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Developing a holistic set of parameters

to evaluate and monitor

indoor environmental quality

Trevor Keeling

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Declaration

I confirm that this is my own work and the use of all material from other sources has been properly and fully acknowledged

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Trevor Keeling

December 2016

Abstract

This thesis uses four studies to outline a series of problems that should be overcome to improve the specification of sensor systems to monitor, measure and evaluate people's experience of the indoor environment. These are also relevant to the use of parameters to define building performance in design as part of parametric design. These problems are:

- It is not simple or straightforward to reduce even simple environmental stimuli to single parameters that are representative of occupant experience:
  - During the post occupancy evaluation that we carried out we uncovered emergent factors that are important for understanding overall building performance; these factors cannot be linked to component indoor environmental quality (IEQ) factors. The factors include the values that occupants associate with their building and the dynamics of group control.
  - In another of our studies we contrast the experience of sound, which is more complex and requires a greater degree of information processing, to that of air temperature, which is simpler and can be modelled according to energetic principles. It is harder to parameterise the former.
- Physiological sensors can be used to identify salient environmental experiences. This might, in the future, help to characterise complex environments. However, it would reveal little about the underlying thought processes (i.e. why the experience was occurring).
- An alternative way to characterise complex experiences (such as privacy or soundscapes) is to categorise, grade and combine elements of the physical environment. This remains problematic for sensor systems.
- Appraisals can be used to understand the thought process that underpins experience of the environment. However, they require that user feedback is incorporated into future sensor systems. Appraisals offer a compact method (as few as five questions) for unlocking some underlying thought processes and they could be used to identify where problems have a psychological as well as physical dimensions.

Extended abstract

This thesis uses four studies to explore the challenges of developing a holistic set of parameters to monitor, measure and evaluate people's experience of their indoor environment. We suggest that a detached, positivist standpoint, measuring only component IEQ factors (i.e. thermal, light, acoustics and air quality), using a bottom up approach, will never capture the full complexity of environmental sensory experience. People's experience is an emergent phenomenon and not directly dependent upon their physiological state or the

physical state of the indoor environment. Understanding a person's experience will always take some synthesis of sensory data. This synthesis is not something that is simple to do and existing approaches to IEQ fall short. Approaches are either too positivist, and don't capture the richness, uniqueness and complexity of experience, or they are too interpretivist, and unsuitable for sensor systems.

The experience of the multisensory environment must be characterised. This is essential for sensor systems monitoring the real time performance of buildings and for the manipulation and evaluation of parametric designs. It is possible to derive a characterisation by bottom up consideration of the physical components of the environment. This type of characterisation might consist of air temperature, background lux level, outdoor air rate and internal background noise levels. Alternatively it is possible to characterise the environment by considering occupant outcomes, such as privacy, emotional experience, thermal comfort and the identity of the building (Table 0-1). We use both types of characterisation to study seven offices and in doing so evaluate both approaches.

Table 0-1: Different ways to characterise building environments.

Bottom up, component approaches, to definition of indoor environments	Occupant outcomes that can be used in top down approaches
Light: background light levels, colour, visual scene, glare Temperature: air, radiant, air speed, humidity Air quality: CO_2, TVOC, NOx Acoustics: background noise levels, reverberation times, privacy factors Spatial: occupant density, amenities, connectivity, texture	Sensation Physiological function Functional comfort: transfer of information and material, ignoring distractions, stress and restorations, cognitive performance Psychological comfort and social relations: controls and ownership, status symbols, accessibility and privacy Organisation factors: function, identity and values

The first of the four studies is a post occupancy evaluation, using a bespoke survey. In it we use a novel method for determining the values of a building, examples of these being practicality, excellence, and variety. The values assigned by occupants to their building can be used to both differentiate between buildings and predict building performance. These are emergent factors that cannot be linked to component IEQ factors; this suggests that sensor systems have to be able to track these emergent factors. The other three studies all focus on specific environmental impacts.

The second study tests the suitability of wearable sensors for multisensory comfort assessment. Participants' heart rates and skin conductivity are measured while they work at their desk. The physiological response to background environmental stimuli is analysed using two different techniques. Firstly, a between-subject analysis of session averages of all ambient conditions, secondly, a within-subject analysis of response to noise levels. The latter is a novel technique for detecting the saliency of sounds in the workplace. It can be used to monitor workers' reaction to their soundscape in real time. Overall, physiological response is correlated with sound, temperature and light levels. However, the usefulness of background levels and physiological response is limited because they are unable to characterise the complex information processes that are part of user experience. To bridge this gap, alternatives are explored in studies three and four.

