A review of what data from sensors worn on the body can tell us about human behaviour

T. Keeling‡†, D. Clements-Croome‡, R. Luck‡ and P. Pointer†
‡University of Reading and †Buro Happold

Abstract
A range of data collection technologies now exist that can be worn on the body. These can provide large amounts of information about a person's location, the surrounding physical environment, personal activity, physiology and their mood. This paper evaluates these particularly in terms of the type of data collected, its use in understanding behaviour in buildings and the level of intrusion of the device.

The data collected falls roughly into four types, measurements of physiological variables such as skin conductivity, measurements of position or acceleration, measures of the physical environment and complex information devices such as sound or video recorders. The level of intrusion varies, devices are embedded in clothing, worn around the neck, head and arm; some require user input most do not.

Keywords: ubiquitous monitoring, human behaviour, buildings, energy, data collection.

1. INTRODUCTION

The relationship between people is neither simple nor static. While buildings serve people by providing shelter, warmth and many other needs so people must serve buildings by acting as their sensory and cognitive partners; perceiving building defects and making decisions to act on them, whether this might be the adjustment of a thermostat or the repairing of a window. Enhancing this relationship is a core part of intelligent building research (Clements-Croome, 2004, Clements-Croome, 1997).

There are many ways to improve this relationship. It can be made easier for the occupants to monitor and understand the building or easier for them to adapt and control the building's response. The occupants could have better knowledge of themselves and the building. The balance between building automation and user control can be modified. A common thread running through all these is the acquisition, analysis and presentation of information on the state of the microclimate, building, its environment and the occupants. This paper explores the growing range of devices that can be worn or carried by a person and provide near continuous data relevant to behaviour. It is a step closer to the concept of a sense diary system that collects occupant's emotional responses and allows the building to respond (Croome, 1990, Wu and Noy, 2010).

Understanding is essential not just to facilities management but also to the relationship of the building designer and the building user. Conventionally a common language must be built up through dialogue between the two to elicit user wants and how those be acted on (Luck, 2003, Luck and McDonnell, 2006). An alternative approach (described as computational social science) is to use the large amounts of data that already exist to better understand the user's requirements and improve the design (Intille et al., 2005, Wu and Clements-Croome, 2007, Lazer and Pentland, 2009). The fact that the information is acquired remotely could have the added bonus of improving design in disperse and international design teams.

Understanding building user's behaviour is currently moving up the design agenda because it is being recognised that a large degree of the variance in energy consumption can be attributed to practised behaviours rather than deployed technologies (Gill et al., 2010). This is partly because controls for energy systems are falling short of what is required of them (Combe et al., 2011) and partly just down to the different lifestyles people lead and the values they have (Poortinga et al., 2004). By better understanding the "socio-technical interface" of people and buildings (i.e. building use behaviours, how it is influenced by technology and vice versa) it is hoped that more effective low energy designs can be developed.

2. REVIEW SCOPE

2.1 The Data Gathering Devices

There are many ways and research methods used to understand people's behaviour; surveys, interviews, observation, walkthrough analysis, trace and unobtrusive measures (such as room bookings or keystrokes) (Gill, 2011), self reporting in the form of recall surveys or time diaries and experience sampling methods (Intille et al., 2003). This paper examines specifically the range of devices that can be positioned on or close to the body to provide longitudinal data over a pre-defined timescale with minimal data collection input from the researcher (and in most cases the user).

The following types of sensors have been looked at:

- Strapped to the head or arm and embedded in clothing (including as part of wristwatch)
- Entering mouth or nose
- Dangling from neck and in pocket

Other information acquisition methods have not been included such as:

- Off body sensors
  - State sensors (on/off) and other physical variable data loggers
  - Cameras and recording devices (CCTV and IR motion capture)
  - Webcam software that learns and recognise emotions from facial expression
- Tests, surveys, interviews and observations
- Medical examinations and biometric testing
- Accessing information from IT systems such as:
  - Presence in building and at terminal
  - Phone monitoring such as number of calls, voice recording and analysis
  - Email, internet or screen monitoring
  - Keystrokes or time between entries on computer

2.2 The Analysis Perspectives

Intille et al. (2003) and Gill (2011) analyse several different information acquisition methods they find that the important factors are:

- Cost, time and ease of use in preparation, acquisition and analysis;
- Level of information possible
  - Are multiple datasets acquired and can they be coordinated?
  - What is the frequency of reading?
  - How widely can it be distributed in the field to obtain representative samples?
    - possible length in field (governed by intrusiveness)
    - possible number in field (governed by cost, ease of use etc)
- Ability to cross reference with other readings or corroborate with precedent studies
- Ethical issues
  - Ease of obtaining permission

    - Possibility of making data anonymous
- Type of information collected
    - External contributing variable
    - Internal attribute (meaning or internal state)
    - Outcomes (e.g. energy consumption)

Ultimately the monitoring device needs to provide meaningful information about people's behaviour with respect to buildings. Theories of behaviour change (Jackson, 2005) explain the complex interaction between the external and internal factors that shape one's intentions to act. Accordingly devices must provides insight into the external factors affecting people, such as temperature, the internal state of the individual, such as heart rate and/or the actions that people perform such as opening windows. Data on any or all of these is useful for understanding behaviour.

3. USER RESPONSES TO BEING MONITORED

The user's response to being monitored is important because it relates to how long the sensor can remain in the field, ethical issues and outcome bias. The outcome of intrusiveness however is not obvious though, monitoring perceived as supporting evaluation of performance can increase performance in contrast to monitoring perceived to be for the purpose of control (Amabile and Pillemer, 2012). Understanding the intrusiveness of the device is therefore essential.

Moran and Nakata (2010) developed a number of factors that characterise how users behaviour is influenced by monitoring devices these are paraphrased below and will be used in this paper's analysis of different sensor types:

- **Perceived affordance:** Does the person understand that the device used collects data about them. This can be broken down into the degree of user familiarity with a monitoring device and the degree to which it is clear that the device is capable of collecting data;
- **Perceived natural border crossing:** The degree to which a person feels that any natural borders have been crossed (e.g. device is in their home or monitors their personal life);
- **Perceived device control:** the degree to which a person feels they have direct control over the monitoring device. This can be broken down into: ability to avoid, ability to switch off and ability to remove;
- **Perceived coverage:** A persons understanding of the area or domain extent covered by the monitoring device;
- **Perceived privacy invasion:** The degree to which a person feels that the monitoring is invasive of their privacy. This is a function of type of information users must give up to attain value from the application and how widely available information about a user is disseminated
- **Perceived trustworthiness:** The degree to which a person feels the observer is trustworthy.

These point towards a range of characteristics and attributes, beyond merely data quality or cost, that will need to be considered in the research design and the selection of sensor devices to use. These decisions will be contingent on the specific circumstances and characteristics of the setting, people and attributes of a person's behaviour that is being monitored.

4. THE MEASURING DEVICES

There are a range of devices that can be worn on or about the body. Devices can be categorised in terms of what they measure and how they do this. These are often related, for example measurement of physiological factors requires body contact whereas measurement of the room temperature at a person's location does not. Devices are ordinarily made up of a single or multiple sensors, memory and a transmitter.

4.1 Physiology

Physiological measurements can be made of heart rate, breathing rate, blood pressure, blood volume, galvanic skin response, EEG, ECG, EOG, EMG[1], skin temperature, capnometer (CO_2) and oximentry (blood oxygen levels).

Physiological measurements require sensors that touch or enter the body. They may also have a data logger or transmitter. For example skin temperature and conductivity require a button size sensors that can be incorporated into watch size devices, they can also be embedded in well fitting clothing. Physiological measurements have received criticism for their validity, signal to noise ratio and intrusive nature (Clements-Croome, 2004).

4.2 Physical Variables

Measurable variables include temperature, light levels, light colour, humidity, sound level and air quality (e.g. CO_2, VOCs, NO_X). All variables can be measured by devices on or off the body. The data loggers required are small and can be easily hidden. Temperature, light level and colour can be measured by devices from around people's necks. There is one device found that measures room temperature in a wristwatch type device.

4.3 Complex Data

These devices provide data that provides more information than the magnitude of a single variable. They include sound recording, social interaction, camera /video, facial expressions and experience sampling (sound recording has been included here because of its direct link to verbal meaning). These devices provide complex information that can be used for multiple purposes for these reasons it is worth describing them in some detail.

