding the sound level sensor, the camera and the GPS.

5.4.4 Capture

Figure 70: An example of capture activities, taking sound level readings and a photo of a wind tunnel

The sensors used in this activity were the Logbook sound sensor, GPS unit and the digital camera. The Logbook automatically recorded readings, and so did the GPS however the users played an important role in pointing the sensor module at potential sound sources to take readings; the main source of explicit manual input was taking pictures with the digital camera. In addition to controlling the sensors themselves the members of the group engaged in capture activities by helping to set up events to record and helping to test individual sources, assessing their potential to create high readings. Referring back to the observations in Chapter 4, Sequence 6 shows how one member of the group adjusts the settings on a tone generator to get the highest reading whilst the participant with the sound sensor holds it in front of the speaker. An example of where the participants specifically stage an event to capture can be seen in Chapter 4 Sequence 7, where they asked an activity helper to hold out the model helicopter he is demonstrating so they can hold the sound sensor up to it.

The main difference in the sensing set-up in this experience compared to SENSE is that there are fewer opportunities to report information and capture contextual information. As with the Carbon Monoxide readings, high sound levels are generally momentary readings, lasting a few seconds at most, the video camera was better suited to catch brief events as the continuous coverage could capture the exact moment easily. The still images can only capture a single moment; during the experience at the Jamboree participants were seen to pay careful attention to this, posing for pictures and synchronising activities to capture an illustrative picture and the sound readings at the same moment – as with Ch. 4 Sequence 2 it can also be seen in Ch. 4 Sequence 3.

There was mixed success in marking high readings with photos, the observations highlighted the number of high readings with and without photos attached and the placement of the photos that were taken. Difficulties also arose from the lack of additional data to link the images to readings, again coming down to the difference in content of video and still images.

5.4.5 Reflection

The reflection activities were concentrated at the end of the activity when the participants returned and their data was loaded on to the large screen computer. The participants viewed their data in a 3D graph on Google Earth, using a Nintendo WiiMote to interact with it. This style of interface was chosen to encourage group based interaction continuing the collaborative nature of the experience, it also worked well to support the planning activities mentioned in 5.4.1, allowing potential participants to preview the activity by watching others.

Figure 71: Jamboree participants viewing their sound level readings on the Google Earth large screen.

The participants could zoom in and out, change the orientation of the graph and view their pictures and individual sensor readings in placemark information balloons. The

Google Earth interface allowed the participants to see their data in the context of the location, using the aerial images and the site map, and viewing it alongside other people's data.

The combination of map information, GPS location and photos acted as a reminder of context for the participants in a similar way that the video footage did in SENSE. As all the participants had visited the same area they were also familiar enough with the surroundings to follow the context of other groups' data with minimal additional information. As opposed to SENSE, sharing with others who had no knowledge of the site may have been more of a problem since there was less contextual information provided.

A couple of issues emerged when reviewing the data in the visualisation, as with the location readings, the sound level readings were averaged over time (in order to reduce the resolution of the visualisation for faster rendering). This meant that the readings shown at the time of capture did not always get shown correctly on the map – short peaks were smoothed, eliminating the momentary high point the participants were trying to record. This added extra difficulties in interpreting the data as it became more difficult to identify the focus for a particular capture episode. Similarly, a second issue that compounded this was in the way photos were also displayed in the visualisation. If multiple photos were taken in close proximity within a short time frame, some of them were dropped from the visualisation. This again made interpreting the data difficult as often a series of photos were taken to illustrate an event of interest.

These issues relate both to the design of the sensing tools themselves, and to the relationship with reflection activities. In relation to the design of the sensors, there was a clear difficulty with the feedback regarding the collected data during the session, which did not effectively allow the participants to capture what they wished to record and what was being recorded. This also relates to feedback about the way the data is processed and used later; this kind of relationship with reflection activities will be discussed in the next section.

5.4.6 Negotiation Between Dialogue Focus

The above sections have again looked at how the Jamboree sensing experience fitted within the five aspects of dialogue: planning, testing, navigation, capture and reflection. Planning and testing were both brief; reduced in scope to fit in with the requirements of the environment. To facilitate this, the design of the sensor tools and the tasks to be performed was kept simple. Navigation was also limited in the range of activities that it covered; as with SENSE this was due to the fact that the activities took place within a set time period allocated to the tasks. During the navigation activities handing noise was introduced into the data as the sound sensor was automatically logging levels every few seconds. Compared with SENSE the capture process was more difficult, whilst the tools were simpler using photos rather than video made it more difficult to capture enough information at the right moment. More effort was put into the taking of pictures, rehearsing events and specifically posing for the photos to show as much information as possible, this met mixed success as peaks were not always matched with photos in the resulting data. The reflection activities were not as in depth as those in SENSE but were primarily designed to be engaging and fun rather than meeting a school lesson standard. There were problems with the way the data was represented however, as some peaks and some photos were not displayed as expected.

As with SENSE, this second part now looks at the combination of all the individual parts, some of the issues experienced are reflected upon and possible solutions will be discussed. This process again starts with a diagram, Figure 72, which shows the transitions between the different activities in the experience.

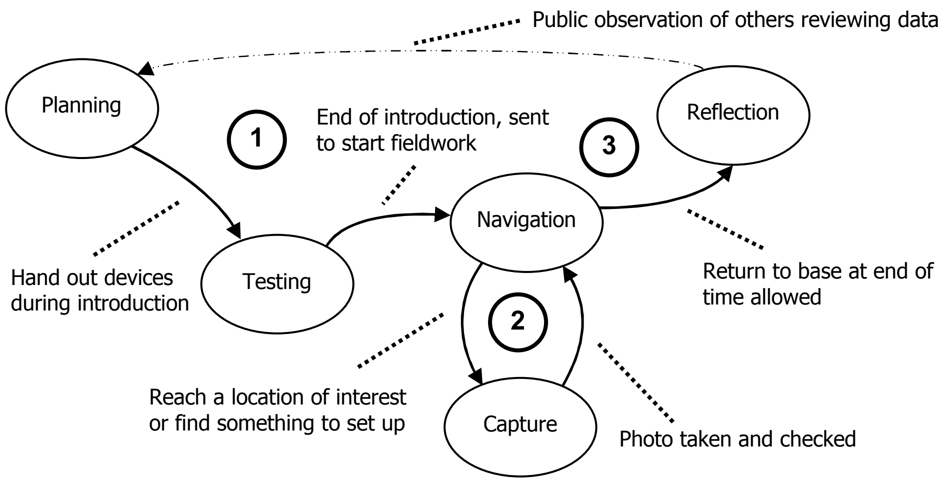


Figure 72: Outline of dialogue focus changes throughout Jamboree activities

As with SENSE the activity was split into a three stage process; (1) the initial preparation which included planning the activity and setting up the equipment; (2) the fieldwork during which data was recorded; (3) visualisation of the data to analyse and reflect on it. In this experience the flow went straight through planning and testing in the first phase and the fieldwork phase consisted of just navigation and capture.

Following through the stages in order, first is planning and the connections to testing and from reflection. The public visibility of the data on the large screen acted as a partial preparation stage, allowing participants to form an idea of the activity and decide whether to participate, and also to help them plan their own involvement. This was not a prerequisite and did not always occur, so it is indicated with a dashed line.

As previously mentioned, planning and testing activities were dominated by the constraints of the activity; the location, sensors used and overall method was set by the activity plan. The transition from planning to testing was managed as part of the lead up to the fieldwork, first the activity was introduced then the equipment handed out and explained, so it was negotiated by the facilitators of the activity who led this process. The brief introductory stage quickly led into the fieldwork stage, moving from testing to navigation as the groups received the equipment, were shown how it worked and then sent off to collect the readings.

During the fieldwork stage the participants' dialogue balances priority between capture and navigation; the transition between the two needed to be more explicit than in SENSE, as the digital camera did not record the context as well as the video footage and written notes did. This could be observed in the way the participants worked, placing more emphasis on setting up situations and posing photos as shown in Ch. 4 Sequence 6. Ch.4 Sequence 7 also highlighted that high readings and sources of noise went unnoticed as the participants did not see or otherwise appreciate the readings where the participants at that time prioritised navigation. As discussed earlier in 5.3.6, feedback from the sensor and ongoing reflection are two possible ways to counter this effect, prompting the user to change focus, or improving their ability to recognise significant things to record. When the required information was captured the transition back to navigation was a simple case of moving on to their next planned destination.

Finally the move to the final stage of reflection activities was initiated as the group returned to the start location when their time had run out or they had completed their trip around the area. As noted above the reflection activities experienced some difficulty as the visualisation of the data did not always represent what the participants believed to have been recorded. Whilst the participants were getting clear feedback about the data they'd recorded from the data logger and camera, the feedback was not well linked to the visualisation tools which worked differently. This suggests a closer relationship between reflection and capture, again as mentioned in the earlier discussion of the SENSE activities, integrating more reflection activities earlier into the experience, providing more useful feedback earlier on in the activity.

The same method applied to SENSE was applied to the Jamboree experience, first the individual activities were looked at, considering the range of different tasks and how well they worked on their own. Then the combination of all the activities was examined, looking at the transitions from one to another and the arrangement of them.

Some of the aspects of the experience shared similarities with SENSE, the initial testing activities were simplified to save time, navigation activities were limited in their variety as the fieldwork took place in a specific time slot.

Following the approach taken to the testing activities, the planning activities in the experience were also limited and brief, as opposed to the in depth preparation conducted in SENSE. Reflection tasks were also quite brief and narrow in scope, recognising the different demands of the exercise.

Looking at the connections and transitions between the activities illustrated how the experience differed from SENSE, with testing and planning taking part in the initial stage, the experience design dictating the transition through to navigation. Again the transitions between navigation and capture were user determined in the fieldwork stage, though testing activities were not involved this time. The final transition was dictated by the experience again, moving from navigation to reflection as the time allowed for the fieldwork ended.

When considering the visualisation as part of the reflection activities in the final stage some issues were identified, highlighting differences between what the users captured and how it was represented. Suggestions to address this returned again to the role of reflection in the experience, implying a need for increased feedback from the sensor and opportunities to review data interleaved with capture and navigation activities.

5.5 Conclusion

This chapter has introduced a framework for understanding the dialogue between humans and sensors in participatory sensing experiences. The framework consists of five activities that the dialogue relates to:

- **Planning** – activities that prepare both the participants and the technology for the sensing tasks, such as covering background material, deciding on sensors or locations, and formulating hypotheses to test as part of the experience.
- **Testing** – relating to the mechanics of the process for example setting up sensors, participants familiarising themselves with the equipment and any ongoing maintenance.
- **Navigation** – when participants are engaged in other activities and the sensing experience is a secondary concern, e.g. in transit from one location to another or interacting with other people they meet.
- **Capture** – when the participants are directly engaged in recording data, such as pointing handheld automatic sensors, setting up things to record or reporting individual readings or observations.
- **Reflection** – reviewing existing data, for example analysing readings, sharing and discussing results and testing hypotheses.

The activities are seen as a set of priorities interleaved with one another, though at a particular time one is the main focus.

The framework was used to describe and analyse the dialogue taking place in the experiences studied in earlier chapters; the SENSE project and the World Scout Jamboree. This provided examples of how the framework fits in to real situations and how it may be used to understand them. The process consisted of two stages, first was an individual review of the experience with respect to the five activities in the framework. The range of different tasks and the way in which they were supported by the design of the sensors was considered, identifying some of the strengths weaknesses and tradeoffs made in the implementation of the experiences. The second stage of the analysis looked at the overall combination of the five activities, mapping out how they were linked and identifying the transitions between them.

It was seen that the range and depth of the activities and transitions from one focus to another could be dictated by the overall design of the experience – which depended on what it was intended to achieve. The sensor devices also played a part as these too are tailored to reflect the needs of the experience. Transitions can also be managed by users, but the design of the tools supports this process by affecting how and when they take place. Examples showed the effects of this, where a transition is simple it allows users to be reactive to changing situations, however this risks a lack of distinction between activities and makes interpreting the results more difficult. Relying on user initiated transitions also depends on the judgement of the participants in order to recognise an appropriate time to do so – the examples highlighted a range of instances with varying degrees of success.

With insights gained from these analyses using the framework described here, the next chapter will use it as a generative tool to assist the development of a new sensing experience which will be implemented in a demonstration application.

6 Prototyping the ‘SensorShare’ PDA Sensing System

6.1 Introduction

The previous chapter described a framework for human-sensor dialogue in participatory sensing experiences. The framework introduced five activities the dialogue relates to: planning, testing, navigation, capture and reflection. Each of these activities takes priority at different times during an experience, and they are interleaved throughout rather than linearly ordered.

The framework was used to analyse the dialogue in the earlier experiences that formed the basis for the SENSE project and World Scout Jamboree studies. The analysis of each took a two part approach, first looking at the individual aspects of the dialogue that relate to the activities – planning, testing, navigation, capture and reflection. The way these aspects came together was then considered, including their ordering of the activities, what triggered each change of focus and how the change took place. This process identified some of the main influences on the way the dialogue is shaped.

Both the Jamboree experience and that of SENSE show how different factors affect the range and depth of dialogue related to the individual activities. Fundamentally they are determined by the objective of the experience (e.g. a school science project or an engaging outdoor activity) and how these objectives are realised through the overall design. The planning stages in both of the activities differed to a large degree; SENSE involved individual participants planning in great depth by conducting a range of preparation tasks, whereas the Jamboree demanded a faster paced introduction, with short and focussed planning and testing activities taking place – consequently the related dialogue was limited in scope.

Having used the framework as an analytical tool in applying it to the past experiences, this chapter introduces a new experience using the framework alongside insights from the previous examples to aid the design process. Following the influences identified in the earlier work, the process taken will be to first consider the overall objectives, the general design of the experience and how these affect the individual activities and their relationships. The individual transitions will be looked at including whether they are specifically directed or user determined, and then this leads on to looking at how the sensors and related devices will support the process. This chapter documents this process, describing the prototyping of a new participatory sensing experience and the ‘SensorShare’ PDA sensing application.

6.2 Prototyping the Experience

Previous examples have focussed on experiences taking place in a dedicated time period, where participants' main focus was to collect the information – other demands on their time and attention were limited. The new experience will specifically introduce further aspects of participatory sensing, in particular to embed the activities within everyday life rather than in a tightly controlled setting. The earlier applications have also concentrated on mobile, person-centric sensors, and so this new experience will also include interaction with fixed sensors by introducing pre-determined sites of special interest.

Following these aims will help develop a different kind of experience from those earlier examples, this will present new design challenges and new possibilities, demonstrating the use of the framework in a new context. The choices will help to explore new forms of human-sensor dialogue and develop the opportunity to conduct longitudinal scientific studies, looking at the collection of data over time as well as space.

These choices influence the selection of a suitable setting for the demonstration application, and with that in mind the scenario detailed below was devised.

6.2.1 Scenario Outline

The new participatory sensing experience will investigate the working conditions in and around the School of Computer Science at the University of Nottingham Jubilee Campus. The campus, and the building that houses the School of Computer Science, was opened in 1999 and form part of an award winning design for its environmentally friendly features (McCarthy, Riddall & Topp, 2001). These features include beds of alpine plants built into the roofs for low cost insulation, solar panels added to the atrium ceilings to offset energy consumption, energy-saving movement-activated lighting within offices and a super-efficient ventilation system utilising the campus lake for ground source cooling. Whilst providing substantial environmental benefits, the performance of these features have proven somewhat controversial amongst the building's occupants throughout the year as environmental conditions change, both outside and inside the building.

A range of workspaces are offered by the building and the surrounding campus, inside this includes computer labs, offices, break-out rooms and communal areas such as the atrium and a selection of alcoves in the corridors. These areas offer a range of environmental conditions, different light levels, temperatures and varying levels of background noise. These conditions vary with the time of day, the building's day to day usage and the outside weather conditions. Using participatory sensing techniques following the aims set out above, the new experience will provide building managers with information about the conditions in the areas, allowing them to improve the working environment for the building’s users. This will involve two elements; determining the actual conditions in each location, but also gathering people’s experiences of them and feedback about their preferred conditions. This second part involves the participation of users of the building (students and staff members), using participatory sensing techniques to facilitate their awareness of the conditions they work in, focus on their experiences of the various workspaces and reporting this information. Initially, three work areas have been chosen for investigation, as shown in Figure 73.

Figure 73: School of Computer Science; campus island (left), central atrium (centre) and alcove workspace (right)

- **Jubilee Campus Island:** outside the building the Jubilee Campus island has a number of picnic tables available for use.
- **Computer Science Atrium:** the atrium sits between two wings of the building. It is used as a general work and social area with a number of large tables. The atrium is also occasionally used for lunch receptions and exhibitions throughout the week when the tables are moved or replaced with poster boards.
- **Corridor Alcoves:** Further within the building there are a number of alcoves set aside from the main corridors, these alcoves provide an alternative work area for individuals or small groups.

Mirroring the analysis process in the previous chapter, the first step is to think about the overall experience and the implications it has on individual activities in the framework. The second stage will move on to consider the links between them; as opposed to the previous work, this presents the opportunity to further plan which ones are desirable, which are required and devise means to create or facilitate appropriate transitions between them, calling on the previous experiences to inform the ideas. This process will help draw out more detailed requirements for the experience and provide the basis for the prototype implementation.

6.2.2 Planning

The experience is intended to involve a number of participants so that results represent the experiences of all the regular users of the workspaces. To gather a coherent set of data, limits on how the data is collected will need to be set, for example by using sensors that provide comparable data or complementary techniques. This has an impact on the range of planning activities; fewer choices are left to the participants and this dictates the nature of the preparatory stage. Participants will be taking part voluntarily in addition to their usual work and so, as with the Jamboree experience, dedicated planning activities will be reduced to lower the participation overhead.

The specific areas of interest are determined by the scenario, i.e. work areas in and around the Computer Science building. In reducing the choices that need to be made by the participants in the preparatory planning stage, devices, sensors and related tools will be fixed, ensuring that data is collected by common means. In addition, the main objectives are pre-determined, being set by the scenario; each participant is monitoring their working environment, in order to provide feedback on their preferred conditions and the environmental conditions of the places that they work. The contributions will be relatively ad-hoc in terms of timing, working alongside a participant’s daily tasks. This implies that the sensor system should attempt to facilitate this and assist with planning on-the-fly, perhaps by suggesting possible options or preparing for likely courses of action in response to changing circumstances.

As the overall object of the exercise, the equipment used and the techniques adopted are all going to be pre-determined to various extents, the initial planning activities should focus on helping the participants understand these limits so that they can work with them effectively. Other parts are left open for the participants to determine themselves, and so the planning features should also have a second focus on allowing participants to determine, and adopt, their preferred approach as the situation dictates; for example in choosing which location to visit, when to do so, and when and what kind of information they choose to record.

6.2.3 Testing

Similar to the planning activities, testing activities such as setting up devices, calibrating sensors, etc places an additional time overhead upon participants. Again the approach is to reduce these tasks, keeping the required activities to the minimum, allowing participation to be as straightforward as possible. The main testing activities the participants will undertake will be familiarisation; as with the previous activities that took this approach the aim is to make the technology straightforward in operation. In order to support this, the design of the sensors and other devices used will need to be carefully considered, ensuring that they do not require a large degree of training and familiarisation in order to use them. These factors will be accounted for as the design progresses to a more detailed level.