The third study uses typologies and design features to characterise the offices. It focuses solely on the privacy and crowding experienced by occupants. Participants report their experiences of privacy using a specially developed survey. We find that occupants of agile workspace have a unique experience of privacy, compared with traditional open plan and cellular offices. This study shows us that privacy is a complex occupant outcome that comprises spatial, visual and acoustic factors, as well as a number of human factors such as management policy, culture and worker mobility. Because of this it is necessary to characterise the environment in an equally complex, and subjective, manner. This would include categorisation of the environment based on physical attributes and user experience.

Finally, the fourth study looks at the importance of psychological factors for predicting occupants' evaluations of their physical environment. Participants are asked to recall a specific time when the temperature gave rise to strong feelings and then they are asked to choose the emotion they felt. We use theories of emotion and apply them to thermal experience, to model the effect of four psychological factors on which emotion was experienced. The factors are: who or what was thought responsible; who or what has control; how much the event was expected; and whether the event was conducive to meeting their needs. Generally, these factors are useful for predicting the emotion. However, some refinements of the method are required. Overall, this demonstrates that emergent, psychological processes are important for understanding even simple environmental sensory experiences.

All four studies also inform how to characterise building environments. Characterisation by occupant outcomes is used and it is a useful compromise between bottom up component approaches and top down user needs analysis. However, evaluating occupant outcomes requires a degree of subjective evaluation. For example, to evaluate the typology of a building for privacy analysis some subjective evaluation about what constitutes a typology is required. This has implications for parametric models that have to characterise a design automatically and sensor systems that have to evaluate real time IEQ. To overcome these difficulties, intelligent systems must be developed. These systems will need to be able to categorise and grade complex environmental information to be able to determine the environmental state. One way to overcome this is for sensor systems to augment (rather than replace) existing modes of building control.

These studies also provide three novel building performance evaluation tools.

1. A survey tool for measurement of the values and identity associated with a building.
2. A method of using wearable sensors for measuring the saliency of environmental events. It could be useful in situations in which traditional one-time survey methods are not appropriate, such as trading floors or other time pressured environments.
3. A recall survey that provides insight into an individual’s peak environmental sensory experiences and the psychological factors that underpin this. The survey could be used to identify where comfort problems originated from user factors rather than from technical faults.

Contents

Publications and awards

Journal papers

Keeling, T., Clements-Croome, D., & Roesch, E. (2015). The effect of agile workspace and remote working on experiences of privacy, crowding and satisfaction. Buildings, 5(3), 880.

Keeling, T., Roesch, E. B., & Clements-Croome, D. (2016). Cognitive appraisals affect both embodiment of thermal sensation and its mapping to thermal evaluation. Frontiers in Psychology, 7.

Keeling, T., Roesch, E. B., & Clements-Croome, D. (2017). Suitability of physiological sensors for multisensory comfort assessment (In preparation)

Keeling, T., Clements-Croome, D. & Roesch, E. (2017). Building values, identity and perceived performance (In preparation)

Book chapter

Keeling, T., Clements-Croome, D., Luck, R., & Pointer, P. (2013). Wireless sensor networks for monitoring people and their close environment. In D. Clements-Croome (Ed.), Intelligent Buildings. London, UK: Telford.

Conference papers

Keeling, T., Clements-Croome, D., Luck, R., & Pointer, P. (2012). How the sensory experience of buildings can contribute to wellbeing and productivity Windsor, UK. http://nceub.org.uk

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Keeling, T., Roesch, E. B., Clements-Croome, D., & Keelin, A. (2015). Field studies of occupant experience in seven UK offices. SuDBE, Reading, UK.

Ramsden, J., Keeling, T., Shepherd, P., Shea, A., & Sharma, S. (2015). SmartBuildingAnalyser: A parametric early-stage analysis tool for multi-objective building design. CIBSE Technical symposium, London, UK.

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Technical reports

Keeling, T., Appleby, P., Newsham, G., Clements-Croome, D., Nathwani, A., & Hampshire, P. (2014). RESEARCH NOTE - ACOUSTICS.