The Sociometer is worn around the neck, it has a microphone, accelerometer and a IR transmitter and receiver. It is designed to work out who is talking to whom, when and for how long. The data is garbled by switching adjacent 100ms speech chunks (Choudhury and Pentland, 2003).

The SenseCam and Ebutton are similar devices, the former worn around the neck, the latter attached to the body. They both take pictures and also provide a selection of contextual data such as temperature, acceleration and GPS. They can take readings either at regular intervals or in response to changes in external conditions. They have been used to work out people's levels of activity and clothing level (Gauthier, 2011) and the photos have been used as prompts to improve the reliability of recall of past events (Intille et al., 2003).

Experience sampling can be done for instance with a PDA or Smartphone device. At regular intervals, either timed or either in response to changes in external variables, respondents are prompted to provide contextual information such as how they feel or their thermal sensation.

4.4 Position And Activity Level

Devices include Bluetooth, radio frequency ID (RFID), GPS, acceleration, altimeter, gyroscope and magnetometer. These are small devices that can be carried in the pocket. Bluetooth can be used to track people without consent. GPS data loggers or RFID systems can be given to people to carry about. RFID in particular has been used to build up very detailed

[1] Measures electrical activity of brain, heart, retina and muscles respectively.

picture of people's position in buildings (Spataru and Gillott, 2011). Alternatively data loggers measuring acceleration, altitude and orientation can be strapped to the body to record activity level.

	EEG	EOG	EMG	ECG	Breathing rate	Blood pressure	Blood volume	Galvanic skin response	Skin temperature	Capnometer (CO2)	Oximentry	Acceleration	Temperature	Light levels	Light colour	GPS	IR motion detector	Altimeter	Gyroscope	Magnetometer	Bluetooth	Sound recording	Camera	Experience sampling
SenseCam (1)												■	■	■	■		■			■			■	
Sociometer (2)												■										■		
Smart phone/PDA																					■			■
Ebutton (1)																■	■		■	■			■	
Fitbit (3)												■						■						
Basis (4)								■	■			■												
Sensewear (3)								■	■			■												
Bodymedia (3)								■	■			■												
Lobin (5)				■					■			■												
Bioharness (3)				■	■				■															
Sensium (6)				■	■				■															
Witherings (7)						■																		
Q-sensor (3)								■																
EBME (6)				■						■	■													
Mindmedia (6)	■	■	■	■	■		■	■	■		■													
Bodywave (8)	■																							
Zeo (9)	■																							
Smartcap (10)	■																							
Emotiv (11)	■																		■					
EGI (12)	■																							

Figure 1: selected sensors from the web and literature. Key: (1): Card box sized box hung from neck, (2): As (1) but attached to shoulder, (3): Button sized on arm strap, (4): Wristwatch, (5): Sensor embedded in clothes with small storage/transmitter device on body (6): Card box sized device strapped to body, has capability for multiple inputs, (7): Arm strap, (8): As 1 but from forearm, (9): Strap around forehead, (10): Device embedded in sports cap, (11): Headset with multiple EEG nodes, (12): Lab quality EEG.

Figure 1 shows a variety of available sensors and the variables they measure. It can be seen that there are patterns between what a given device measures. EEG products are mainly aimed at the gaming market and ordinarily measure only EEG. Products for measuring physiological variables are most often associated with fitness training, they measure a mixture of variables that correspond to activity level and metabolism level (e.g. acceleration and breathing rate). The complex data capture a complex data stream and sometimes contextual data such as temperature or acceleration.

5. DISCUSSION

5.1 Sensor Characteristics

Physiological sensors are mostly small and discreet, although some such as a Capnometer and EEG are larger and encroach on the head and face. They offer long term continuous data on the internal state of the user but the data is often one dimensional and lacks an explanatory meaning for an observed preference or attitude; i.e. it may be possible to tell that someone is alert or excited but not why or how that influences their decision making. However these sensors are cheap enough to deploy in number.

Sensors that measure position, activity and other related variables have similar charecteristics as physiological sensors in terms of data quality and physical characteristics. The perceived natural border crossings for the two will be different depending upon the context in which they are used; is it less intrusive to have one's position or one's mood known at a particular time? Position and activity level are actually quite complex variables that could be interpreted in many ways, they could be indicative of a particular set of external variables, internal states or outcomes. Their interpretation rests on where they suggest the person is and what this means. Ultimately they may be most useful to allow the mapping of other variables that are being studied and so provide richer contextual information for understanding behaviour.