The responsibility for ongoing maintenance should also be considered; in earlier experiences facilitators were close on hand to assist with malfunctions and other issues, the time spans were also short, giving less opportunity for problems to occur. In this experience participants will be working on their own for extended periods of time, and will not have the same kind of support on hand. This provides the first motivation to include fixed sensors in the design, moving as much of the complex sensing equipment as possible to installations at the chosen locations. This will allow administrators to calibrate and test the installation, and closely monitor the ongoing operation of sensors throughout the experience without inconveniencing the participants. This approach also compliments the design of the mobile parts of the sensors, reducing their complexity and allowing them to be simpler and light weight.

6.2.4 Navigation

This experience will be taking place alongside the usual work tasks, it will also span a larger amount of time in order to gather the necessary information. Consequently, navigation activities will be more varied than the earlier examples as participants will engage in a wider range of alternative activities. In the last chapter, section 5.2.3 suggested other modes of operation for the handheld devices that the user works with; ‘packed-away’ i.e. switched off and in storage; standby – not active but waiting for a ‘wake-up’ trigger; active-in-background; and repurposed – in use for other tasks. Catering for this range of navigation activity types will be expected in the experience.

As discussed earlier, the sensing opportunities in the experience will often be opportunistic as the participants pause at or visit the locations of interest in the course of their normal work, rather than with the intention to record data. The navigation features should therefore also facilitate this process by allowing the users to become aware of and exploit any opportunities as they occur – a particular focus should therefore be on standby and background states, providing them with the ability to respond to proximity to sensors and other indicators of data gathering opportunities.

6.2.5 Capture

The scenario outlines two purposes for which the data is collected, first to inform the building managers of the current working environment and users’ feedback on it. In order to do so, individual participants will collect data, informing their awareness of and preferences for the conditions they work in. For data capture there are therefore two objectives, recording environmental conditions and also user reported observations and comments. Part of this is location-centric, gathering ongoing, long term data for particular locations. Part of this is person-centric, recording a participants 'exposure' throughout their working day.

Returning to the scenario, it is intended that recording the data is to occur alongside everyday activities, and participants are to act independently rather than in set groups. In their everyday work participants are likely to move around to other locations of interest or to somewhere else (e.g. to a lecture theatre, or going for a lunch break, going home, etc). Participants will be a sample of the building's occupants, as each workspace has limited capacity and is not always occupied, it will be difficult to record continuous data for each location using person-centric sensors alone. Participants may be too busy to specifically collect data, or may be in the wrong location to record information of use. This suggests a two part sensing system, a set of fixed sensors in locations of interest collecting long term data, coupled with handheld devices on which participants collect that information to monitor personal exposure and to add to it with feedback and comments. This once more develops the idea of both fixed and mobile devices working together, allowing both forms of information to be captured.

Another aspect of capture is the relationship with others, whilst primarily intended as an individual task, collaboration between participants may take place, for example when they work together or share the same space. Many forms of collaboration are possible in this environment however simplifying the capture process and the devices is an established priority, so this should be specifically limited to only a simple implementation to reduce complexity.

6.2.6 Reflection

Reflection activities involve reviewing collected data, processing it and visualising it, and sharing and discussing it. There are several different needs for reflection in this scenario, first is the need for immediate feedback for participants, providing immediate gratification when they contribute data. Unlike the earlier activities, over a longer term the enthusiasm to contribute may easily wear off, without the presence of facilitators to keep them "on task" participants' engagement will require more effort to sustain.

A second need is to provide more specific reviewing of the data, allowing participants to review their experience in order to reflect on it and develop their own understanding of the data. This follows on to the third need, which is to generate feedback for building managers who will be the ultimate users of the data. In order to facilitate this, the final need is a way to present back this data for it to be analysed and reviewed by the building managers on a location by location basis.

6.2.7 Relationship Between Activities

The initial stage started the process of designing the experience by thinking about the individual aspects of each activity; what breadth of tasks they might include and the depth to which they would be conducted based on the objectives of the scenario. Continuing the design of the experience this section develops the relationships between those activities; Figure 74 shows a diagram of relationships between the five activities, this indicates the desired connections between each activity, providing an outline from which to form the final implementation of the experience.

The experience is divided into three parts reminiscent of the earlier work: (1) the preparatory stage, (2) the fieldwork stage and (3) the analysis stage. In this experience however the relationships are more complex as it is not a simple progression through all three. The analysis stage feeds back into the fieldwork and brings in a re-planning element. Although there is minimal initial planning in the preparation stage, planning (and re-planning) takes place throughout the activity in response to new circumstances and information. In addition to this the fieldwork element and analysis element are closely linked with two way transitions between navigation, capture and reflection. This shows the requirement for the experience to interleave the activities even more than previously seen; this is explained further below where the activities and links they involve will be described.

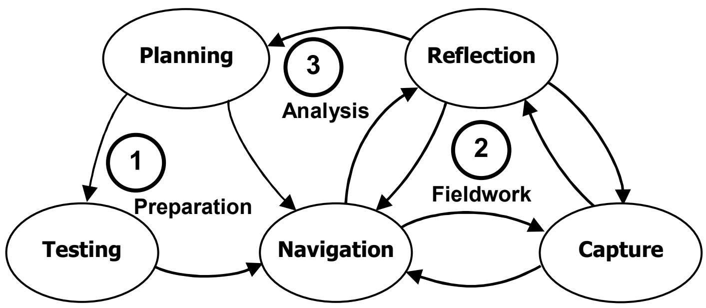


Figure 74: Planned relationships between activities in the new experience

First, the initial preparation stage (1) is similar to the Jamboree experience, involving both planning activities (background briefing and overall objectives) and testing activities (familiarisation with devices). The introduction is intended to be short and specific; the transition from planning to testing will be smoothly managed as the tasks involved in this stage are complementary to each other. From testing to navigation the transition will also be specifically directed, as this will signal the start of the fieldwork activities.

The fieldwork element (2) comprises of links between navigation, capture and reflection and represents the most complex part of the diagram. Participants move around and collect readings on an opportunistic as well as planned basis, this is represented by the connections between navigation and capture, as seen in both previous examples. The transitions between the two are user mediated allowing capture activities to take place when the circumstances are right. These transitions depend on the judgement of individual participants to decide on the timing and what their information capture activities will focus on, however they may be supported in this by appropriate features of the sensors. Earlier work suggested feedback from the sensors and opportunities for ongoing reflection as part of the fieldwork process. Following this concept, connections with reflection are planned, increasing the amount of feedback from the sensor to help inform users, and developing the integration of reflection activities into the fieldwork to specifically interleave transitions to and from reflection within the experience.

Inspired by the analysis of the previous applications, this feedback will include contextually triggered alerts, informing users of unusual readings, and soliciting comments linked to them to prompt a change to data capture or at least help develop the user’s understanding of the significance of the sensor readings they see. This both develops further understanding and is complementary to the capture process, as part of the data required is feedback from participants about their working conditions and the sensor readings of them.

Part (3), the analysis stage comprises of both the ongoing analysis and reflection tasks and the final results. The ongoing reflection activities involved with the fieldwork provide the opportunity for re-planning, so links are made from reflection to planning as part of this stage, and from planning to navigation. These transitions will be user managed; again placing the individual in control of the process, though supporting this through the flexible design of the sensors will be necessary. In the final stage, the data will be reviewed by the building management, who will be looking for a location-centric view of all the data collected. With the exception of setting the constraints of the scenario they are not included in the rest of the experience, the participatory sensing aspect involving the building users only (a more involved scenario may perhaps involve ongoing feedback and responses from them too). As concentrating on the participatory sensing aspect of the experience is the priority for this exercise, the main design effort will focus on the aspects involving them.

Table 7 summarises the features discussed in the chapter so far, listing them as requirements for the application that be developed to implement the experience.

Table 7: Summary of requirements for the sensor application

Planning	• Minimal initial planning stage • Set choice of sensors • Support ad-hoc planning – present options and inform users of opportunities
Testing	• Fixed sensors to eliminate unnecessary set-up and maintenance tasks • Opportunity for familiarisation • Straightforward in operation
Navigation	• Support a range of background modes; off, standby, background-working and repurposed. • Highlight opportunities for data collection when working in background • Respond to proximity of sensors
Capture	• Record person-centric and location-centric data – using fixed sensors and handheld devices • Collect environmental readings and participant feedback • Support participants working as individuals • Basic support for ad-hoc collaboration between users in the same location
Reflection	• Immediate feedback on results for participants • Ability to review batches of collected data • Record feedback from participants • Provide data for building managers to review.
Integration of activities	• Brief preparation stage including initial planning and familiarisation • Fieldwork stage involving navigation, capture and reflection • Feedback to develop ongoing reflection with notifications for unusual readings and prompts for further data. • Flexibility to allow re-planning

6.3 Features of the Application

Having developed the general requirements for the design, this section now looks at the sensor devices and “SensorShare”, the software application built by the author to implement the experience. The following sections will give an overview of the main features of the application describing the sensor system, how is it intended to be used and how the features relate to the earlier design work. A technical overview with a more detailed description of the hardware and software involved will be covered in the subsequent section, 6.4. First, the overall experience will be outlined, describing the setting in which the application will work. This consists of the preparation, the sensing activity and the final results stage as shown in Figure 75.

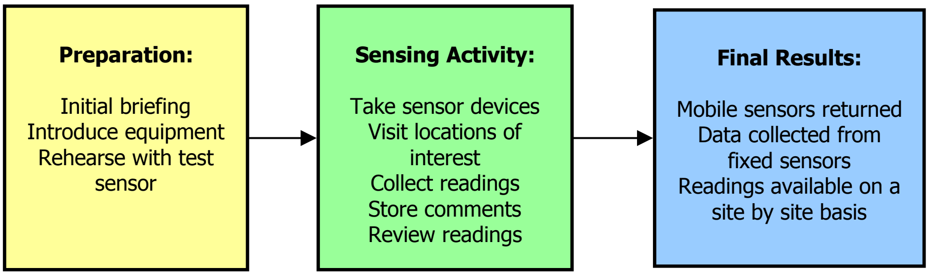


Figure 75: Three general stages of the new sensing experience

It is assumed that participants will be recruited to take part in the exercise in advance, and so the experience starts at the initial preparation stage with a participant ready to begin. They will be introduced to the activity with background information and the aims of the exercise being explained by the coordinator of the experience. The initial briefing, lasting only a few minutes, then moves on to the equipment with a short introduction about how it works. At this stage the participant will be allowed to try out the system with technical help on hand; they will be using two different handheld devices to interact with a fixed sensor specifically installed for testing purposes. The participant will keep the handheld devices for the duration of the experience; these devices are PDA "sensor interface" and an additional camera-phone "annotator". (Ideally these two devices would be one single unit, however in the prototype implementation this could not be the case).

During the fieldwork stage the participants go about their usual activities taking the devices along with them. When they approach a location of interest a notification will appear on the screen giving details of the fixed sensor nearby. Participants will have already informed of each location during the preparation stage, so this acts as a reminder a well as indicating that the sensor is present, functioning and available for access. Accessing the fixed sensor in a particular location allows participants to gather information by activating the capture mode on the PDA. When connected to a fixed sensor, the PDA begins to log the readings taken by the sensor and displays an instantaneous readout on the screen. The PDA application may also receive and display alerts about unusual readings, and participants may contribute further information using the camera-phone. They may also view the data in more detail using an additional graph display on the PDA; these features will be explained in detail in the following sections.

Collaboration is supported between two or more participants if they are collecting data from the same fixed sensor at the same time. Any annotations they make (responses to prompts, photos, written notes) will be pooled, allowing co-located participants to share and compare their contributions. All the data that participants view is stored on their PDA, so they may look back and review it at any time using another graph display mode. This allows them to review their data and reflect on their experiences; again these features will be specifically detailed in the following section.

The participants will take part in the experience over a number of days, allowing them time to collect a range of data and record details of various conditions – i.e. changes in weather day to day, or different uses of the area as the weekly timetable progresses.

The concluding stage of the experience is collecting the final results. In addition to the individual logs created by the users, the fixed sensors continually log the environmental conditions independently of the participants’ presence. When additional data is contributed by the participants this is also stored on the fixed sensors as well as their own device. This provides the location specific dataset required by the building managers – each fixed sensor can be collected, and the information downloaded onto a PC for analysis.

At the end of the experience, the devices are returned by the participants. They may choose to allow their own log data to be kept for review by the activity coordinators, so revealing the sensor readings they collected, the locations they visited and time spent at each place. Alternatively this information can be deleted to leave only the data from the fixed sensor logs: the annotations they specifically contributed alongside the complete set of sensor readings for that location. This will be done when the sensors are returned so that the choice can be clearly explained.

The rest of this section will now concentrate on the sensor application itself, explaining the features in more detail with screen shots and technical explanations.

6.3.1 Overview of Fieldwork Activities

The central part of the sensor application is the PDA based interface that each participant will carry during the experience. This interface provides the main point of interaction between each user and the sensor system, and it also keeps a personal log of the data they collect. The handheld device works alongside the fixed sensors installed in locations of interest which log the environmental conditions of the area and transmit them to the handheld units. This configuration allows each participant to log the environmental conditions in the locations they visit and create a record of their experiences. The fixed sensors also log the readings, even when there is nobody present, so the combined system collects both a person-centric and location-centric set of readings.

If unusual readings for a location are detected by a fixed sensor it may alert any users currently recording its readings. The alert comes in the form of a question dialogue box containing a description of the readings and a prompt for feedback. The user may choose to respond to the question with a few lines of text or dismiss the alert if they don’t want to reply. Responses submitted by each participant are stored on the fixed sensor alongside the readings for that location, they are also stored on the user’s own handheld device for them to review later. If other participants are viewing readings from the same sensor the annotations will also be passed on to them, allowing users in the same location at the same time to share their annotations.

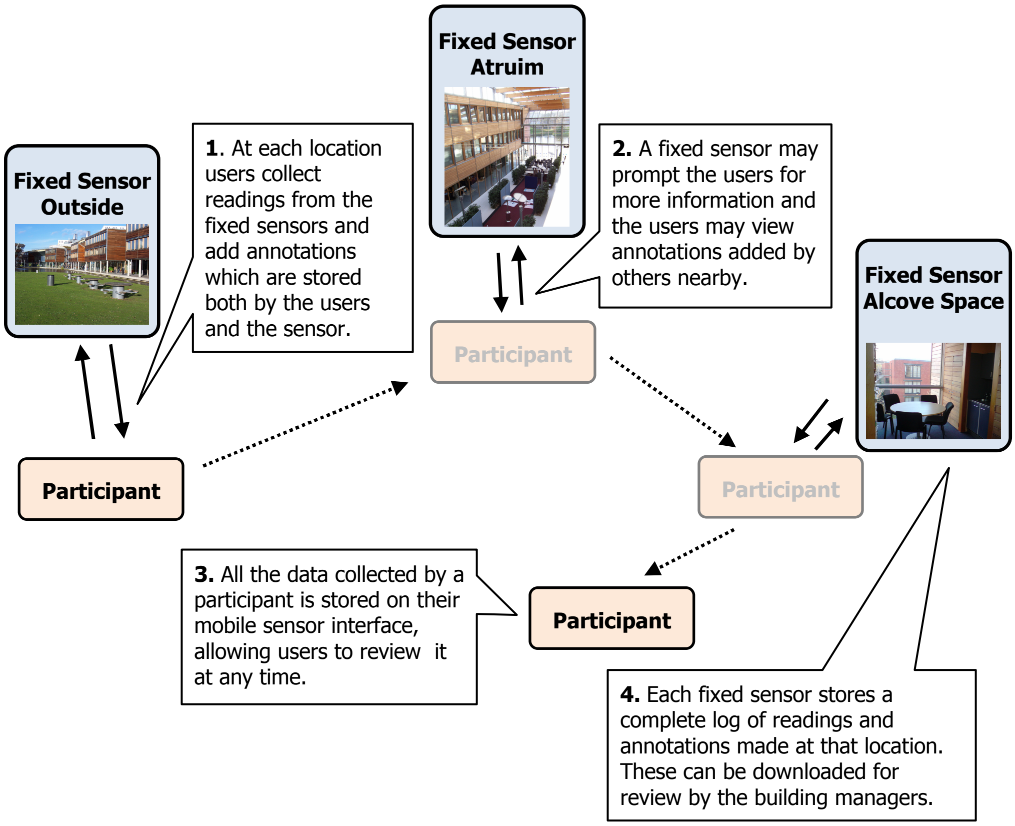


Figure 76: Overview of SensorShare system

Two more sensor applications can also annotate the sensor data collected by the SensorShare system, these are designed to run on a mobile phone; users can switch between the two as desired. One application allows photographs to be taken and attached to the sensor log, the other allows written notes to be added. As with the sensor readings and question responses, these annotations are stored both by the fixed sensor at the location they are recorded and by any participants recording this sensor’s data at the time.

The relationship between the fixed sensor, the PDA interface and the phone applications are illustrated in Figure 77. This shows how the main PDA based Mobile Sensor Interface, the Fixed Sensor and the two additional mobile phone annotator applications (Camera Sensor and Note Sensor) communicate with each other at one location.

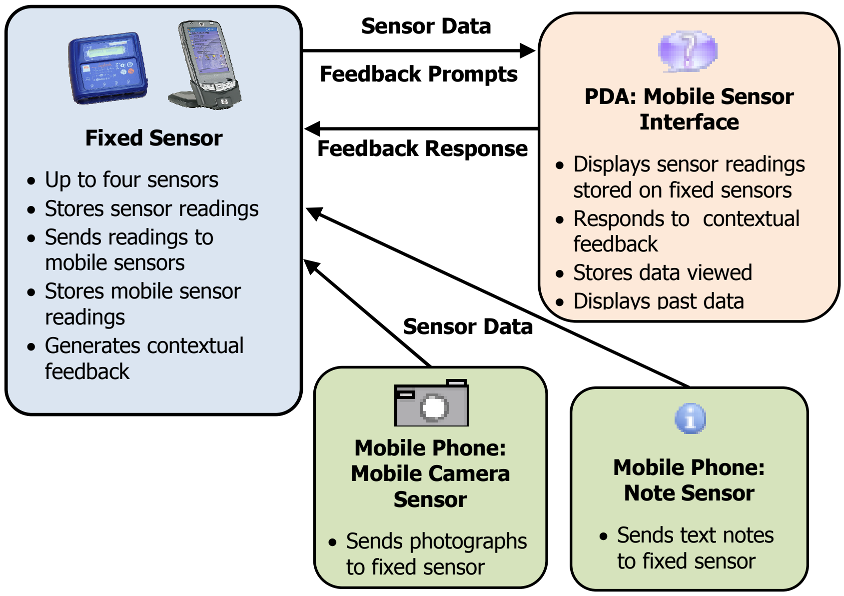


Figure 77: SensorShare components and overview of functions

The fixed sensor uses a commercial datalogger (a ScienceScope Logbook, as used in earlier work) paired with a PDA unit. The device supports up to four sensors chosen from a range of sensor modules. These allow each sensor installation to be customised to detect a variety of elements; for the environmental conditions investigation three modules will be used to record light level, sound level and temperature.

The combination of fixed and mobile sensors was mentioned in the earlier section; the static sensors provide reliable long term readings at each place, the mobile device on the other hand gathers data from each location a participant visits – providing person specific readings for them to recall later. As the environmental readings come from a fixed location they are less subject to the noise and interference inherent with handheld sensors, as seen to pick in the earlier studies. This configuration also simplifies the handheld device, so reduces the time required for set-up and familiarisation; another need that was identified earlier. The use of a standard PDA rather than a custom unit supports this further by drawing on existing familiarity with these devices.