WGBC. (2014). Health, wellbeing and productivity in office buildings: measuring impact and sharing best practice.

Awards

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Glossary, acronyms and abbreviations

Ambient conditions	Conditions of air quality, temperature, sound and light.
ANS (autonomic nervous system)	The bodily nervous system that controls the level of response of involuntary bodily functions such as digestion, heart rate, sweat rate, breathing rate and pupil dilation. (Compare CNS and SNS.)
ASHRAE	American Society of Heating, Refrigerating and Air-Conditioning Engineers
Bottom up components	Physical parameters derived from fundamental physical or material properties of a building (such as height, air temperature, glazing percentage). (Compare to: Occupant outcome.)
Building environment	In this thesis this is taken to mean the ambient conditions and spatial arrangement.
Building values and identity	This thesis uses a 12 attribute model to describe the values a building has. As a whole these are the identity that the building projects. The values were: “practicality”, “excellence”, “variety”, “decisiveness”, “orderliness”, “goal orientation”, “support and consideration”, “conformity”, “recognition”, “independence”, “generosity” and “leadership and authority”.
Building zone	An area of building where the environment can be controlled independently of other areas.
Characterisation	A way to conceptualise and represent a design. This could be by choosing a number of parameters, by assigning it to one of a number of typologies, by listing features that the building has or by use of descriptive prose. This representation is necessary to specify a sensor system and to predict the effect a building will have.
CIBSE	Chartered Institute of Building Service Engineers
CNS (central nervous system)	Brain and spinal cord (compare ANS and SNS).
Cognitive appraisal	The cognitive processing of a stimuli or sensation. In particular, the attribution of particular properties to a stimuli such as who was responsible for it. (Compare: conduciveness, expectation, control, responsibility.)
Conduciveness	The degree to which an event supports one’s goals or is pleasurable. (Compare: cognitive appraisal, expectation, control, responsibility.)
Control	The degree to which a person or circumstance is able to change the state of the (thermal) environment after an event has happened. (Compare: cognitive appraisal, conduciveness, expectation, responsibility.)

Complex characterisation	When it is hard to characterise the building environment using a small set of parameters. Visual scene and soundscape require complex characterisations.
Design feature	A separable component of a building (such as doorknob, window, chair).
ECG (electro-cardiogram)	The electric potential caused by the function of the heart. Measured using electrodes attached to the chest.
Experience sampling a.k.a. ecological momentary assessment	Asking regular questions over a period of time. Questions can be prompted by time (e.g. every 30 minutes) or by environmental context (e.g. when temperature go above a certain level).
Expectation	An event is unexpected if it happens suddenly and without warning or if it rarely happens. An event is expected if it is predictable or happens often. (Compare: cognitive appraisal, conduciveness, control, responsibility.)
HWP	Health, wellbeing and productivity.
Heat (energy) gains	Heat (energy) input into a building zone (i.e. from solar exposure, equipment use, human activity).
HR (heart rate)	Heart beats per minute
HRV (heart rate variability)	The variation of RR interval over a given time period. This thesis quantifies this by using the variance of the HR time series.
IAQ	Indoor air quality
IEQ	Indoor environmental quality
Occupant outcome	An effect seen in occupants that is caused by a building and its environment (such as: thermal comfort, privacy, visual acuity...).
PANAS (positive and negative affect scale)	A standard 20 question survey used to understand people's experience on the 2-D scale of positive and negative affect.
Parametric model	A model of a building that is defined by a limited number of parameters (such as: height, width, breadth , orientation, glazing percentage …). These parameters can be used to predict performance against design objectives (such as: energy consumption, thermal comfort…). (Compare: characterisation.)
Passive design	Maintaining comfort conditions with energy predominately from the external environment.
Responsibility	The degree to which a person or circumstance is thought responsible for the state of the (thermal) environment after an event has happened. (Compare: cognitive appraisal, conduciveness, expectation, control.)
Retrofit	Refurbishment of buildings, especially to improve energy performance.
RR (RR interval)	The time in milliseconds between two successive heart beats. This is useful for detecting heart rate acceleration or deceleration.