Information rich data give plenty of contextual information. They can act as prompts to supply regular and systemised reports on a person's internal psychological state. Because of the systemised method of recall and the link to the measurement of external variables that is possible they could be a powerful tool to connect the external contributing variables, internal attributes and the outcomes that together describe behaviour. However there may be so much data and it may be so laborious to code, that it would be difficult to get the breadth of study required to support certain hypotheses.

Most of the devices are small and don't restrict movement, physically they are unobtrusive and could be used for extended periods of time. They capture large amounts of data mostly automatically. The difference in the level of intrusiveness will then depend to a large part on the situation and user but also to the relationship between the observer and the observed. It is likely that they will be accepted more in a research situation, where the observer has a greater level of independence from the hierarchal structures present in the user's life or work.

One aspect that differentiates the intrusiveness of devices is their purpose for the user and how much this requires the user to engage with what is being measured. For example a smart phone can be used to track your movement but it is unlikely to affect where you go but providing people with accelerometers may affect their activity levels. It would be interesting to perform position tracking using RFID chips and Bluetooth simultaneously to compare the outcomes of covert and overt monitoring.

5.2 Determining Appropriate Sensors For Different Purposes

Numerical data offer the possibility of automatic analysis that could provide rapid insights for use in building design or management. Use of this type of data in an intelligent building management system is proposed in Wu and Noy (2010) where the optimum trade off between user preferences and energy consumption would continually be calculated and acted on. A problem with this approach is how computer intelligence would learn to negotiate the different trade-offs between comfort and energy over many different users; it may be hard to interpret the values, attitudes and social norms that influence behaviour from raw data alone.

Devices that provide a greater insight into meaning tend to require often large amounts of human input to their analysis. This may not be appropriate for the day to day work of a design consultancy or facilities management team or possible for a computer. However they could be useful tools for researchers to develop rules of thumb about the relationship between buildings, their environment and the people inside them.

The highest value might be obtained by researchers using a number of devices that together provide data and meaning. This would allow the development of rules of thumb for data analysis that could improve the design and management of buildings. Perhaps particular clusters of data could be indicative of certain behaviours. For instance low temperatures and frequent window opening might be indicative of a naturally ventilated office where people were willing to take control whereas high temperatures and less frequently opened windows could be indicative of a similar office but with less autonomous occupants. This link between data and meaning could then be transposed to a similar situation where resources only allow the acquisition of data.

6. CONCLUSIONS

There are many options available to obtain information about the physical environment, people's internal state and their behaviour. Data is useful for broad and long representative studies whereas discursive methods are more useful at assigning meaning. It is becoming easier to coordinate and correlate these different data sources and types, allowing a better understanding of the link between physical environment, sensory experience, psychological state and physiological response. This could lead to the development of standard approaches for automatically interpreting large quantities of data and a better understanding of how particular physical environments are suitable for particular activities.

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Table 1: sources of further information for devices.

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Emotiv	http://emotiv.com/researchers/
EGI	http://www.egi.com/research-division-research-products
Bodywave	http://www.freerlogic.com/body-wave/
Neurosky Mindset	http://www.neurosky.com/
eButton	http://www.business.pitt.edu/student-entrepreneurs/bigidea/poweredby.pdf
The Zeo	http://myzeo.co.uk/
Fitbit	http://www.fitbit.com/product/specs
Basis	http://mybasis.com/
Bodymedia	http://www.bodymedia.com/
Affectiva	http://www.affectiva.com/q-sensor/
BioHarness BT	http://www.zephyr-technology.com/
Witherings	http://www.withings.com/en/bloodpressuremonitor
Sensium	http://www.toumaz.com/page.php?page=sensium_life_platform
Sensewear	http://www.apccardiovascular.co.uk/sensewear_armband.htm
Sociometer	http://alumni.media.mit.edu/~tanzeem/TR-554.pdf
Lobin	http://www.uc3m.es/portal/page/portal/actualidad_cientifica/noticias/intelligent_tshirts
Biotex	http://www.biotex-eu.com/pdf/biotex_flyer.pdf
Smartcap	http://www.smartcap.com.au/index.html
Mindmedia	http://www.mindmedia.nl/CMS/index.php
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