Another design requirement was to solicit feedback from participants and encourage ongoing reflection within the experience. Features of the application have been introduced to support this, particularly the question prompts which alert the user to unusual readings and ask for more details. This is intended to compare their experience with what the sensor data indicates, and provides an opportunity for feedback based on it. Further reflection opportunities are provided by the ability to view comments of other people viewing the same data, giving another perspective on the readings.

Finally a third objective was to provide flexibility to account for re-planning within the fieldwork stage. Including the additional reporting devices, the camera-phone based annotation tools provide flexibility to record observations in different ways. It was not possible to integrate the annotation features and the sensor interface due to the processing limitations of the devices available however the phone platform provided an appropriate supplementary unit for a number of reasons. It is another consumer product that is familiar in operation, in addition a mobile phone is often carried alongside a PDA, so should not present a significant additional burden on the participants. The phone can be packed away until needed and brought out relatively easily as mobile phones are designed for a long standby life and a short wake-up time.

6.3.2 Interaction with the Sensor Server

This section gives a walkthrough of the sensor applications in more detail, demonstrating the use of the sensor devices and the features of the interfaces. First the Mobile Sensor Interface will be explained and then the additional components will be shown.

6.3.2.1 Mobile Sensor Interface: Searching and Connecting to a Sensor

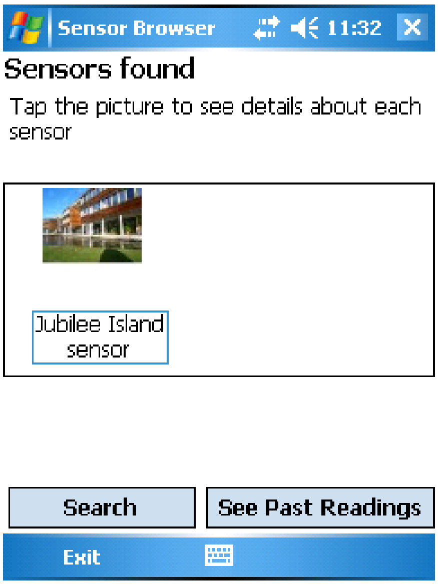


Figure 78: Mobile sensor interface: Sensor search screen

The initial screen on the mobile sensor interface application displays a list of fixed sensors within range of the PDA's wireless networks, this updates periodically and users may specifically start the update process by tapping the search button. This screen also allows the user to review information they have gathered so far by tapping the "See past readings" button, this accesses the stored data on the PDA and as shown further below in section 6.3.3.

The results of the search show the name of the sensor and an image which is associated with it (Figure 78). When it is selected a further description of the sensor is shown at the bottom of the search results (see Figure 79, left). This information can be configured on each of the fixed sensors, allowing them to be identified by a name, image and text description. Choosing a sensor lets the user click the "Collect Readings" button, starting the recording of data from that sensor and bringing up the sensor information page which displays the sensor's data. When the sensor information page is opened the latest reading received is shown on the screen as well as the detailed description of the sensor, as shown in Figure 79, right.

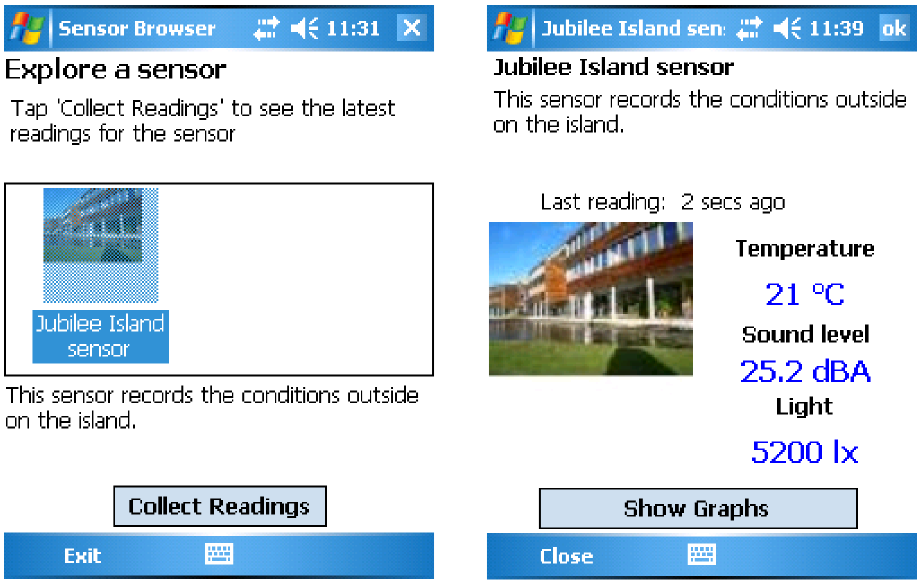


Figure 79: Mobile sensor interface: Sensor details (left), initial sensor information screen (right)

In addition to the readings a timer counts up to show how long ago the last reading was received. This gives an indication of how up to date the readings are and how frequently the readings are taken. The final part of this screen is a "Show Graphs" button which opens page to display the sensor readings in more detailed graphs.

The initial screen acts as a starting point for the application, it updates as sensors come into range of the wireless network on the PDA and can be left running in the background, or stopped and restarted, supporting the range of navigation activities discussed in 6.2.4; standby, 'packed-away' and repurposed. The sensor detail screen continues logging the readings unattended, and so this supports background operation as another aspect of navigation activities.

The sensor detail screen is more oriented toward capture activities and as well as showing the latest readings, provides additional features to support this. As noted in the earlier work understanding of the way individual sensors worked was an issue, the additional information provided is designed to give more information about them, for example the photo and text can provide further details about the fixed sensor, and the "last reading" timer can help participants build an understanding of the frequency that readings are being collected at. The timer also helps the user maintain their balance between capture and navigation activities. It shows when the readings were last updated so they don't have to closely follow the readout when recording readings. This is developed further in with the graphs page, described next.

6.3.2.2 Mobile Sensor Interface: Viewing Graphs and Comparing Readings

From the sensor details page, tapping the "Show Graphs" button opens the sensor graph page, which displays a rolling graph of the sensor readings. As readings are received the graph is updated, adjusting the time axis to keep the current time at the right hand side of the screen. When the graph page is first loaded the previous 120 seconds of readings are retrieved from the fixed sensor, populating the graph with a small amount of current data to compare alongside the current readings. A time-span of two minutes was selected to provide enough data to give an impression of current conditions, filling the graph display but not adding in data over a time period that misrepresents the user's experience.

The graph page has a set of tabs, representing each sensor module on the fixed sensor the user is currently collecting data from. Controls on the page allow the user to zoom in and out and scroll the time scale to explore the readings; the graphs across all the tabs are synchronised, so the same time-span is shown for all three kinds of readings at the same time. When the user changes the view, the graph stops scrolling, allowing them to hold particular readings in view, the "Back To Now" button resets the graph so that it again scrolls along with time again.

Readings are represented on the graph as thin red bars located at the instant the reading was received from the fixed sensor. This graph format was chosen in order to represent the instantaneous nature of the readings, taken at a particular moment rather than an average over the period between updates. A line graph that connected one reading to another implies a continuous recording, the thin bars in this case are intended to help build understanding of the sensors used, as with the other features described earlier.

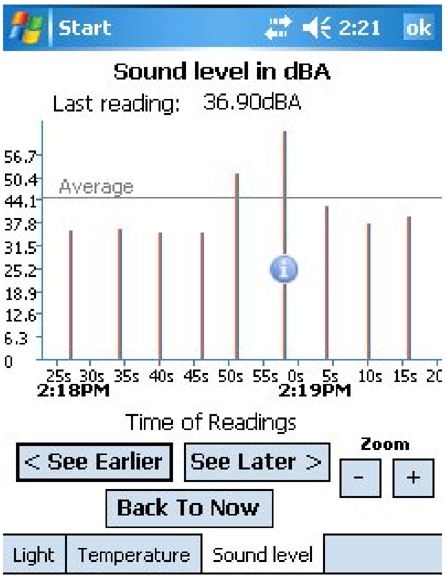


Figure 80: Mobile sensor interface graphs page, showing icons indicating annotations added to the data.

The graph page also shows a number of other pieces of information as well as ongoing readings. One feature is an average line indicating the cumulative average of the readings measured by the fixed sensor. This includes all the readings stored for the lifetime of the sensor, giving a "historical" perspective of the current readings in relation to the usual conditions.

The graph feature introduces two elements to the dialogue with the sensors; first as with the timer on the sensor information page, the live updates of the graph help give a sense of timeliness to the data and gives more feedback from the sensors, providing information to help the participants make more informed decisions over what data they collect. The second element to this is the reflective part, allowing viewers to review a series of readings in the field, compare them with the overall average and build up experience of how they correspond to the conditions and improving the ability to distinguish trends from sensor noise.

The final aspect to the graph display are the three kinds of information icons, these indicate the presence of annotations added to the data as mentioned earlier. Different icons represent photographs, notes and question/answer icons, clicking on each of these opens the annotation viewing page, prompting the mobile interface application to download the annotation from the fixed sensor; this is described in the next section.

6.3.2.3 Mobile Sensor Interface: Viewing Annotations

On the graph view tapping on an annotation icon opens the annotation page as shown in Figure 81. When the page opens the process of downloading the annotation is started, and while the download takes place, a holding message is shown. Depending on the annotation type, either the photo is shown along with the details recorded with it, a graphic alongside the question/answer, or the text note is shown. When an annotation is viewed it is also stored so that users can access it later along with the sensor readings the annotation is attached to. If multiple annotations are attached to the same moment then they appear as additional tabs which can be selected at the bottom of the screen.

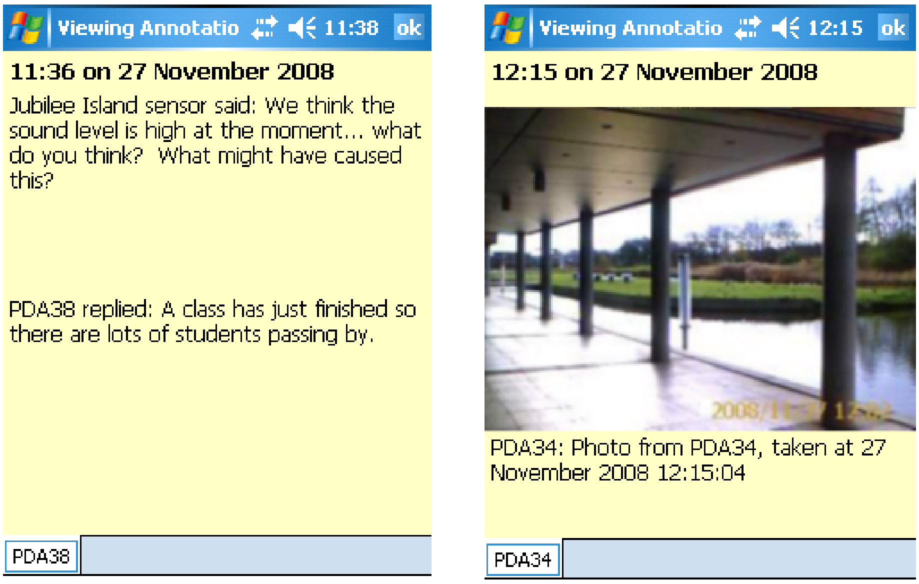


Figure 81: Mobile sensor interface annotation viewing page showing a question and answer annotation on the left and a photo annotation on the right.

The annotation viewing feature provides more reflection activities within the experience through commenting on the readings and the ability to see additions by other participants sharing the same space. This encourages the transition between reflection and capture, which is further developed by the next feature to be introduced, the question and answer prompts.

6.3.2.4 Mobile Sensor Interface: Question and Answer Prompts

The fixed sensor sends question messages to the mobile interface on the basis of the readings it collects. These question messages pop up on the mobile interface application as shown in Figure 82. The question page shows a question generated by the fixed sensor, and it also displays the latest readings sent by the fixed sensor. The user is given two options, to type an answer and send it to the fixed sensor, or to pass the question and go back to their previous activity. If the user doesn’t enter anything into the answer box then it will automatically close after 20 seconds and if a newer question is received before the user starts to write an answer it will be replaced. These features are intended to keep the questions up to date with the latest readings and ensure that any observations are made within a short period of the readings that initiated the question.

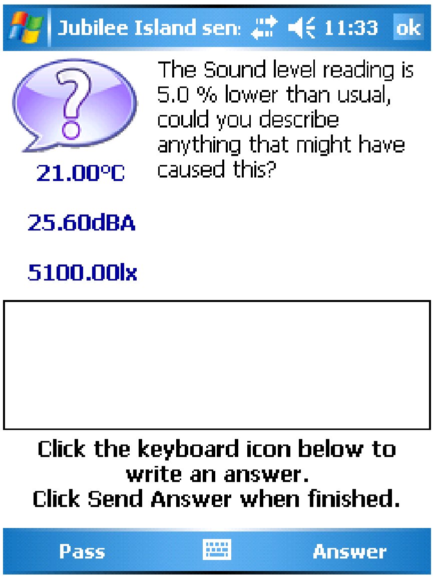


Figure 82: A question message popup window on the mobile sensor interface application

6.3.2.5 Mobile Phone Sensors: Adding Photos and Notes

The PDA phone applications that create photo and text annotations both function in a similar manner, the initial screen is very simple (Figure 83), displaying a list of sensors detected within range and search and exit buttons. Tapping a sensor icon selects the sensor that the annotation will be sent to and switches to the phone's camera mode or to the text entry screen as shown in Figure 84 and Figure 85.

Figure 83: PDA Phone sensor fixed sensor search screen

Both annotation authoring screens are designed to work with the device in landscape mode as the phones use this orientation for camera and text entry modes (see Figure 88 in section 6.4). When the annotation is created it is sent directly to the fixed sensor where it is stored and then relayed to any mobile interface applications in range.

Figure 84: PDA Phone photo sensor – camera mode

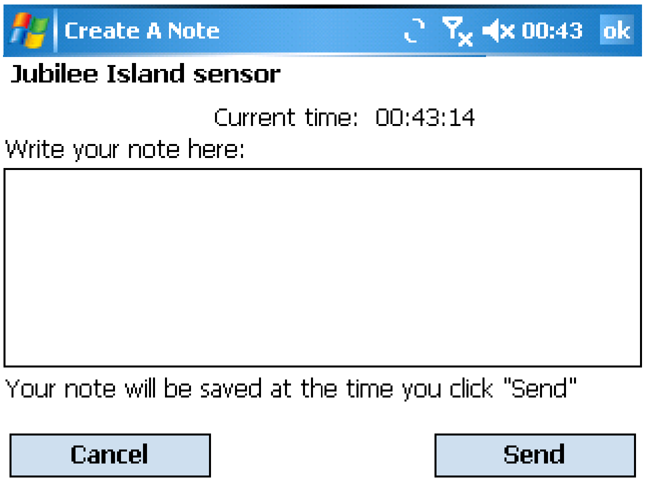
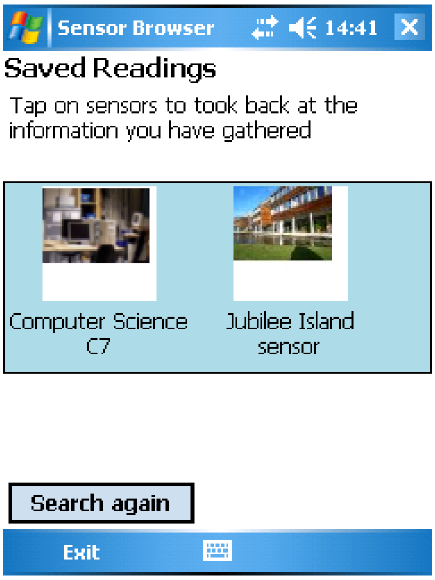


Figure 85: PDA Phone text sensor, text entry mode.

6.3.3 Mobile Sensor Interface: Reviewing Data

The data viewed on the mobile sensor interface is stored on the PDA allowing readings and annotations associated with each fixed sensor to be recalled by clicking on the “See past readings” button on the initial screen. This replaces the search results with a list of all the fixed sensors, selecting one of them opens the graph view page populated with the readings stored (Figure 86). Initially the graph is scrolled to the last reading seen from which the user can scroll back or zoom out to see further readings and any annotations that are included with them.



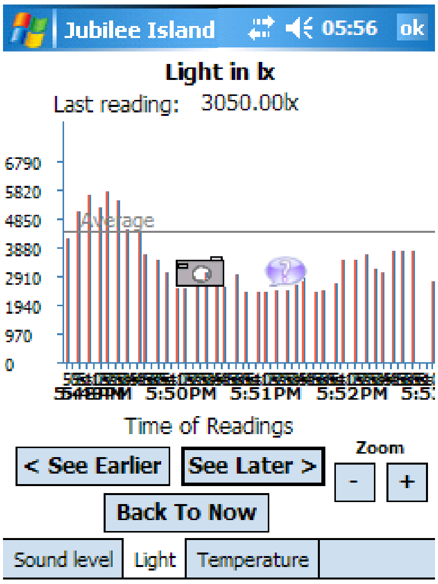


Figure 86: Mobile sensor interface, past sensor browser, selection screen (left), graph view (right).

When reviewing past readings the average line of the graph indicates the average of the readings stored by the user, rather than the long term average for a location which is shown on the live graphs screen – this helps participants form an understanding of how their experiences compare with the average for each location.

6.4 Technical Implementation

This section gives more details about the hardware and software used in the SensorShare sensing system. The Logbook datalogger, PDAs and phones are commercially available devices, the PDAs and phones run the specifically designed software that has been explained above; this consists of four applications "SensorServer", "SensorClient", "CameraSensor" and "NoteSensor". The hardware will be described first, then the network communication components that allow the system to interoperate will be explained, then finally more details about the design of the application will be given, explaining the data storage components and the question generating part of the SensorServer (fixed sensor) application.

6.4.1 PDA Platform

Three handheld devices are used within the SensorShare application: the HP iPAQ hx2795 (Figure 87), the i-mate K-JAM (Figure 88) and HTC TyTN (Figure 89); they are all Windows Mobile based devices, running either Windows Mobile 5, or Windows Mobile 6. All of the devices have Wi-Fi networking, Bluetooth capability and have a touch screen interface. The i-mate and HTC PDA phones have built in digital cameras and slide out keyboards. When the keyboard is opened, the device switches to landscape orientation mode, rotating the display on the screen accordingly; it is used in this configuration for the note taking sensor application. Two kinds of phones are used, demonstrating the application with different hardware specifications and catering to availability (the more powerful HTC phones were not widely available at the time of development). Detailed specifications are given in the table below:

Table 8: Specification of handheld devices used

	iPAQ hx2795	i-mate K-JAM	HTC TyTN
Main Processor	Intel PXA270 624MHz	TI OMAP 850 200MHz	Samsung SC322442 400MHz
RAM	64MB	64MB	64MB
Storage Space	144MB	128MB	128MB
Screen Resolution	240x320	240x320	240x320
Operating System	Windows Mobile 5	Windows Mobile 5	Windows Mobile 6

Figure 87: HP iPAQ hx2700 series PDA, standalone (left) and in docking cradle (right).