SCL (skin conductance level)	The ability of the surface of the skin to conduct electricity.
SCV (skin conductance variation)	The variation of the skin conductance level over a given time period. This thesis quantifies this by using the variance of the SCL time series.
SLL	Society of Light and Lighting
SNS (somatic nervous system)	The bodily nervous system devoted to sensation from external sense organs and control of the musculoskeletal system. (Compare CNS and ANS.)
Thermal environment	The thermal properties of the physical environment. Defined by various metrics based upon air temperature, radiant temperature, humidity and air movement.
Thermal evaluation	An occupant's opinion about a thermal environment and the sensation that they have. This could be comfort or discomfort or any other evaluative concept such as joy or sadness.
Thermal experience	This is used to refer collectively to the thermal environment, thermal sensation and thermal evaluation.
Thermal sensation	The initial perception of the thermal environment. Such as hot, cold, humid, airy. This is primarily a description of how something feels not whether it is considered good or bad for a person.
TRVs	Thermostatic radiator valves

Part 1

Setting the scene

Chapter 1

Introduction

This chapter

There are a number of external factors that have driven this research; the two most prominent are the requirements of multidisciplinary engineering design and the latest research about productive workplaces (Clements-Croome, 2006a). These point to a great opportunity to remotely monitor buildings using sensors. To do this we must be able to characterise the performance of a building concisely. Similarly, in parametric design there is a need to summarise the performance using a limited number of parameters.

Consulting engineers require tools that can quickly evaluate the performance of real and virtual buildings. This requires an approach that is multi-sensory and cross-disciplinary, optimising the building as a whole, not just a single component such as lighting. These are challenges that are important for the productivity and energy expenditure of nations. Offices provide many opportunities for improvements and an extensive existing knowledge base to build upon.

Next

After this chapter, the literature review is presented. This identifies the key challenges with characterising the multisensory environment.

See also

Ramsden, J., Keeling, T., Shepherd, P., Shea, A., & Sharma, S. (2015, 16–17 April). SmartBuildingAnalyser: A parametric early-stage analysis tool for multi-objective building design. CIBSE Technical symposium, London, UK

1.1 Industrial context: the potential of remote sensing and parametric design

Technological innovation presents a number of opportunities to radically re-shape the role of the consulting engineer. Two of these innovations are central to this thesis: they are the remote sensing of existing buildings and parametric design. Currently post occupancy evaluation (POE) requires understanding the building, its systems, resource consumption and occupant experience. A large part of this is done through the analysis of remote data, such as occupancy data, survey data and temperature measurements. In part, these data are used to build up a picture of people's behaviour and experience. Understanding how sensor systems can be specified to provide a more complete picture of occupant behaviour and experience is the starting point of this EngD.

Parametric design is used to optimise the design of the internal conditions of a building. This uses design criteria, for example, daylight levels, temperature or air quality to optimise computer based designs. The design parameters used to specify IEQ are relatively simple (for example CO_2 levels, daylight factor and operative temperature). These design criteria are combined to form a building performance score which is used to test the relative merit of thousands of parametrically defined versions of the same building. This process relies on the correct specification of building performance score.

Behind these two services lies an assumption that it is possible to characterise a building parametrically and assess its performance against a set of predefined objectives. That design can be considered a problem of multi-objective optimisation. An example of some of those multiple objectives are cost, energy consumption, thermal comfort, visual comfort and so forth (Ramsden *et al.*, 2015). Many of the objectives are concerned with the performance and wellbeing of occupants. This thesis explores the most appropriate characterisations to support the design and evaluation of indoor environments.

At its narrowest, characterisations of the indoor environment must account for the thermal, lighting, air and sound environment of a building (Bluyssen, 2009). A broader, more holistic view takes account of spatial factors and other factors that can include spatial settings, ergonomics, biophilia and views out (Clements-Croome, 2013a). This broader view is useful because it is hard to separate the immediate sensual experience of the ambient conditions from the building that shapes them. The broader view is rooted in a user perspective rather than the silos of different design disciplines. This wider approach is taken by this thesis because we wish to improve the design of buildings holistically rather than focus on a single component of buildings such as lighting or acoustics.

1.2 The importance of indoor environmental quality

1.2.1 Productivity

Offices account for only a small fraction of the total floorspace of buildings in England, Wales and Northern Ireland (Table 1-1). However, approximately a sixth of the population work in offices (Table 1-2). This suggests they may offer a cost effective method for improving the health, wellbeing and productivity of the population.