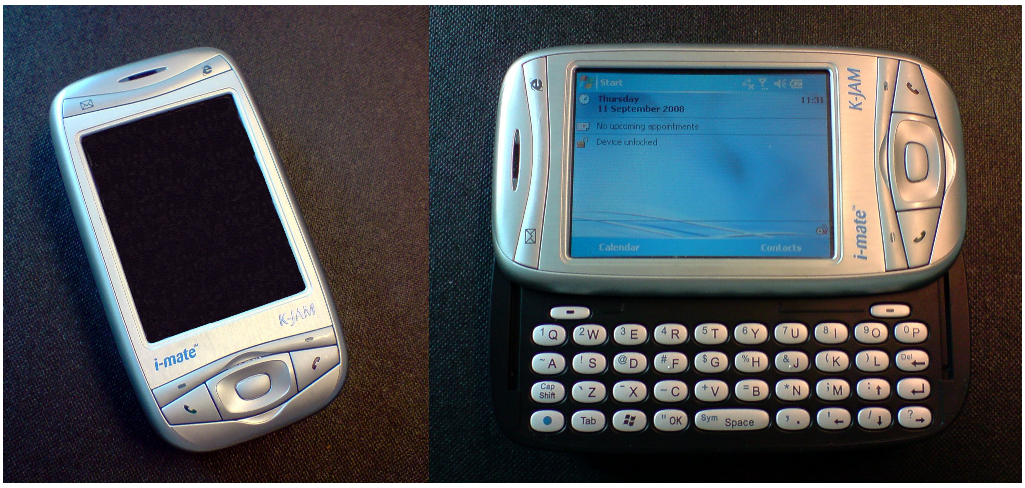


Figure 88: i-mate K-JAM PDA phone, with keyboard closed (left) and keyboard open (right).

Figure 89: HTC TyTN PDA Phone, front view (left) and reverse view showing the camera (right).

6.4.2 ScienceScope Logbook

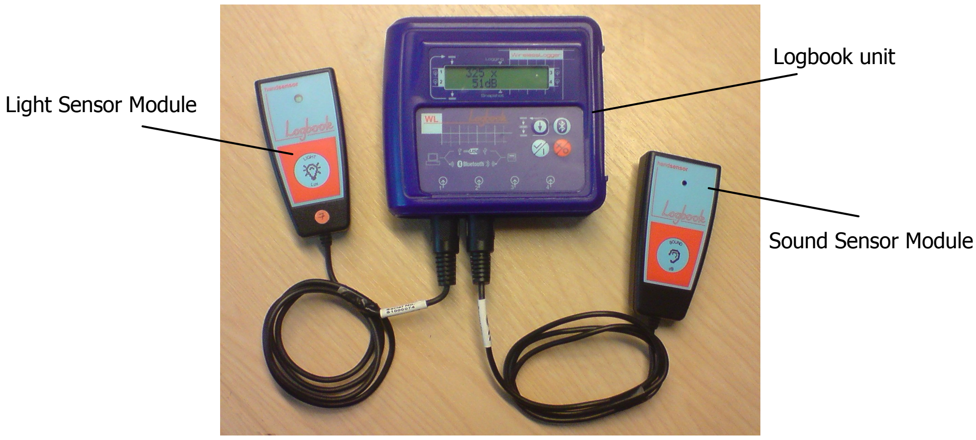


Figure 91: ScienceScope Logbook unit with two sensor modules

The ScienceScope Logbook is used alongside one of the iPAQ PDAs to form the fixed sensor in the SensorShare system. It was not feasible to modify the hardware directly to provide an all-in-one unit, so for this prototype design the two devices were used together, combining the processing and communications ability of the PDA with the high quality, modular sensing system of the Logbook.

The dataloggers were used in the earlier work for the Participate project and used for the study at the World Scout Jamboree. In this sensor system the Logbook is used in a different way; rather than logging the readings they are relayed instantly to the PDA. This is done using the Bluetooth serial port built into the device, allowing the PDA to connect to it and receive readings. The Logbook’s modular sensor system means it can be used with various sensor configurations and also support a number of sensors at the same time. Some additional sensor modules are shown in Figure 92.

Figure 92: Examples of logbook sensor modules: temperature (left), sound (top), light (bottom)

6.4.3 Connections between Devices

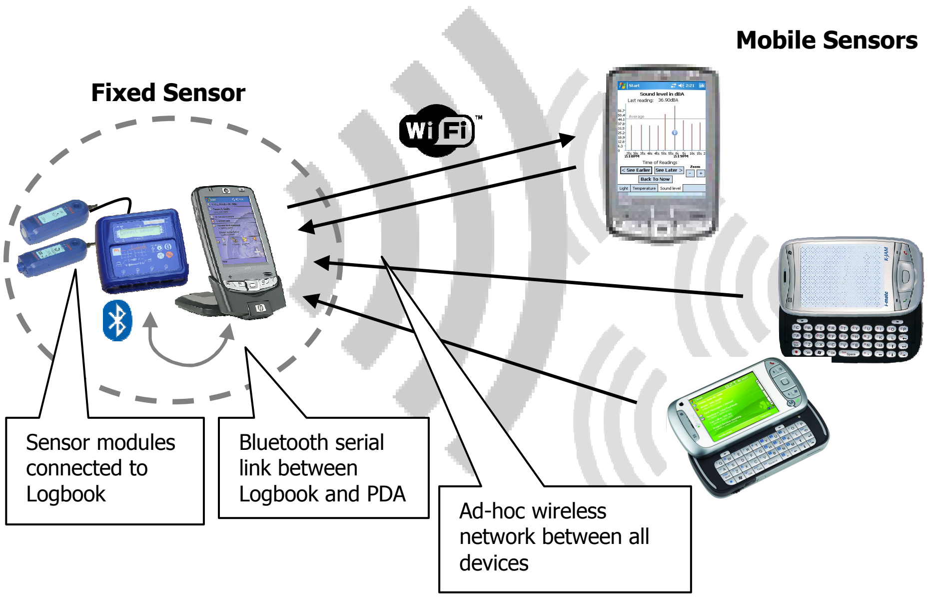


Figure 93: Wireless connections between the devices in the SensorShare system

Figure 93 illustrates the connections between the components of the system. The fixed sensor is comprised of the Logbook (with sound, light and temperature sensor modules plugged into it) linked to the fixed sensor PDA using a Bluetooth serial port connection over which readings are received.

The fixed sensor PDA and the mobile PDAs communicate using an ad-hoc peer-to-peer wireless network. The users are expected to move from fixed sensor to fixed sensor, each installed at a different location, so individual device will frequently come into or go out of range. The ad-hoc wireless network allows devices to communicate with those nearby with no additional configuration required when this happens. The range limits of the wireless network adaptors limit which sensors are accessible, meaning users should be near enough to a fixed sensor to use the sensor description to locate it and observe the area the readings are relevant to. As the users bring their mobile devices within range of a fixed sensor the automated search will pick up the sensor and update the search page with its details, which can display a number of sensors at the same time.

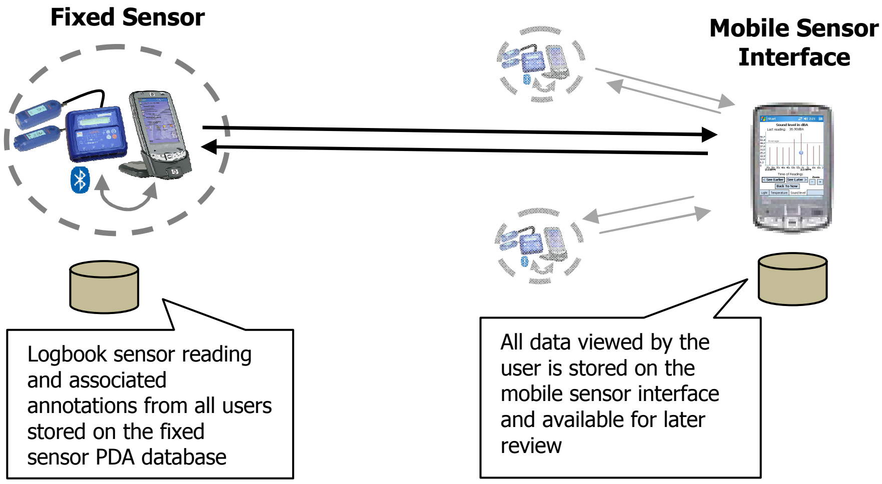


Figure 94: Data stored on static and mobile devices

Sensor data is stored in databases on both the fixed sensors and the mobile sensor interface PDAs. Both devices store different sets of data, on the fixed sensor all Logbook readings and annotations contributed by the users are stored, giving a sensor/location centric set of readings. As different users visit the sensor and leave annotations, the database builds up to provide a compilation of multiple users' reports alongside the sensor readings. The mobile sensor interface instead stores user centric data, logging all the readings and annotations viewed by the user during their activities allowing the users to review their experience a later time.

6.4.4 The Application Setup

This section covers the details of the applications written for the SensorShare system. They were written using the C# programming language, based on the Microsoft .NET Compact Framework (version 3.5)[9]. Additional open source libraries were used from the OpenNETCF Smart Device Framework Community Edition (version 2.2)[10]. A number of different components of the system are described below, covering the details of the network communication system, the databases used to store sensor readings and annotations and the way in which question messages are generated and stored.

[9] Microsoft .NET Compact Framework, http://msdn.microsoft.com/en-gb/netframework/aa497273.aspx
[10] OpenNETCF Smart Device Framework, http://www.opennetcf.com/

6.4.4.1 Network Communication

The underlying component of the SensorShare applications is the communication component. This allows the devices to communicate with each other using the wireless network. Communication over wireless networks can be intermittent, especially as in this application users will be moving in and out of range of the fixed sensors. Based on the approach taken by the WiFi Communications Framework sample (Wilson, 2004) the network communications component uses UDP datagrams to send data, both as packet broadcasts and to individually addressed endpoints. The use of a peer-to-peer wireless network means that multicasting methods are not as suitable; since network connections are intermittent the application would be required to reconfigure to receive multicast each time the connection was re-established – presenting an additional programming overhead. The intermittent network connectivity also means that connection based protocols (i.e. TCP) are less suitable, so a custom UDP based communication layer provided the simplest option in this case. The applications are designed to connect all the devices to the same peer-to-peer ad-hoc network with a fixed SSID and WPA encryption key, ensuring only SensorShare devices may connect to the network. This also means no further network configuration is necessary during the fieldwork and that fixed sensors do not conflict when a participant is in range of both.

The fixed sensor application uses broadcast messages to send sensor readings over the network, this means that any devices within range will receive the readings without having to explicitly notify the sender (of both subscriptions and unsubscriptions). This is beneficial when devices drop in and out of network range as their specific IP address may change or connections may be lost unexpectedly.

In order to discover the fixed sensors the mobile sensor applications also use UDP broadcasts to request description messages. Any fixed sensors within range will reply with a message containing the description, consisting of name, description, sensor image and sensor types. The packet size limit for broadcasting on the wireless network prevents the fixed sensors from directly broadcasting their descriptions, so these and other larger messages (i.e. image annotations) are sent directly to the IP address of the requesting device. This is automatically handled by the networking component; when a large message is sent an initial “message available” message is broadcast first, trigging the intended receiver to reply with a message - the IP address of the recipient is determined from this reply, allowing the message to be specifically targeted. This technique helps compensate for the wireless network devices’ intermittent network connectivity as they join and leave the ad-hoc network.

When sending directed messages a second size limit is imposed on data sent over the network; the maximum size of a UDP datagram is 65,535 bytes; messages greater than this size are spanned across a number of packets. UDP neither guarantees that each individual packet will arrive or that they arrive in order of transmission, so the network component of the sensor system has to account for this too. The larger the message size, the more likely it is not to be received; this is particularly a factor when transferring the sensor description and photo annotation messages which both contain JPEG images (a 320x240 pixel photograph taken by a PDA phone is on average 10,240 bytes in size). The network communications component compensates for this by splitting large messages into 500 byte parts and implementing a basic caching and retransmission protocol. The 500 byte size was chosen based on existing work such as (Xylomenos & Polyzos, 1999), indicating a higher throughput at this size, and it was provisionally validated with basic prototyping during development.

Each message fragment includes a message ID, fragment ID, fragment total and lifetime value. Fragments are cached by the sender for twice the given lifetime. The recipient may then request retransmission of individual fragments to account for packets that were lost. When the parts of a fragmented message are received they are added to a buffer on the receiving device. The buffer is checked periodically and missing fragments are requested, until the lifetime of the message is exceeded (this is timed from the moment the first message fragment is received), messages stored on the server are cached for twice this time, allowing time for communication delays and transmission time. If a message fails to be fully received in this period, it is considered lost, so the application must account for this when a message is anticipated. This architecture was chosen as a compromise between reliability and the implementation of a more complex protocol requiring additional resources.

The communication process is illustrated in Figure 95, this gives the sequence of events for two messages, first a description request broadcast and then the description message being sent directly in response – this shows the two methods of message sending.

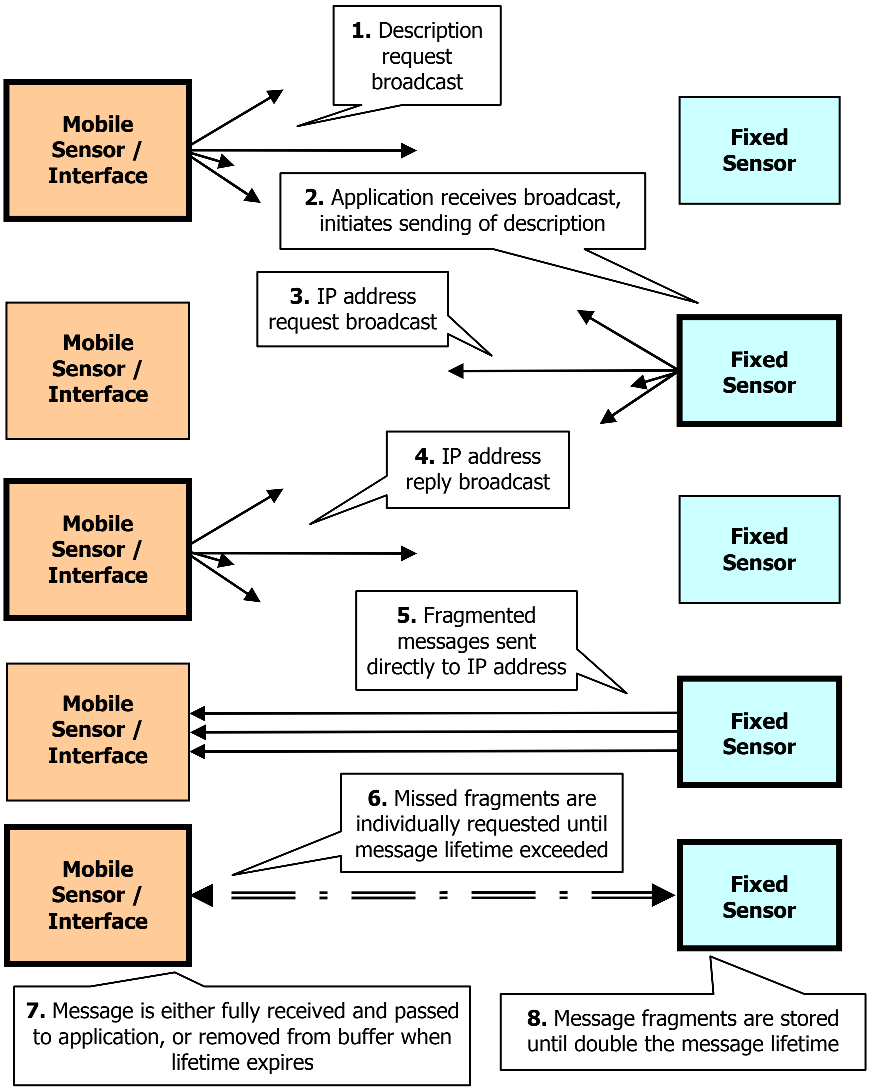


Figure 95: Sequence of events in sending a description request and directly sending large messages

The first message is handled relatively simply, the response to the description request is handled at the application level rather than within the networking component. Description requests and sensor readings are also sent using this method.

The second message is a large message which requires fragments to be directly sent and the receiver to check for missing fragments, the network component automatically handles this with the received message being passed on to the application level when it is completed. As well as description messages, this technique is used for sending photo annotation messages to and from the fixed sensor.

The steps of the process in Figure 95 are explained in more detail here:

1. **(Application)** Mobile device broadcasts description request message on the local network, the message contains the unique ID of the device.

2. **(Application)** The fixed sensor receives description request and the application initiates sending of a description message.

3. **(Network Component)** The network component of the application splits the description message into fragments and places them in a buffer. An IP address request message is broadcast, containing the ID of the target device (the mobile sensor).

4. **(Network Component)** The network component of the requesting device automatically replies.

5. **(Network Component)** The IP address origin of the reply message us used by the fixed sensor to send all the message fragments in the buffer.

6. **(Network Component)** The mobile device requests any fragments it has not received after a short period and the fixed sensor re-sends them from the buffer.

7. **(Network Component)** If all fragments are received, the message is passed on from the network component to the application. If the message lifetime expires first, the buffer is cleared.

8. **(Network Component)** The sending device stores the message fragments in the buffer for twice the message lifetime, allowing time for the receiver to request missing fragments.

6.4.4.2 Storing Readings

Readings on both the fixed sensor and the mobile sensor interface are stored in a Microsoft SQL Server Compact database. Figure 96 shows the database tables and their relationships on the fixed sensor. The “Sessions” table stores information about each installation of the sensor server, assigning a unique ID number to each installation (with a given name, description, the time it was set up and the file location of the image used with it). Readings from the Logbook are stored in the “Readings” table, along with the session ID, linking readings stored to an individual installation. Similarly the “Questions” and “Annotations” tables store questions generated by the fixed sensor application (each question with a unique ID), and any annotations added by mobile sensors. The “Annotations” table contains a field for annotation type (answer, note or picture annotation) – with fields included for each kind of data – answer annotations store the question ID, allowing this to be included as part of the annotation data when it is viewed. In addition, annotations have an author ID (the unique ID of the device that sent it), and an author field, which can be the username of the user of the device at the time. The Question table also has an author field allowing the fixed sensor name to be stored along with the question, or a specific user name attributed to the question if needed. Finally the "Log" table stores time-stamped log information for debugging purposes.

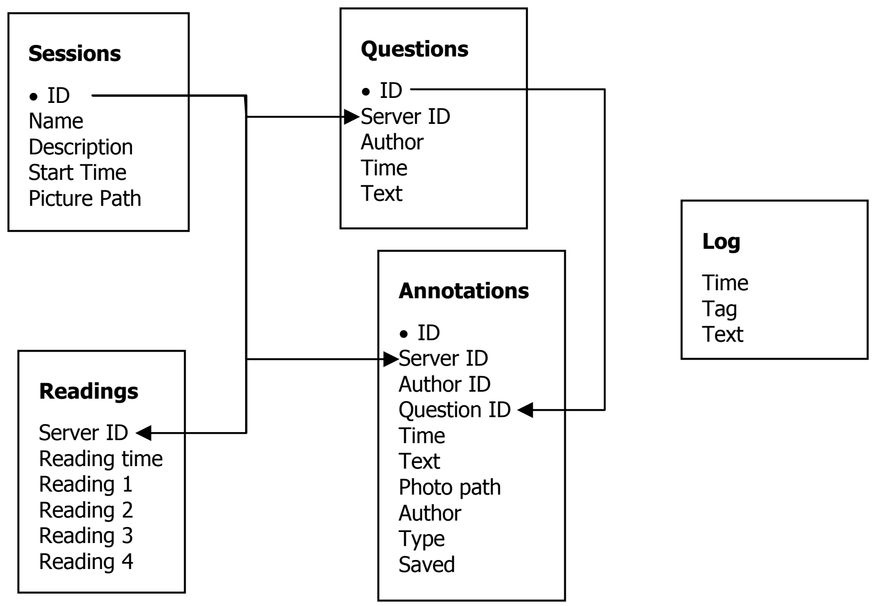


Figure 96: Fixed sensor database schema

The database on the mobile sensor interface follows a similar format (Figure 97), further information about the fixed sensors is stored in the "Servers" table, which includes the same information as the "Sessions" table above, but also further details about the sensors plugged into it (sensor identification numbers, sensor names, and the units the readings are given in). The "Readings", "Questions", "Log" and "Annotations" tables also follow a similar format, though the Annotations table includes an additional field "Saved" indicating whether the annotation data is yet to be fully downloaded from the server or is stored in the database already.

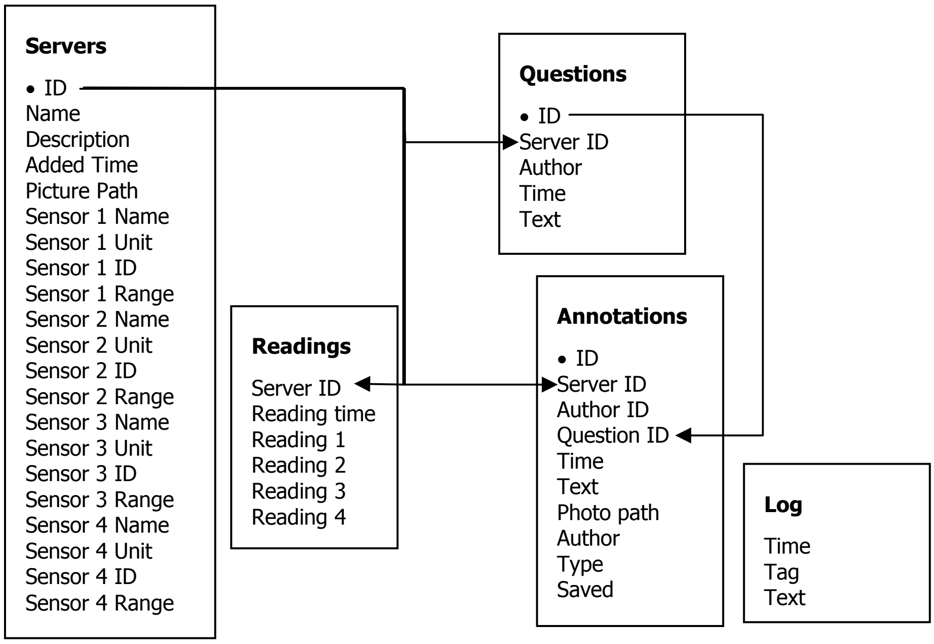


Figure 97: Mobile sensor interface database schema

6.4.4.3 Generating Questions and Answers

The fixed sensor application generates questions based on the last one minute worth of readings compared with all the previous readings stored in the database. The questions generated fall into three categories, as chosen by the process in Figure 98.

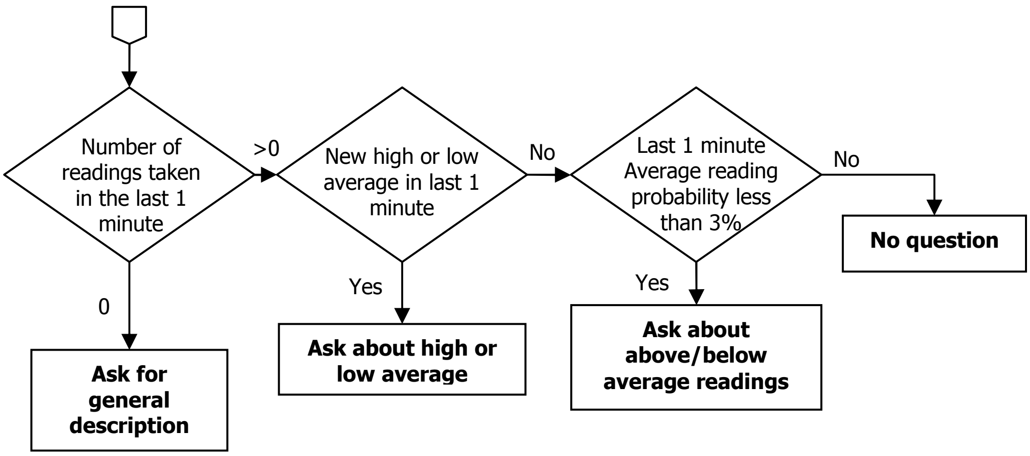


Figure 98: Fixed sensor process to choose question type

The process examines the readings over the last 60 seconds. This time period was chosen as a threshold to ensure that questions reflected readings collected recently enough to ensure participants can report related observations (such as a possible cause of new high or low figures). Three types of question can be generated; the first type of question accounts for potential problems with the sensor: if no readings have been received in the past minute then the sensor will generate a question asking for a general description of the area as below:

```
Help us record the area, tell us something you can see happening nearby...
```

This helps mitigate any problems with the sensor, collecting alternative observations instead, and provides further potential to develop error reports to assist in the management of the system.

The second type of question is asked if the maximum or minimum figure in the last minute exceeded the previous maximum or minimum – these questions are based on a template where the sensor type, the units and the values in question are added, as shown below (template variables in square brackets):

```
In the last few minutes the [sound] reading reached a new high! It was [96dBA],
[10%] higher than before.  Can you explain this?
```

```
The lowest [sound] reading has recently been set.  It has fallen [9%] from
[67dBA] to [61dBA].  Can you describe what you're currently doing or what is
happening around you at the moment?
```

If the highest or lowest reading of more than one of the sensor modules is recorded then the application will choose the one with the largest change. If the relative change is equal maximum, then the first sensors are chosen in numerical order based on their port on the Logbook. This allows an order precedence to be configured by the user when the sensor is installed.

If no high or low readings are set by the current reading the third type of question looks at the last minute worth of statistics. The mean of the last 1 minute of readings is compared in respect to all earlier readings collected by the sensor. The probability of each reading is calculated using a normal distribution approximation based on the earlier data. If the probability of the current 1 minute average is less than 3% then a question is generated about this reading. As with the high or low readings, if more than one reading meets these criteria they are chosen in the order of the sensor ports on the Logbook. The text of these questions also fits into a template:

```
The current [sound] reading is [15%] above average, at [81dBA].  Do you know
what could be causing this?
```

```
The [sound] reading is [15%] lower than usual, could you describe anything that
might have caused this?
```

This process generating these questions executes every 60 seconds when the sensor is running. In addition another process generates questions when sensor readings are received. This accounts for instantaneous high readings and generates a question as soon as they happen:

```
We think the [sound] is high at the moment... what do you think?  What might
have caused this?
```

```
Low [sound] readings have been detected, has anything happened that might
explain this?
```

This question generating system demonstrates a basic implementation of what could be a more complex dialogue, providing contextually relevant information and requests in response to sensor readings. Developing this further, the process could be improved with more accurate statistical models of sensor parameters, such as expected daylight levels throughout a day, it could also take into account the average readings based on what the participant has recorded, rather than the location, or across multiple locations. Further feedback may also include questions generated by other participants, or other responses to similar readings, and account for readings across multiple sites at the same time.

6.5 Preliminary Testing and Use

The majority of this chapter focuses on the design and implementation of the SensorShare system. The system has been presented as a demonstration prototype to exemplify and embody the framework by linking the theory up to practical work. Continuing to evaluate it as a final product would have been desirable though this was beyond the time and resources available; this section therefore briefly reports the on the preliminary testing that took place as part of the development process and through a number of demonstration events.

During development the software underwent testing in an iterative manner. Functional components were isolated and tested individually: the networking elements, database access, Bluetooth connections and Logbook communications, etc. These were then combined and tested in the individual applications: fixed sensor, handheld PDA, and the camera-phone applications. The testing process prioritised stability and responsiveness to user input in order to provide consistent operation and fit in with the ad-hoc usage envisaged in the design. This involved the need to switch to alternative options in some cases, for example an early version used Bluetooth Personal Area Networking rather than Wi-Fi. Following initial tests the speed and reliability of this system could not meet expectations and ad-hoc wireless networking was used instead. This process also resulted in the use of two handheld devices, when the test results indicated that a single application would cause additional complications and performance sacrifices.

In order to test the fixed sensor system it was deployed in locations around the computer science building and left to log readings for a number of hours, including overnight. The sensor logs were combined with specific debug logs to identify any errors that occurred and whether the sensor had logged data for the full period (this helped to identify and eliminate Bluetooth communication problems with the Logbook). The handheld devices were then introduced, initially to test the process of searching and identifying fixed sensors, then communicating with them to receive readings and annotation data. Extreme conditions were created to provide a basic form of load testing, for example three fixed sensors and four handheld devices operating at the same time. Debug information and data logs on the handheld devices were used to isolate and correct bugs as with the fixed sensors.

The iterative testing process and incremental introduction of features resulted in a stable set of applications with the features as described in the previous pages reliably functioning as illustrated. The process provided a baseline performance level with the tests showing the system can run continually over a number of hours, with the handheld devices operating consistently with no apparent major faults.

Complimenting this developer-oriented testing regime the system was also presented in a number of demonstrations; this provided a further opportunity to assess its performance and receive some informal feedback. Each of these demos followed a similar format, installing a fixed sensor in a particular location and then demonstrating the features of the handheld devices in order: searching for a fixed sensor; selecting it and receiving readings; viewing the rolling sensor data graphs; answering a question prompt and reviewing it on the rolling graph; creating a photo annotation and reviewing it as it appeared on the PDA interface; and finally, reviewing collected data on the PDA interface. These demonstrations provided an opportunity to assess the robustness of the system in use ‘out of the lab’ and test the applications against the tight demo constraints: features needed to work first time, and provide a prompt response. Several demos took place; the audiences included Participate project partners (see Chapter 4), interested parties at public exhibitions, and various colleagues in ad-hoc demos. The main occasions are summarised below:

Participate project plenary, January 2007: Demonstration to project partners with sensors in three locations around the Computer Science Building. This was an initial version using Bluetooth networking.

Offload event[11] at CREATE Centre, Bristol, September 2007: One day event at the Offload interactive media festival in at the CREATE environmental centre. Demonstrated single sensor setup to fellow exhibitors – a mix of artists and educational technologists.

BBC Future Media & Technology, December 2007: Demonstration to BBC staff alongside Participate project work.

[11] http://www.offloadfestival.org/offload07/

British Education and Training Technology (BETT) Show[12], January 2008: Sensors installed on two stands at a large trade show, this ran over four days and demonstrations were given to a range of people visiting the show.

Further to these demos the SensorShare system was also borrowed by colleagues for independent demos. These demos were unsupervised; instructions were given beforehand allowing them to give a demo on their own. The system was demonstrated by a colleague from ScienceScope at the Gulf Educational Supplies and Solutions (GESS) trade show[13] in Dubai, and by a colleague from the University of Nottingham, Learning Sciences Research Institute[14] (LSRI) as part of a technology demonstration in the Personal Inquiry project[15].

Whilst no formal feedback was gathered during the demonstrations, as stated above, this provided a proving ground to test the applications for stability and consistency in more varied circumstances. These experiences proved positive, the demos operated over extended periods of time with little trouble (for example at the BETT show, where the fixed sensors were left to run throughout opening hours of the exhibition), and also operated on demand in the shorter demos. The independent demos were organised on request, which also provided an indication of confidence in them from those involved.

6.6 Conclusion

This chapter has described the design and implementation of a participatory sensing experience intended to collect environmental data about a workplace, and gather feedback and reflections on this data by the users of those spaces. The earlier section considered the needs of the design scenario with respect to the framework introduced in the previous chapter. The five aspects of the dialogue the framework identified were considered individually; planning, testing, navigation, capture and reflection, and then how these aspects combined and worked alongside each other as a group was also looked at.

Based on the factors indentified during this analysis, a list of requirements for the experience were developed, and then implemented in a demonstration application. These requirements will now be shown again in Table 9 with brief details of how they were met given alongside.

[12] http://*www.bettshow.com*
[13] http://www.gulfeducation.info
[14] http://www.lsri.nottingham.ac.uk
[15] http://www.pi-project.ac.uk

Table 9: Implementation of requirements in SensorShare application

Planning	• Minimal initial planning stage *Use of fixed locations and recording methods reduces amount of initial needed planning.* • Set choice of sensors *Sound, light and temperature sensors, plus question, photo and comment annotations.* • Support ad-hoc planning – present options and inform users of opportunities *Sensors in range displayed on PDA screen, question prompts alert users of opportunities to annotate unusual readings.*
Testing	• Fixed sensors to eliminate unnecessary set-up and maintenance tasks *Logbook and PDA used to create fixed sensor device, installed and maintained by administrator rather than users.* • Opportunity for familiarisation *Test server set up during preparation stage.* • Straightforward in operation *Consumer devices with familiar interfaces used, configuration and set-up for devices simplified by excluding custom sensors.*
Navigation	• Support a range of background modes; off, standby, background-working and repurposed. *PDA and phone allow these modes, readings recorded by PDA automatically providing background operation.* • Highlight opportunities for data collection when working in background *Question prompts provide notification of unusual sensor readings.* • Respond to proximity of sensors *Application automatically searches for sensors in range and updates display.*

Capture	• Record person-centric and location-centric data – using fixed sensors and handheld devices *Fixed sensor PDA records location-centric data, handheld sensor interface records person-centric data.* • Collect environmental readings and participant feedback *Fixed sensor collects environmental readings and annotations are provided by the handheld devices.* • Support participants working as individuals *Handheld device links with fixed sensor to collect readings from multiple sensors simultaneously without need for help.* • Basic support for ad-hoc collaboration between users in the same location *Co-located participants can view each other’s annotations as they are added.*
Reflection	• Immediate feedback on results for participants *Rolling graph view shows annotations and sensor readings updating as they are received.* • Ability to review batches of collected data *Readings stored on PDA and can be viewed with a previous readings graph display.* • Record feedback from participants *Annotations stored alongside sensor data on fixed sensors* • Provide data for building managers to review. *Fixed sensor data stored in database to be downloaded by building managers. Participant data can optionally be reviewed if downloaded from PDA interface.*
Integration of activities	• Brief preparation stage including initial planning and familiarisation *Initial preparation stage managed by activity coordinator. As mentioned above, use of fixed locations and recording methods reduces amount of initial needed planning and fixed sensors reduce complexity of equipment the participants need to learn.* • Fieldwork stage involving navigation, capture and reflection *Background operation of PDA sensor interface allows navigation to be easily interleaved with capture. Question prompts and rolling graph page allows reflection to take place during fieldwork.* • Feedback to develop ongoing reflection with notifications for unusual readings and prompts for further data. *Question prompts highlight these readings and collect responses and feedback from the participants.* • Flexibility to allow re-planning *Participants may revisit locations and collect further data as the application does not limit data collected from fixed sensor or require a pre-set order.*

The conclusion now returns to the relationship diagram of the dialogue activities which was shown in Figure 74. With the final features described, the diagram can now be updated to show what has been developed to facilitate each transition.

The diagram highlights the wide range of dialogue in the experience, showing the features of the experience and the application design that facilitate transitions of dialogue from one activity to another. The transitions in and from preparatory stage (1) are one way and largely dictated by the experience plan, highlighting how this is intended to be closely managed to be simple and short.

The fieldwork stage (2) is a lot more complex, with user managed transitions both ways between navigation, capture and reflection. A number of application generated features are also included to prompt the transitions (for example the question prompts and additional processing of readings to display average values for locations and users' collected data), supporting the need to provide additional feedback and sensor information to support the participants decision making process.

The analysis stage (3) involves reflection and re-planning, it is again user directed with aspects of the design allowing user determination of location and sensing activities, plus the provision of different sensor types with which to record information.

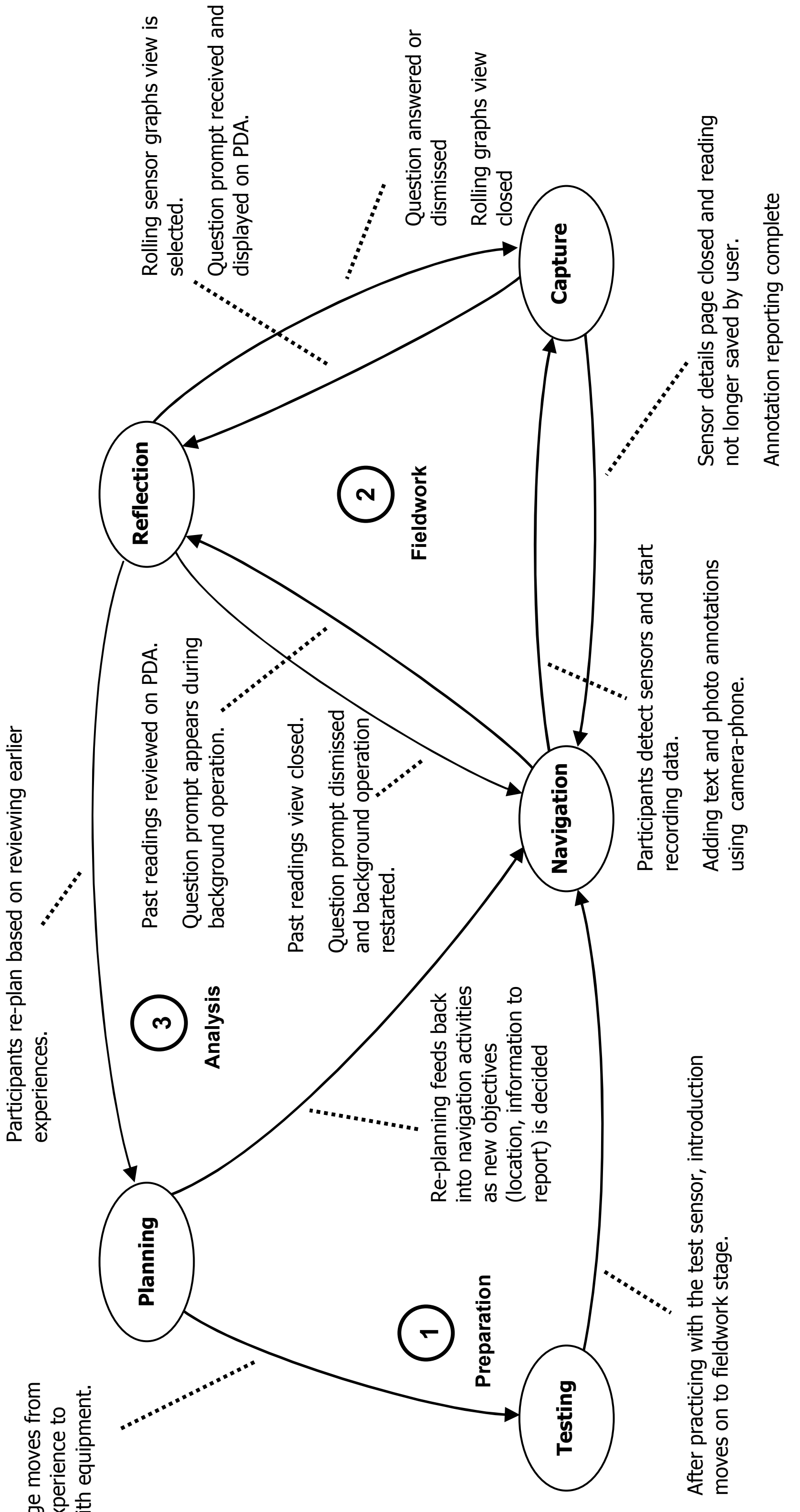


Figure 99: Relationships between activities in the new experience showing details of transitions.

This chapter has shown how the framework, developed from the initial experiences with SENSE and the World Scout Jamboree can be constructively applied to a new scenario with a different range of objectives, hardware and a different timescale. The analysis of the earlier projects using the framework also supplied useful insight into the design of the new experience, demonstrating how it functions as both an analysis tool and a generative framework.

After providing a summary of the work detailed throughout this thesis, the final chapter will continue to suggest directions for further work. This looks at both the framework that has been introduced and the features of the application described in this chapter, suggesting further ways to build upon them and more deeply explore the forms of human-sensor dialogue developed throughout.

7 Conclusion

7.1 Summary

Participatory sensing is an emerging field using pervasive technology to create new forms of sensing networks combining people, their personal devices and other sensors. Participatory sensing systems use the internet and other communication technologies to report data and to coordinate activities. As the capability and number of mobile devices increases, and as communications technology allows them to be linked with increased reliability and bandwidth, the potential for participatory sensing technology promises powerful sensing systems on a mass scale. Particularly as the challenges of climate change become clearer, the desire to measure and understand the environment has become stronger, motivating work to pursue new and potentially more powerful methods.

Following an examination of key areas that contribute to the field of participatory sensing, this thesis identified and pursued an investigation of human-sensor dialogue, specifically how to support new forms of dialogue in future participatory sensing experiences. An iterative, user-centred approach is taken to the research, in which prototyping, studies, technical innovation and theoretical work are tightly interwoven, informing one another as the work progresses.

The research is centred on two studies, examining participatory sensing activities using ethnographic techniques for naturalistic evaluation; using observations, video footage and system logs and data. A key principle in the research has been to work "in the wild", an approach pioneered, among others, by the Equator IRC (Crabtree et al., 2006). This approach involved working in the field with participants using the technology for real activities. Working alongside the SENSE and Participate projects assisted in this, allowing independent studies to be conducted in parallel to their own work. From the work with the studies, a framework for human-sensor dialogue was developed, providing a tool to analyse the dialogue in existing participatory sensing experiences and uncover the potential for new forms of dialogue in future experiences. The framework was also used to develop a prototype experience, defining a set of requirements for the dialogue within the experience based on the analytical approach the framework outlines.

This chapter outlines the contributions made by the thesis in more detail, then discusses this work, looking at the methodology and relating the contributions back to the literature covered in Chapter 2. It concludes by considering further work and future directions of this research.

7.2 Contributions of the Thesis

7.2.1 Literature review

The first main part of the thesis was the literature review, which formed the basis for the rest of the work. This chapter contributed an outline of participatory sensing and related fields that feed into it; this included observation networks and public engagement with science, both of which are brought together alongside pervasive computing. The chapter outlined these three areas and identified a further three sub-fields that fall within the convergence of the larger categories; context-aware computing, participatory science and e-science and learning. A venn diagram illustrated these areas:

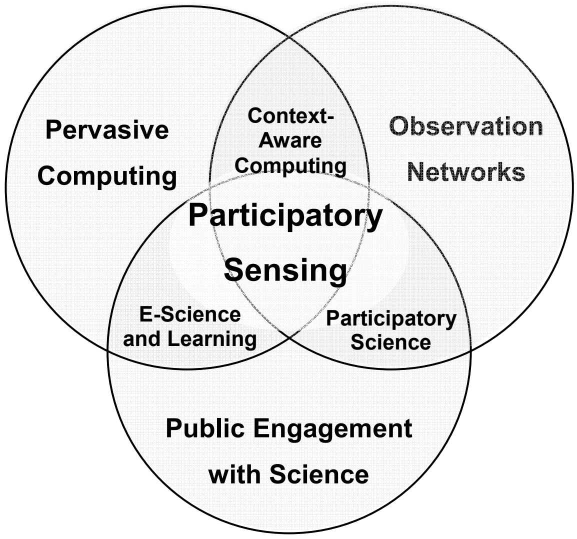


Figure 100: Topics contributing to participatory sensing from convergence of the three main areas

As the newest field of the three areas, pervasive computing inspired the concept of participatory sensing, providing the technological foundation for the ideas. These are based on a foundation of sensor-based interaction which authors such as (Bellotti et al., 2002) and (Mynatt & Nguyen, 2001) have discussed and raised a number of challenges. Detailing these issues and a selection of frameworks for sensor-based interaction, Chapter 2 drew attention to the dialogue taking place between humans and sensors. This introduced a key focus of the thesis and developed motivation for the subsequent investigations.

The literature review moved on to look at technological contributions from the areas surrounding participatory sensing, taking a range of applications and experiences from across the spectrum. These examples ranged from 'classic' pervasive computing examples to educational gaming experiences as well as specifically developed participatory sensing platforms. The examples were classified according to the sensor information that was captured and the domain to which it was applied. This showed a diverse range of sensors featuring a tendency toward location as the primary element.

A second classification of the examples considered the mobility of the sensor devices used, and the degree to which they were automatically or manually operated. Plotting these on two axes showed there was a tendency toward automatic and mobile sensors and a polarisation between the extremes.

The work in the literature review developed the motivation to explore human-sensor dialogue in participatory sensing experiences. This led from existing concerns in pervasive and particularly context-aware computing. The review of technology and applications from across the spectrum of contributing fields framed the following work, highlighting related aspects of relevant technology, giving an impression of the context of the work.

7.2.2 SENSE Study

The first study presented in the thesis conducted an initial exploration into human-sensor dialogue. This took place alongside another project, SENSE: Schools E-science Network for the Study of the Environment. The activities in this project involved groups of school children from two geographically separate schools (inner city vs. suburban area); participants used a selection of both automatic and manual sensors to gather information about airborne pollution around their schools. This data was collected and afterwards replayed in the classroom using custom made software allowing the information to be reviewed and annotated. The software, called Sense Data Explorer, displayed Carbon Monoxide readings and video footage on a linked timeline, also linked to this were marker points that were set during the fieldwork, with written notes of observations and details of the wind conditions recorded at the same time. Using the SDE application, participants could edit the comments, revising and adding to earlier observations.

The analysis focussed on the use of the sensing tools during the fieldwork part of the activity and took into account the contributions made during the subsequent classroom work using SDE. The observations laid the groundwork for the understanding of dialogue that was developed into the framework described in Chapter 5. It was seen that whilst the automatic sensors continually logged readings (CO and video footage) the participants' engagement occurred in an episodic manner, focusing on individual events then returning to a more background involvement as they concentrated on other tasks. These events were either sensor based, for example responding to a sharp rise in readings; related to the surroundings such as arriving at a significant location; or related to the mechanics of the activity itself, performing trial runs and taking practice readings to familiarise themselves with the equipment. This method allowed the participants to respond to sudden changes and meant that additional data and more consistent sensor readings were taken during the ‘episodes’ but this relied on the judgement and attention of the participants in order to do so. This resulted in varied success in collecting relevant data as the participants were also learning as they went along – they were not experienced or expert users.

The review process highlighted the benefits drawn from getting feedback regarding the data, participants used the process to identify points they had initially missed and to elaborate further on their notes. This also allowed them to identify errors in the data and reflect on the methods they used.

The study of the SENSE activities provided an initial experience with human-sensor dialogue in a participatory sensing setting, outlining some of the key aspects that were incorporated into the dialogue framework.

7.2.3 Jamboree Study

The second study in the thesis provided further experience of human-sensor dialogue in a participatory sensing oriented experience. The activity took advantage of a sensor toolkit and visualisation system developed within the Participate project, this allowed participants to combine sound level readings, GPS location data and digital photographs into a 3D representation on top of aerial images on Google Earth. The experience took place at the World Scout Jamboree in 2007, a summer camp style event with young people from all over the world. Groups were invited to collect sound level readings from the camp site area, recording the high readings with photos. When the data was collected they returned to the starting point and viewed their readings on a large screen using a movement sensitive Nintendo ‘WiiMote’ controller, viewing it alongside a map of the sites, the aerial images and other groups’ data.

As with the analysis of SENSE, video recordings and the collected data were reviewed and combined with observations of the participants when taking part. It was seen that high readings were often not marked with photos and the photos taken did not strongly correlate with higher sound levels, tending to be spread across the range of readings.

The analysis revealed a number of factors that affected how and why the participants did not match the photos and high readings more successfully. As they conducted the activity they moved from place to place, chatted within the group and with other people they encountered. This meant that their attention was frequently diverted from the sensor readout, so when high readings were displayed they were missed and not marked. Linked to this was balancing of priorities between these other activities and collecting data; participants may have been aware of the high readings but did not act on them in favour of something else.

Another aspect to this was where participants took photos when the readings were not high, as with missing high readings one factor was their familiarity with the sound level scale and understanding the significance of the values they recorded. Contributing to this also were photos taken to document other events, such as general pictures of the activity area and taking pictures of their own group or people they met; as no additional information accompanied the photos, distinguishing these kinds of photos from readings related images was difficult.

A final factor that was acknowledged was the design and operation of the sensors and visualisation software, feedback from the sensors did not always match what was recorded or displayed – this resulted in difficulties in matching photos to relevant data and capturing events that the participants set out to record.

The study further informed the understanding of the complex nature of human-sensor dialogue, drawing attention to a range of factors to consider; attention to the sensor readings, understanding the significance of readings and the conflicts between the participants' assessment of what is noteworthy and the recorded data. Factors related to the equipment were also seen; participants' understanding of the way the sensors work and understanding how the information will be represented later on. All these elements built on the initial experiences with SENSE and were taken forward into the design of the sensor dialogue framework in Chapter 5.

7.2.4 Framework for Human-Sensor Dialogue

The framework draws on earlier experiences, developing from the studies of SENSE and at the Jamboree. It provides a means to describe and analyse the human-sensor dialogue for participatory sensing experiences based on five general activities that dialogue may relate to; planning, testing, navigation, capture and reflection. These activities occur interleaved throughout an experience; in addition to identifying which activities each aspect of an experience relates to, considering the relationships and transitions between the activities is a key element of the framework. The five activities are briefly recapped below.

Planning accounts for preparation work, forming hypotheses and objectives. This might also include dealing with background information and explanatory briefings. Taking examples from the earlier studies, planning activities seen were determining locations and routes, the data to be recorded and the methods used.

Testing is concerned with the overall operation of the sensing system, both the devices used and the people involved. This means it encompasses any set up and maintenance tasks (e.g. battery charging, calibration), and additionally any familiarisation and practice the participants undertake to learn how to operated sensors or report information. Testing may also include recognising and dealing with faults throughout the experience, such as crashed software, flat batteries or damage to equipment.

The third activity, navigation encompasses times when participants are not directly engaged with the sensing tasks, for example when they are en-route to another location (hence the label of ‘navigation’) or when they are involved in unrelated tasks such as talking to friends or going about any other day-to-day business. During testing activities the sensor devices may be off and packed away, on standby waiting for an activation trigger (such as an incoming message on a mobile phone), active in the background where users maintain a peripheral awareness of the devices, or finally, they may be repurposed for other duties – like a PDA based sensor being used to send an email or GPS receiver providing wayfinding instructions.

Capture is the most prominent of the activities in the framework, accounting for anything that is directly recording information. This can be with handheld devices, pointing them, activating them or entering data; or with remote devices, accessing them and downloading (or uploading) information. Multiple devices may be involved, requiring co-ordination and synchronisation, similarly, other people may be involved, requiring additional collaboration, for example over targets or priorities.

Finally reflection, as opposed to capture, is associated with working with collected data; reviewing and revising it; analysing and testing hypotheses; sharing and discussing it. As seen in SENSE and from the Jamboree study, specialist software and hardware may be used to facilitate this, processing or consolidating the data and presenting it in a more powerful visualisation. Errors and discrepancies can be highlighted and corrected, additional points of interest can be added and existing ones embellished. Sharing, presenting and discussing the information are also included.

These five activities form the basis of the framework, this was elaborated upon using the earlier studies to demonstrate the use of the framework as an analytical tool, describing the dialogue within an experience and highlighting the interaction between the five activities. This process consisted of two stages; first, considering the tasks in the experience and how they fit into and supported each of the five activities. The second stage concentrated on how the activities worked together, identifying the changes of focus from one to another and what triggered those transitions. The analyses showed both experiences had a similar three stage structure; preparation, fieldwork and results. Differences emerged in the stages, for example in SENSE planning was conducted in detail and in depth, whereas with the Jamboree experience this was brief with a narrow focus. Links between activities also differed, for example with SENSE testing occurred both as part as the preparation stage and during the fieldwork, whereas the Jamboree experience constrained testing to the preparatory stage alone.

These analyses helped explain and explore the framework, showing how it can be used to look at the human-sensor dialogue in experiences and develop an idea of how it affects or is affected by different aspects.

7.2.5 Prototyping the SensorShare PDA Sensing System

The framework is further exploited in Chapter 6, using it to assist the prototyping of a new participatory sensing experience. The process is similar to the analysis process used previously, first looking at the individual activities, then at the links between them and the desired transitions.

It was intended that the new experience differed from the SENSE and Jamboree activities, focussing on a desire to embed participatory sensing into everyday life, rather than as a fixed term activity where participants' primary focus is the sensing experience. This moves toward a prototype experience suitable for longitudinal scientific studies, allowing for further study over time as well as space.

The process started by outlining a scenario to investigate the environmental conditions in work areas in and around the School of Computer Science at the University of Nottingham. This building uses an environmentally friendly climate management system, and does not use a conventional air-conditioning system; the performance of the alterative being somewhat controversial for the users of the building. The object of the exercise therefore was to collect both specific measurements of the conditions in various areas and also comments and feedback about those conditions from the users of those areas over an extended period of time.

The prototyping process began to shape the requirements of the new experience by considering the demands and constraints of each individual activity area. Both planning and testing activities were required to be straightforward and brief, in order to reduce the commitment required to collect data. A need to support a greater range of navigation activities was noted, responding to the need to further integrate with day-to-day work. The sensing tools also should be more supportive of the navigation activities, responding to the participant's proximity to locations of interest. Considering capture activities identified a need for location-centric and person-centric sensing, recording environmental data at key locations regardless of participants presence, and gathering human annotations when possible. Reflection activities were required to support ongoing reflection, providing immediate feedback to participants and the help inform their understanding of the readings and solicit feedback. The system also required that building managers could review the complete set of data on a location by location basis.

Looking at the relationships between the activities resulted in a process that was less linear and less pre-planned than the earlier experiences, allowing for reflection and re-planning and closer links between navigation and reflection. This resulted in a diagram showing preparation (1), fieldwork (2) and analysis (3) stages in a new configuration as shown Figure 74.

Having used the framework to elicit requirements for the experience the prototype application was built to implement it. The system was based on a combination of fixed and mobile devices; static sensors placed in the location of interest, consisting of a set of environmental sensors linked to a PDA unit recording the readings and relaying them to nearby participants. Participants carried a PDA receiving the readings and providing a readout of them, acting as a point of interaction between the fixed sensors and themselves. Additionally a smartphone could be used to report additional data; written notes and photographs.

On their PDA interface participants may search for and connect to nearby sensors, viewing photos and descriptions of each in range in order to select the most appropriate. Selecting a sensor allows users to log the readings for later reference and view graphs as the readings are received. The interface also allows participants to select and view annotations; notes, photos and participants' answers to questions generated by the fixed sensor. The fixed sensor uses the database of readings it collects to establish when current readings are statistically significant (high, low, etc). This triggers a question prompt to appear on the screens of participants viewing the readings of the sensor, asking them to enter further information.

The features of the application build up to support the dialogue and transitions mapped out using the framework, responding to evaluation of the earlier experiences as well as the requirements identified in the initial stages. This demonstrated how the framework can be used as both an analytical tool and a generative tool, mapping out requirements for a new experience as well as examining the human-sensor dialogue in past experiences.

7.3 Discussion

This section provides a critique of the work in this thesis, starting by discussing the methodology and then looking at back at related areas and specific literature introduced in Chapter 2. The contributions are considered in relation to the field of participatory sensing, and then the three areas closely linked to it: context-aware computing, participatory science, and e-science and learning. Following this, the sensor interaction frameworks and issues relating to them are recalled from the literature review, setting the contributions of this thesis alongside them.

The practical work throughout this thesis relies on the use of naturalistic observation and participant observation methods. As mentioned earlier, evidence is drawn from not only direct observation and video footage, but from a range of system data, such as sensor logs and user input. The initial literature review work identified the broad notion of dialogue which was drawn from a synthesis of a range of issues highlighted in recent research. In-situ studies allowed the area to be explored and the concept refined through practical investigations, having first scoped the range of sensor based applications seen in pervasive computing: the balance and combination of automatic, manual, fixed and mobile sensors. This exposed some of the variable factors in sensor based applications and provided background knowledge to support investigating human-sensor dialogue.

Starting with a broad focus for the studies meant that it was difficult to intentionally gather specific information that would have been useful in presenting a detailed, hypothesis based analysis; salient issues emerged as the studies developed. The second study provided an opportunity to be more specific, based on initial responses to the first; it was possible to select the activities that the participants undertook within the confines of the Jamboree setting, though again only a selection of general data could be gathered as it was still not possible to be highly specific about when and what events would take place.

The studies worked alongside other projects (SENSE and Participate); along with the methods used, this restricted the scope of a more specific experimental approach. The observations and conclusions presented provide a descriptive and explanatory account of the activities taking place. The technique allowed the capture of these activities to take place in an authentic environment that can't be accounted for in a lab based study. This is especially important when investigating interaction with sensor based technology: the studies necessarily involved – and aimed to capture – events in 'real life', these are difficult to define and intentionally recreate in a controlled setting.

The two studies allowed a process of sensitisation, exploration and refinement to take place, resulting in a generalised framework that draws out aspects of the dialogue encountered throughout. The framework therefore takes direct influences from the setting of these studies, so the transferability of it to a more general setting may be restricted because of this. Both studies worked with small groups of young people, who already knew each other and were working in an organised and planned educational activity. This leaves a number of possibilities open to consider; will the aspects of dialogue that have been identified effectively describe what takes place when participants are more dispersed, in different locations or over time? Will the nature of the dialogue change when the activity takes place in a more casual setting, alongside day-to-day activities? Would there be the differences when adults take part? Similarly, the participants were also working with new devices and systems to which they had only recently been introduced, so it may be important to consider how the dialogue may change as users become experienced, skilled users. These issues highlight where the contributions of this thesis fit within a broader field of participatory sensing. This thesis has studied relatively basic implementations of participatory sensing systems, drawing on some core characteristic features but leaving aside some others. This clearly leaves scope for further work to take place, both to drill down into specific aspects, or to take a wider generalised approach looking at a variety of diverse settings.

Taking a wider view of the work, in the outset participatory sensing was introduced as a sophisticated network of humans and sensors of all kinds, linked together to provide a powerful, dynamic sensing system. Authors describe contextually aware applications that exploit mobile, person-centric sensors for opportunistic, collaborative sensing, alongside infrastructural sensing systems, such as weather stations or traffic monitoring systems. The systems featured in both the SENSE study and the Jamboree study both feature mobile, handheld sensors in a very specific environment, they are not networked and are location and time specific, so collaboration takes place within a pre-defined group. Whilst simplified, these basic examples of participatory sensing support an exploration of human-sensor dialogue that can be expanded upon and developed with more complex systems as they are developed. The framework developed provides a mechanism to describe, help analyse and elicit requirements for the human-sensor dialogue in these systems. The prototype application provides a demonstration of how it can be applied, by using it alongside the understanding of the dialogue developed in the studies. The underlying choices in the prototype application acknowledge some of these questions of generalisation mentioned above, placing the exercise in a setting that challenges the framework. Creating the SensorShare application demonstrates that the concepts and methods can be sensibly applied in a different context to the earlier studies, though further evaluation and investigation will be necessary to really put the results to the test. The process also demonstrated the importance of experience and domain specific knowledge in the management of the dialogue in an application, the design of the application taking inspiration from features of the applications in the studies, the framework works alongside this knowledge; it does not act a replacement for it.

In Chapter 2 participatory sensing was introduced and set within the convergence of a number of areas, having considered the overall methodology and participatory sensing specifically, this section now goes on to relate the work of this thesis back to the most closely related areas, and then some more of the literature covered earlier.

7.3.1 Context-Aware Computing

Participatory sensing systems present a new genre of context-aware applications using sensed data to adapt the behaviour of a sensor network, going beyond the hardware and software, and encompassing the behaviour of individual users. Applications may inform and assist users in the gathering data based on context-aware features; proximate selection, reconfiguration, contextual information and context-triggered actions. On this basis the contributions in this thesis have, by proxy of tackling issues in participatory sensing, informed the field of context aware computing, by facilitating the design and analysis of such applications.

The practice of participatory sensing, and the focus on the human-sensor dialogue taking place in these applications, also highlights a new technique for gathering contextual data following participatory sensing principles. Context-aware applications and related literature predominantly focus on the automatic recognition and processing of context: establishing parameters such as location, activity, attention, identity, emotion or relationships between people. Whilst some manual sensing techniques have been used they are rarely seen as ‘first choice’ options and are mostly seen as ‘fall-back’ or temporary solutions. Participatory sensing introduces the idea of human-in-the-loop sensing; applying this principle to context-aware computing challenges the presumption that the user will not be concerned with the actuation of contextually dependant features. This approach yields new possibilities in context-sensing: involving the user in the process of actually supplying raw information with more manual features presents the chance to collect more personal, accurate and timely information that is difficult or impossible to derive from automated sensors. As will be discussed later, this also presents further opportunities for awareness, feedback, control and privacy, as identified as issues right across the field of sensor-based interfaces.

7.3.2 Participatory Science

Participatory science seeks to engage the public with science issues through public, and often mass-scale, experiments in which participants are recruited to take some role in either generating the results, through data gathering or processing data; or by directing the agenda, making choices that affect the direction the experiment takes. Chapter 2 (Section 2.2.5) described a number of examples, illustrating the links between participatory science practices and participatory sensing, by providing a new platform through which participatory science can be conducted. A key part in the potential for this is the coordinated use of personal mobile devices as platforms for gathering data, both automatically logged and through manual reports from participants. Through the observations of SENSE, the Jamboree activities, and the human-sensor dialogue framework, a number of factors have been shown that affect the way in which participants deploy, operate and engage with data collection activities. This included identifying different modes of dialogue between the user and the sensor devices, and how this might affect the sensor data. Of key interest is the episodic pattern of data collection, reflected in the framework as the movement between capture related dialogue and other aspects: planning, navigation, testing, and reflection. The studies showed how participants focussed on various events that they encountered from their surrounding environment, relating to the sensor data and relating to the sensing process itself. It was seen that appropriate contextual knowledge was needed it order to relate the readings to the event that the participants focussed on, for example, whether they are as expected, why they were chosen and is they are linked to any others.

In adopting participatory sensing techniques into participatory science an important factor is quality of data, as there will be wide variations between individual contributors, depending on their equipment, experience and motivations. Many authors propose data aggregation and averaging techniques as a means to overcome these problems. Considering the experiences within this thesis suggests an alternative approach; using contextually rich data collection through detailed attention to the ongoing dialogue between the participants and their sensing devices. This would involve designing the sensors and activities to appropriately gather the necessary information and perhaps a different approach to interpreting the data. Where numbers of participants are low, data aggregation techniques may not perform well, so this method may provide a good alternative for smaller participatory science activities, or in the early stages of a larger investigation.

7.3.3 E-Science and Learning

Recalling Section 2.2.6, e-science and learning activities were introduced as another of the fields related to participatory sensing, combining pervasive computing with public engagement with science. Whilst the studies undertaken were both learning activities to different degrees, the educational aspects were not specifically considered. It is possible however to relate some of the findings back to this area, with both studies introducing young people to new technology and new techniques to gather and interpret scientific data. As discussed earlier, participatory sensing has strong links with technology in education and learning in general, as envisaged in both the SENSE and Participate projects this kind of technology can provide new ways for students and schools to collaborate with each other and with a wider community, including subject experts and people with access to scarce resources.

The prototype application provides a selection of features that could be adapted for use in a specifically educational setting. Its design was led by using the framework to generate requirements on a high level and inspire features on a lower level. This process drew in reflections and responses to the issues faced in the applications used in the preceding studies and in doing so incorporated some new or improved features based on them. The prototype itself incorporates the ScienceScope Logbook datalogger, extending and enhancing its capabilities; this also provides some useful examples of how current educational technology can evolve towards more capable, networked sensors.

The sensor server application provides the ability to trigger question prompts on the handheld PDA interface, with specific tuning to an individual set-up this can allow contextually relevant questions to appear based on the sensor data. These could be used, as shown in the prototype scenario, to foster responses and reflection about those readings as they happen, or alternatively, in a more focussed fashion to help direct participants through the stages of an activity. In their work on the Lilly ARBOR project Rogers, et al. begin by commenting on the need to develop applications that support reflection and analysis in the field (Rogers et al., 2007); this kind of feature presents another approach to do so. The ability to personalise the data, such as adding photos can also assist in the process, and the fact that this can all be stored on the PDA for later viewing also adds capability for use as an educational e-science tool. On a more practical level the application allows for multiple fixed sensors, and simultaneous access from a number of users; this makes it useful in class based activities where many pupils may need to share equipment, or interact with a range of pre-prepared examples in a particular location. The fixed sensor system, with a PDA alongside the logbook makes much of this possible and provides an example of the way in which dataloggers could be enhanced with the current and developing generation of mobile, embedded technology.

As mentioned in previous sections, though the implementations of distributed, networked sensing in the thesis are relatively basic, the focus on interaction and user dialogue provides a foundation upon which to begin to introduce more advanced features. For e-science activities in learning and education, the observations from the studies and the development of the prototype application demonstrate opportunities to develop enhanced data collecting systems, though the work in itself does not take on a dedicated educationally focussed evaluation.

7.3.4 Sensor-Based Interaction

The previous sections have looked at participatory sensing and the most closely related areas to it that were described in Chapter 2. This section now takes a look at some of the general issues in sensor-based interaction that were also detailed earlier and motivated the focus on human-sensor dialogue throughout the thesis. Section 2.3 drew together and generalised specific issues common to all the areas involving pervasive computing and sensing applications. This included a range of contributions from existing literature describing sensor interaction frameworks or design guidelines as well as highlighting areas of concern. This section will review the contributions of this thesis with respect to this existing work.

An ongoing concern throughout the literature regarded implicit interaction, specifically how users of a system would be aware of, control, and understand the sensors and their attached applications. These were concisely summarised by the five questions posed by Bellotti, et al; these came under headings of address, attention, action, alignment and accident (Bellotti et al., 2002). Participatory sensing in general deals with both implicit sensing, when sensors collect data as users go about their lives, but it also deals with more explicit sensing when users intentionally gather and report information. Hinckley et al. consider this distinction by looking at foreground and background modes of operation (for handheld devices), rather than implicit and explicit interaction (Hinckley et al., 2005). The resulting design guidance stresses the need to be aware of and manage these modes of usage, by having an awareness of not only the two states but also the user's transitions between those states as well.

The literature review introduced a scale of sensor automation which takes a more fine grained approach to implicit, explicit, foreground and background interaction with sensor based systems. In a participatory sensing application a user's interaction with sensors is more involved; they may have partial control over an otherwise automatic sensor, for example deciding what to point it at or what it is exposed to; they may also have a manual sensor that automatically records/transmits readings on the user's command. As the observations in the studies reveal, the distinction between implicit and explicit interaction or foreground and background interaction can be hard to make, vary per sensor involved, and can change throughout an experience. Sensors may also be owned or operated by others, and the data shared, further affecting the distinction between the same sensor for one user and another.

The five questions framework is intended to apply to applications where their functions are derived from interpreting the sensor data, and may not directly concern that sensor data in itself. In participatory sensing applications the intention is primarily data gathering, and so there is at least some peripheral awareness of the sensors and the data being gathered. In the above section (7.3.1) human-in-the loop sensing techniques were proposed as another approach for context-aware applications, stemming from the user's awareness of and collaboration with (or undermining of) the sensors in question. Similarly, exploring these systems and techniques provides a source of experience that can be transferred to a wide range of more abstract sensor-based applications and interfaces, to help find appropriate answers to Bellotti, et al's questions. Exploring human-sensor dialogue in participatory sensing contributes to the wider effort to build sensor-based interfaces that are increasingly becoming part of pervasive computing systems.

As Hinckley et al. stress the management of foreground and background interaction, the human-sensor dialogue framework breaks the interaction down with a more situated view of different modes of dialogue with the sensing application. Whilst the distinction between foreground and background may be more difficult to make, identifying planning, testing, navigation, capture and reflection related interaction provides a more task focussed approach. Despite this difference, the framework similarly requires an understanding of the details of the tasks involved and transitions between them, particularly echoing two of the lessons leaned presented (Hinckley et al., 2005):

"L3. Provide feedback of transitions between the grounds and awareness of whether user activity will be interpreted as foreground or background."

"L4. Scope foreground interpretation of possible interactions via background sensing."

Chalmers and MacColl talk about seamful design in ubiquitous computing, arguing that designers should consider exposing "beautiful seams" in applications, rather than hiding them and aiming for seamlessness (Chalmers & MacColl, 2004). Identifying the transitions between the dialogue focus, and identifying the different type of activity are evident seams in sensor based applications; often users are required to negotiate these seams, whether they are aware of them or not. The dialogue framework is based on experiences of sensing activities, and so in this way it can be indirectly applied to activities where sensing is a lesser part of it, by helping to identify, understand and create "beautiful seams" in sensor-based applications.

Chapter 5 introduced then used the dialogue framework to characterise and understand the human-sensor dialogue in the SENSE and Jamboree experiences; Chapter 6 then went on to used it to elicit the requirements for and to aid the design of a new sensing application. As mentioned in Section 2.6, this approach was inspired by the "Expected, Sensed, Desired" framework (Benford et al., 2005) which mapped out a sensor-interaction design space based on the combinations of those aspects. This generative use of the framework also drew on the technique used by Mynatt and Nguyen (Mynatt & Nguyen, 2001) in providing examples of applications that fit within some of the lesser explored areas of the design space by introducing new features. In comparison to Sensed, Expected and Desired, the human-sensor dialogue framework is not as straightforward as it is not directly linked to the mechanics of sensing; it has more parts to think about – different activities as well as the relationships and transitions between them. Though this limits its transferability to the wider area of sensor based interaction, it does provide depth and detail in the specific area of participatory sensing that it is rooted in. Similarly, the SensorShare application was used to showcase new features inspired by the framework, emphasising aspects of the dialogue that were desired. Whilst this provided an application to demonstrate the interesting new features, these may not be suitable for everyday use and perhaps may need further refinement after a detailed evaluation.

A final theme from the literature covered in Section 2.3 regarded concerns about privacy and trust, linked to this in particular were advice and guidelines regarding identity and accountability within sensor based systems. This featured in comments by Bellotti & Edwards and also as part of Langheinrich’s work (Bellotti & Edwards, 2001; Langheinrich, 2001). Observations from the studies touched on accountability, through the use of contextual information alongside raw sensor data. In the SENSE study the video footage linked to marker points allowed information to be justified and features accounted for, but in the Jamboree study this was less so, with less information linking photographs to sensor data. The framework does not specifically deal with this area, and the SensorShare application does not make it a priority. Though it is not strongly represented in the work it does not exclude dealing with those issues; accountability can be considered when thinking about the transitions between different dialogue focuses, representing why this happened, how it happened and how the user may perceive it. In the studies forward looking accountability was touched on with the Jamboree work especially: participants took photos but the final implications of their actions were not clear since it was not obvious how they would appear in the final visualisation. Reflections on this highlighted the fact that reflection related dialogue occurred toward the end of the experience and was not as interleaved throughout it. Access and recourse were aspects also stressed in the literature alongside identity and accountability; the structure of the dialogue as shown using the framework does reflect the availability of opportunities for this if considered in that way.

This part of the chapter has provided a discussion of the work in the rest of the thesis, initially looking at the methodology and the overall approach taken. It discussed the method of in-situ evaluation of sensing technology ‘in the wild’ which was used alongside technical innovation to observe and study human-sensor dialogue then generalise it into a framework, demonstrating its use as a generative tool by designing a prototype application. The discussion moved on to look at aspects of the thesis related to literature covered in Chapter 2. This initially looked at the core area of participatory sensing, before moving on to the closely related areas of context-aware computing, participatory science, and e-science and learning. This identified where contributions can be applied to these areas. The final section looked at some wider HCI issues on sensor-based interaction that were identified earlier. The sensor interaction frameworks introduced in Section 2.3, and general themes from these, were discussed in comparison to the human-sensor dialogue framework and the prototype sensing application introduced and developed in Chapter 5 and Chapter 6. The framework was set in context with the previous work, highlighting similarities and differences. The final section of this chapter will now go on to look at potential further work that could be done to further extend the work of this thesis.

7.4 Further Work

This final section looks toward further work, building on the contents of this thesis and the direction the research has taken. Two immediate avenues are open, pursuing the technical development work that has been undertaken and continuing investigation using the framework which has underpinned the technical development. These directions are not mutually exclusive – indeed this thesis adopted a combined approach to the technical and theoretical work as described earlier. Outlining possible developments in both areas provides a clear impression of the possibilities and potential for each aspect, whether they are pursued together or not.

There are a number of directions for further work with the SensorShare prototype. An immediate action would be to conduct a pilot trial of the system in the setting for which it was designed. This would provide feedback for a detailed formative evaluation and also an opportunity to conduct a longitudinal study, looking at human-sensor dialogue over an extended period of time, rather than the intensive, short term activities seen so far.

The reconfigurable features of the SensorShare system can be re-used and extended further, allowing it to be tailored to and deployed in other scenarios. As well as providing a means of further investigation, with appropriate modification it offers a platform for investigations into dynamic tasking, data sharing and privacy issues and exploring combinations of alternative viewpoints on the data such as web and remote access views as well as local access. A range of potential additions are described below, based on four themes:

7.4.1 Technical Improvements

Technical improvements can be made to take advantage of newer technology, additional resources and time that was not available for initial development. This includes developing the fixed sensor device further to create a specifically designed network-based datalogger/sensor that integrates the functionality of both the Logbook and PDA used in the current design. On the handheld side, improved mobile devices can be used, combining the PDA and camera-phone into a single unit. New, more capable, devices can be used to achieve this, such as the Apple iPhone and the latest Nokia and HTC Smartphones.

Another limited aspect of the prototype was the sensor data visualisation; further development could enhance this by providing more tailored sensor-specific representations as an alternative to the general purpose line graph display.

Another set of enhancements to the annotation system could also be made, allowing ‘offline’ (detached from a fixed sensor) editing and authoring of annotations, with retrospective updating of the remote sensor logs.

7.4.2 Sharing and Social Aspects

As well as making technical improvements to the system, new features can be added to create a platform to explore the sharing and social aspects of the dialogue in participatory sensing. This could include a more advanced range of collaboration features, for example a group annotation mode, allowing participants to preview and modify annotations as a group before submitting them to the sensor. In order to facilitate distributed collaboration, an instant messaging system could be included, and collaborative work could be encouraged with the introduction of a group membership system, for example to represent campaigns or particular tasks.

7.4.3 Management and Operational Monitoring Capabilities

The current system is based on a deployment on a small scale, with 3 fixed sensors that are relatively close together and monitored by an administrator over the time of deployment. To increase the scale of use, both in terms of the number of sensors and geographic range, additional management and operational monitoring features would be of benefit.

Remote connection to the fixed sensors would enable a range of monitoring and management options, perhaps through existing network connections (wi-fi, mobile phone networks) or more indirect means, relaying messages via users’ devices as they move between locations.

Maintenance of remote deployments may also become an issue and the fixed sensors could be enhanced to include a failure management system. This could use other nearby sensors to check and verify sensor readings – alerting administrators or prompting users to take remedial action e.g. by reporting alternative observations or attempting to rectify a fault.

In order to achieve these tasks, improved networking methods would be needed, particularly the use of multi-hop communications and sensor network systems as demonstrated by (Mainwaring et al., 2002).

7.4.4 Sensing and Sensor Networking

The Logbook provides a modular sensing system allowing a range of sensors to be used. The mobile sensors however are more limited, contributing only photograph and text based data. To further extend the sensor system this range of annotation data can be expanded; there is potential to include video footage recorded by mobile phones or additional data from specialist handheld sensors. User input could adopt a more form based approach, for example using multiple choice questions to collect information that may be more readily used by the system. Other forms of data could also be integrated into the annotation system, such as adding links to external websites, or including snapshot views of data collected by other sensors.

The question prompt system within the fixed sensors presents a starting point to create more in depth responses and contextually relevant questions. Initially, improved statistical models could be used on a per-sensor basis, such as a model of daylight levels used in combination with a light sensor. Questions or prompts could also be pre-set, triggered by a user, a set time or a particular combination of readings. More sources of data can also be drawn on, including comparisons with a participant's logged data or other sensors. Data from multiple sensors could be used to provide comparisons based across space as well as time.

7.4.5 Human-Sensor Dialogue Framework

The additional features described above continue to develop a novel participatory sensing platform; they also provide a means to explore other aspects of sensing experiences that are as yet little explored. This section moves on to the framework specifically and its use for exploring and designing participatory sensing experiences. Continuing the methods used with the analysis of the SENSE and Jamboree experiences, and the design of the SensorShare system, further work may develop examples of more of the possible interactions between the dialogue activities and how they are supported in experiences. In particular this thesis has highlighted some of the aspects to consider, such as whether transitions between activities are automatically dictated, or whether participants are left to control them and how to support these options. The analysis also highlighted the relationships between the activities in the framework, for example the balancing of navigation, capture and reflection activities. These and other factors identified throughout the thesis can be investigated by continuing to develop solutions for new scenarios and applying the framework in a wide range of settings. Pursuing opportunities to engage with existing designers and practitioners in the field of participatory sensing will help to enhance this process, allowing the framework to be applied from alternative perspectives and within a wider range of situations.

As seen in the thesis, the framework may be used to analyse existing experiences, informing further development, or to elicit requirements for a new experience. Collaborating with practitioners and researchers from across the range of participatory sensing related fields holds the potential to provide new viewpoints and interpretations of the results and reveal new and unexpected forms of dialogue and further options for sensor based interaction.

This framework may also be of interest in the wider field of sensor based interaction. A key challenge for pervasive computing is how people will interact with new pervasive systems. As raised in the initial stages of this thesis, authors have highlighted the need for improved dialogue with users in order to address these issues. The work in this thesis, using the framework developed, provides both a tool to describe and assess aspects of human-sensor dialogue and also a means to uncover and apply new forms of this dialogue. This informs the field of sensor based interaction in general, with a case study and new techniques which may be transferred and adapted for use in other sensor based interaction environments.

8 References

8.1 Published Literature

Abdelzaher, T., Anokwa, Y., Boda, P., Burke, J., Estrin, D., Guibas, L., Kansal, A., Madden, S. & Reich, J. 2007, 'Mobiscopes for Human Spaces', *IEEE Pervasive Computing*, vol. 6, no. 2, pp. 20-29.

Abowd, G.D., Atkeson, C.G., Hong, J., Long, S., Kooper, R. & Pinkerton, M. 1997, 'Cyberguide: a mobile context-aware tour guide', *Wirel. Netw.*, vol. 3, no. 5, pp. 421-433.

Abowd, G.D. & Mynatt, E.D. 2000, 'Charting past, present, and future research in ubiquitous computing', *ACM Trans. Comput.-Hum. Interact.*, vol. 7, no. 1, pp. 29-58.

Beigl, M., Gellersen, H.W. & Schmidt, A. 2001, 'Mediacups: experience with design and use of computer-augmented everyday artefacts', *Comput. Netw.*, vol. 35, no. 4, pp. 401-409.

Bellotti, V., Back, M., Edwards, W.K., Grinter, R.E., Henderson, A. & Lopes, C. 2002, 'Making sense of sensing systems: Five questions for designers and researchers', in proceedings of *SIGCHI Conference on Human Factors in Computing Systems (CHI)*, Minneapolis, Minnesota, USA.

Bellotti, V. & Edwards, K. 2001, 'Intelligibility and accountability: human considerations in context-aware systems', *Human-Computer Interaction*, vol. 16, no. 2, pp. 193-212.

Bellotti, V. & Sellen, A. 1993, 'Design for Privacy in Ubiquitous Computing Environments', in proceedings of *Third European Conference on Computer Supported Cooperative Work (ECSCW'93)*.

Benford, S., Crabtree, A., Flintham, M., Drozd, A., Anastasi, R., Paxton, M., Tandavanitj, N., Adams, M. & Row-Farr, J. 2006, 'Can you see me now?' *ACM Trans. Comput.-Hum. Interact.*, vol. 13, no. 1, pp. 100-133.

Benford, S., Flintham, M., Drozd, A., Anastasi, R., Rowland, D., Tandavanitj, N., Adams, M., Row-Farr, J., Oldroyd, A. & Sutton, J. 2004a, 'Uncle Roy All Around You: Implicating the City in a Location-Based Performance', in proceedings of *Conference on Advanced Computer Entertainment (ACE)*, Singapore, June.

Benford, S., Rowland, D., Flintham, M., Hull, R., Reid, J., Morrison, J., Facer, K. & Clayton, B. 2004b, '"Savannah": Designing a Location-Based Game Simulating Lion Behaviour', in proceedings of *Conference on Advances in Computer Entertainment (ACE)*, Singapore, June.

Benford, S., Schnädelbach, H., Koleva, B., Anastasi, R., Greenhalgh, C., Rodden, T., Green, J., Ghali, A., Pridmore, T., Gaver, B., Boucher, A., Walker, B., Pennington, S., Schmidt, A., Gellersen, H. & Steed, A. 2005, 'Expected, sensed, and desired: A framework for designing sensing-based interaction', *ACM Trans. Comput.-Hum. Interact.*, vol. 12, no. 1, pp. 3-30.

Burke, J.A., Estrin, D., Hansen, M., Parker, A., Ramanathan, N., Reddy, S. & Srivastava, M.B. 2006, 'Participatory sensing', in proceedings of *World Sensor Web Workshop, ACM Sensys*, Boulder, Colorado, USA, October 31, 2006, http://repositories.cdlib.org/cens/wps/140/.

Chalmers, M. & MacColl, I. 2004, *Seamful and Seamless Design in Ubiquitous Computing*, Computing Science, University of Glasgow.

Cheverst, K., Davies, N., Mitchell, K., Friday, A. & Efstratiou, C. 2000, 'Developing a context-aware electronic tourist guide: some issues and experiences', in proceedings of *SIGCHI conference on Human factors in computing systems*, The Hague, The Netherlands.

Crabtree, A., Benford, S., Greenhalgh, C., Tennent, P., Chalmers, M. & Brown, B. 2006, 'Supporting ethnographic studies of ubiquitous computing in the wild', in proceedings of *6th conference on Designing Interactive Systems (DIS)*, University Park, PA, USA, http://portal.acm.org/citation.cfm?id=1142417.

Dey, A.K. & Mankoff, J. 2005, 'Designing mediation for context-aware applications', *ACM Transactions on Computer-Human Interaction (TOCHI)*, vol. 12, no. 1, pp. 53-80.

Dey, A.K., Salber, D., Abowd, G.D. & Futakawa, M. 1999, 'The Conference Assistant: Combining Context-Awareness with Wearable Computing', in proceedings of *3rd IEEE International Symposium on Wearable Computers*.

Eisenman, S.B., Miluzzo, E., Lane, N.D., Peterson, R.A., Ahn, G.S. & Campbell, A.T. 2007, 'The BikeNet mobile sensing system for cyclist experience mapping', in proceedings of *5th international conference on Embedded networked sensor systems*, Sydney, Australia.

Elrod, S., Bruce, R., Gold, R., Goldberg, D., Halasz, F., Janssen, W., Lee, D., McCall, K., Pedersen, E., Pier, K., Tang, J. & Welch, B. 1992, 'Liveboard: a large interactive display supporting group meetings, presentations, and remote collaboration', in proceedings of *SIGCHI conference on Human factors in computing systems*, Monterey, California, United States.

Fernández, W.D., Lehmann, H.P. & Underwood, A. 2002, 'Rigour And Relevance In Studies Of IS Innovation : A Grounded Theory Methodology Approach', in proceedings of *10th European Conference on Information Systems, Information Systems and the Future of the Digital Economy (ECIS)*, Gdansk, Poland, June 6-8.

Ferris, D. 2007, 'Science Cafés Tap Nation's Fascination With Research and Discoveries', *Wired News*, 15th December 2007, viewed 18th December 2008, http://www.wired.com/science/discoveries/news/2007/12/science_cafe.

Flintham, M., Anastasi, R., Benford, S., Drozd, A., Mathrick, J., Rowland, D., Tandavanitj, N., Adams, M., Row-Farr, J., Oldroyd, A. & Sutton, J. 2003, 'Uncle Roy All Around You: Mixing Games and Theatre on the City Streets', in proceedings of *Level Up: The First International Conference of the Digital Games Research Association (DIGRA)*, Utrecht, The Netherlands, November.

Frey, J.G., Gledhill, R., Kent, S., Hudson, B. & Essex, J. 2005, 'Schools Malaria Project', in proceedings of *UK e-Science All Hands Meeting*, Nottingham, UK, 19 - 22nd September, http://eprints.soton.ac.uk/17453/.

Frohlich, D., Thomas, P., Hawley, M. & Hirade, K. 1997, 'Inaugural issue editorial: Future personal computing', *Personal and Ubiquitous Computing*, vol. 1, no. 1, pp. 1-5.

Gaver, W., Beaver, J. & Benford, S. 2003, 'Ambiguity as a resource for design', in proceedings of *Conference on Human Factors in Computing Systems (CHI)*, Fort Lauderdale, Florida, USA.

Gellersen, H.W., Schmidt, A. & Beigl, M. 2002, 'Multi-Sensor Context-Awareness in Mobile Devices and Smart Artefacts', *Mob. Netw. Appl.*, vol. 7, no. 5, pp. 341-351.

Glaser, B.G. & Strauss, A.L. 1973, *The Discovery of Grounded Theory: Strategies for Qualitative Research*, Aldine, Chicago :.

Highfield, R. & Irwin, A. 1999, 'Megalab 99', *The Telegraph (Connected)*, 18th March 1999, viewed 18th December 2008, http://64.233.183.132/search?q=cache:oYnF9jz8PVIJ:www.telegraph.co.uk/connected/main.jhtml%3Fxml%3D/connected/1999/03/18/ecrmega18.xml.

Hinckley, K., Pierce, J., Horvitz, E. & Sinclair, M. 2005, 'Foreground and background interaction with sensor-enhanced mobile devices', *ACM Transactions on Computer-Human Interaction (TOCHI)*, vol. 12, no. 1, pp. 31-52.

Honicky, R., Brewer, E.A., Paulos, E. & White, R. 2008, 'N-smarts: Networked Suite of Mobile Atmospheric Real-Time Sensors', in proceedings of *Second ACM SIGCOMM Workshop on Networked Systems for Developing Regions*, Seattle, WA, USA.

Jorgensen, D.L. 1989, *Participant observation: A Methodology for Human Studies*, vol. 15, Sage Publications, Newbury Park, Calif.

Kidd, C., Orr, R., Abowd, G., Atkeson, C., Essa, I., MacIntyre, B., Mynatt, E., Starner, T. & Newstetter, W. 1999, 'The Aware Home: A Living Laboratory for Ubiquitous Computing Research', in, *Cooperative Buildings. Integrating Information, Organizations and Architecture*, pp. 191-198.

Kidd, C.D., O'Connell, T., Nagel, K.S., Patil, S. & Abowd, G.D. 2000, *Building a Better Intercom: Context-Mediated Communication within the Home*, Georgia Institute of Technology, viewed 18th December 2008, http://hdl.handle.net/1853/3459.

Lamming, M. & Flynn, M. 1994, 'Forget-me-not: intimate computing in support of human memory', in proceedings of *FRIEND21 Symposium on Next Generation Human Interfaces*, http://citeseer.ist.psu.edu/lamming94forgetmenot.html

Langheinrich, M. 2001, 'Privacy by Design - Principles of Privacy-Aware Ubiquitous Systems', in proceedings of *Ubicomp 2001*.

Langheinrich, M. 2002, 'A Privacy Awareness System for Ubiquitous Computing Environments', in proceedings of *4th international conference on Ubiquitous Computing*, Göteborg, Sweden, September 29 - October 01, http://citeseer.ist.psu.edu/langheinrich02privacy.html.

Mainwaring, A., Culler, D., Polastre, J., Szewczyk, R. & Anderson, J. 2002, 'Wireless sensor networks for habitat monitoring', in proceedings of *1st ACM international workshop on Wireless sensor networks and applications*, Atlanta, Georgia, USA.

McCarthy, J., Riddall, R. & Topp, C. 2001, 'Jubilee Campus, University of Nottingham, Nottingham, UK', *Arup Journal*, viewed 2nd January 2009.

Mynatt, E.D. & Nguyen, D. 2001, 'Making Ubiquitous Computing Visible', in proceedings of *CHI 2001 Workshop: Building the Ubiquitous Computing User Experience*.

Neustaedter, C. & Brush, A.J.B. 2006, '"LINC-ing" the family: the participatory design of an inkable family calendar', in proceedings of *SIGCHI conference on Human Factors in computing systems*, Montréal, Québec, Canada.

Oldroyd, A., Harper, R., Woolard, A., Crellin, D., Adams, M., Benford, S. & Fraser, D.S. 2005, 'Participate Project, DTI, Competition For Funding Reference TP/3/PIT/6/I/15342', unpublished.

Page, M. & Vande Moere, A. 2007, 'Evaluating a Wearable Display Jersey for Augmenting Team Sports Awareness', in, *Pervasive Computing*, pp. 91-108.

Paulos, E., Honicky, R. & Goodman, E. 2007, 'Sensing Atmosphere', in proceedings of *Workshop position paper for the Sensing on Everyday Mobile Phones in Support of Participatory Research at ACM SenSys*, Sydney, Australia, 6–9 November 2007.

Pizzey, S. 1988, *The Discovery Dome*, viewed 18th December 2008.

Pizzey, S. 1996, *Science Projects 10 Years On*, *1986 - 1996*, Science Projects.

Rogers, Y., Connelly, K., Tedesco, L., Hazlewood, W., Kurtz, A., Hall, R., Hursey, J. & Toscos, T. 2007, 'Why It's Worth the Hassle: The Value of In-Situ Studies When Designing Ubicomp', in, *UbiComp 2007*, pp. 336-353.

Rogers, Y. & Muller, H. 2006, 'A framework for designing sensor-based interactions to promote exploration and reflection in play', *International Journal of Human-Computer Studies*, vol. 64, no. 1, pp. 1-14.

Rogers, Y., Price, S., Fitzpatrick, G., Fleck, R., Harris, E., Smith, H., Randell, C., Muller, H., Malley, C.O., Stanton, D., Thompson, M. & Weal, M. 2004, 'Ambient wood: designing new forms of digital augmentation for learning outdoors', in proceedings of *2004 conference on Interaction design and children: building a community*, Maryland.

Salber, D., Dey, A.K., Orr, R.J. & Abowd, G.D. 1999, *Designing for Ubiquitous Computing: A Case Study in Context Sensing*, viewed 18th December 2008, http://www.cc.gt.atl.ga.us/gvu/reports/1999/abstracts/99-29.html.

Satyanarayanan, M. 2002, 'A Catalyst for Mobile and Ubiquitous Computing', *IEEE Pervasive Computing*, vol. 1, no. 1, pp. 2-5.

Schilit, B., Adams, N. & Want, R. 1994, 'Context-Aware Computing Applications', *IEEE Workshop on Mobile Computing Systems and Applications*, Santa Cruz, CA, US.

Stanton Fraser, D., Smith, H., Tallyn, E., Kirk, D., Benford, S., Rowland, D., Paxton, M., Price, S. & Fitzpatrick, G. 2005, 'The SENSE project: a context-inclusive approach to studying environmental science within and across schools', in proceedings of *Computer Supported Collaborative Learning (CSCL) 2005*, Taipei, Taiwan, May 30 - June 4.

Steed, A., Spinello, S., Croxford, B. & Greenhalgh, C. 2003, 'e-Science in the Streets: Urban Pollution Monitoring', in proceedings of *UK e-Science All Hands Meeting*.

Steed, A., Spinello, S., Croxford, B. & Milton, R. 2004, 'Data visualization within urban models', in proceedings of *Theory and Practice of Computer Graphics (TPCG)* University of Bournemouth, 8-10th June, http://doi.ieeecomputersociety.org/10.1109/TPCG.2004.1314447.

Want, R., Hopper, A., Falc, V. & Gibbons, J. 1992, 'The active badge location system', *ACM Trans. Inf. Syst.*, vol. 10, no. 1, pp. 91-102.

Want, R., Schilit, B.N., Adams, N.I., Gold, R., Petersen, K., Goldberg, D., Ellis, J.R. & Weiser, M. 1995, 'An overview of the PARCTAB ubiquitous computing experiment', *Personal Communications, IEEE*, vol. 2, no. 6, pp. 28-43.

Weiser, M. 1991, 'The Computer for the Twenty-First Century', *Scientific American*, pp. 94-104.

Wiseman, R. 1995, 'The megalab truth test', *Nature*, vol. 373, no. 6513, pp. 391-391.

Xylomenos, G. & Polyzos, G.C. 1999, 'TCP and UDP performance over a wireless LAN', in proceedings of *INFOCOM '99. Eighteenth Annual Joint Conference of the IEEE Computer and Communications Societies*, New York, NY, USA, 21-25 Mar 1999, http://citeseerx.ist.psu.edu/viewdoc/summary?doi=10.1.1.52.2630.

8.2 Online References

'Big Bang Week' 2008, *Big Bang Week*, BBC Radio 4, viewed 18th December 2008, http://www.bbc.co.uk/radio4/bigbang/.

'Bikenet Portal', *Bikenet Portal*, viewed 18th December 2008, http://bikenet.cs.dartmouth.edu/.

'Butterflies for the New Millennium project', *Butterflies for the New Millennium project*, Butterfly Conservation (UK), viewed 18th December 2008, http://www.butterfly-conservation.org/text/64/butterfly_distribution.html.

'Cafe Scientifique', *Cafe Scientifique*, viewed 18th December 2008, http://www.cafescientifique.org/.

'Campaignr by Center for Embedded Network Sensing', *Campaignr by Center for Embedded Network Sensing*, Center for Embedded Network Sensing, viewed 18th December 2008, http://www.campaignr.com/.

'CERN: The European Organisation for Nuclear Research', *CERN: The European Organisation for Nuclear Research*, European Organization for Nuclear Research, viewed 18th December 2008, http://public.web.cern.ch/public/.

'Christmas Bird Count', *Christmas Bird Count*, The Audubon Society, viewed 18th December 2008, http://www.audubon.org/bird/cbc/.

'Christmas Bird Count History', *Christmas Bird Count History*, The Audubon Society, viewed 18th December 2008, http://www.audubon.org/bird/cbc/history.html.

Honicky, R., *N-SMARTS: Networked Suite of Mobile Atmospheric Real-Time Sensors* viewed 18th December 2008, http://www.cs.berkeley.edu/~honicky/nsmarts/index.shtml.

Jebson, S. 2008, *Fact sheet No. 17 – Weather observations*, National Meteorological Library and Archive, viewed 18th December 2008, http://www.metoffice.gov.uk/corporate/library/factsheets/factsheet17.pdf.

Joki, A., Burke, J.A. & Estrin, D. 2007, *Campaignr: A Framework for Participatory Data Collection on Mobile Phones*, Center for Embedded Network Sensing, viewed 18th December 2008, http://repositories.cdlib.org/cens/wps/770.

Kenner, C. 2007, *Glove Programmable Input Emulator 0.30*, viewed 31st December 2008, http://carl.kenner.googlepages.com/glovepie.

'Large Hadron Collider', *Large Hadron Collider*, viewed 18th December 2008, http://www.lhc.ac.uk/.

'Live ship location tracker', *Live ship location tracker*, Mobile Geographics LLC, viewed 18th December 2008, http://www.sailwx.info/shiptrack/shiplocations.phtml.

'The Mass Observation Project', *The Mass Observation Project*, The Mass Observation Archive, viewed 18th December 2008, http://www.massobs.org.uk/.

'MetroSense', *MetroSense*, Dartmouth College's ISTS, Computer Science, and the Thayer School of Engineering, Columbia University's Electrical Engineering, and Intel Corporation and Nokia Research, viewed 18th November 2008, http://metrosense.cs.dartmouth.edu/.

'National Traffic Control Centre', *National Traffic Control Centre*, Highways Agency, viewed 18th December 2008, http://www.highways.gov.uk/knowledge/15228.aspx.

Paulos, E., Smith, I. & Honicky, R., *Participatory Urbanism* viewed 18th December 2008, http://www.urban-atmospheres.net/ParticipatoryUrbanism/.

'SensorBase', *SensorBase*, Center for Embedded Network Sensing, viewed 18th December 2008, http://sensorbase.org/.

'UK Air Quality Archive, Automatic Urban Network (AUN)', *UK Air Quality Archive, Automatic Urban Network (AUN)*, UK Department for Environment, Food & Rural Affairs and the Devolved Administrations, viewed 18th December 2008, http://www.airquality.co.uk/archive/monitoring_networks.php?n=aun.

'UK climate: Synoptic and climate stations', *UK climate: Synoptic and climate stations*, Met Office, viewed 18th December 2008, http://www.metoffice.gov.uk/climate/uk/networks/index.html.

'Urban Pollution research', *Urban Pollution research*, viewed 18th December 2008, http://www.bartlett.ucl.ac.uk/web/ben/.

Wald, D., Wald, L., Dewey, J., Quitoriano, V. & Adams, E. 2001, 'U.S. Geological Survey Fact Sheet 030-01', *Did You Feel It? Community-Made Earthquake Shaking Maps*, viewed 18th December 2008, http://pubs.usgs.gov/fs/fs030-01/.

Wilson, J. 2004, *Developing Smart Device WiFi Applications with the .NET Compact Framework*, viewed 4th January 2009, http://msdn.microsoft.com/en-us/library/aa446527.aspx#multicommframework_topic_06.