Table 1-1: Area of commercial, industrial and dwellings in England, Wales and Northern Ireland.

Building type	Floor space (000m^2)	Reference
Retail	106,299	
Offices	101,456	
Factories & warehouses	367,113	
Higher education (E, W & NI)	23,000	
NHS	26,000	
Dwellings (England only)	2,023,749	(DCLG, 2010b)

Fisk (2000) estimates that improving the indoor environmental quality of offices could contribute $37–208 billion annually to the US economy, based on reduced health care costs and worker productivity gains. This was approximately 0.5% of the GDP at the time of calculation. Elsewhere, Clements-Croome (2006b) reviews productivity gains in offices due to environmental conditions, and finds them to range between 3 and 15%. This suggests that the average UK worker could work 1 to 6 weeks less per year or enjoy an average salary increase of £800 to £3,800.

Table 1-2: Number of UK workers in offices.

Industry type	Number employed	Estimated % in offices	Number in offices
All jobs	33,673,000 (ONS, 2015)	28%	9,540,450

1.2.2 Climate change

The UK total energy consumption across all sectors, including transport, in 2013 was 137Mtoe equivalent (Table 1-3). Of this total, 31% was used for space heating in buildings (this excludes process heating, water heating and catering), 1% was used for the cooling and ventilation of service buildings, and 4% was used for lighting of buildings. Adjusted for rounding, 35% of the UK energy is used to provide comfort to occupants of buildings. This neglects the energy used for the same purpose in transport. This shows that a very large proportion of UK energy is used for providing safe, hospitable and productive environments.

Table 1-3: UK energy use statistics (DECC, 2013, 2014).

Item	Energy consumption (ktoe equivalent)	% of total
Total (inc. industrial and transport)	136,786	100%
Space heating	41,922	31%
Cooling and ventilation	784	1%
Lighting and appliances	5,049	4%

1.3 Thesis scope and structure

Consulting engineers require tools that can quickly evaluate the performance of real and virtual buildings. This requires an approach that is multi-sensory and cross-disciplinary, optimising the building as a whole, not just a single component such as lighting. These are challenges that are important for the productivity and energy expenditure of nations. Offices provide many opportunities for improvements and an extensive existing knowledge base to build upon.

Part 1 Setting the scene

To begin we explore the sets of parameters that can be used to define and characterise IEQ. This quickly widens in scope to include alternative ways to define, explore and evaluate IEQ. At the end of Chapter 2 a research framework is developed that identifies key issues that could lead to improvements in how IEQ is parametrised. In Chapter 3, the scope of the thesis is developed into a specific aim and four objectives. Chapter 4 addresses the research strategy required and also the overall methods that were used. (There is also further method description within the individual study chapters.)

Part 2 The studies

Each of the four objectives is predominantly addressed in its own study, each of which has its own chapter. The data for the studies were gathered in eight (non-consecutive) weeks, in eight buildings. Chapter 5 presents an overview of the holistic performance of seven of the eight buildings — this chapter is similar in style to a case study. The next three studies delve into specific aspects of the relationship between buildings and their occupants. These four chapters contain all the analyses and results of the thesis. Each can be read independently.

Part 3 Discussion and conclusions

The final two chapters draw together the different elements of the thesis and discuss the implications for sensor systems and parametric design (i.e. the performance evaluation of real and virtual buildings).

Table 1-4: Detailed map of thesis structure.

	Literature review	Methods	Participants and buildings	Discussion	Conclusions
1: Intro.					
2: Literature review	Characterising the physical environment. Bottom up and other approaches.				
3: Aims & obj					
4: Methodology	Methods for real-time access to user experience	Establish methodological stance and its effect on the research. Develop survey questions and physical measurements for evaluation of IEQ at different levels of hierarchy. Identify most suitable wearable sensors.			
5: POE	Environmental sensory design.	Pertinert methodological desscription.	Detailed description of buildings. Key details about participants	Variation and IEQ Building user interactions Values & identity of building	The implications for Environmental Sensory Design approach and design practice
6: Sensors	Multi-sensory approaches Use of PANAS and physiology in BPE	Pertinert methodological desscription.		The usefulness of background levels Energy vs information content of sensory stimuli Potential for physiological sensors to detect salience of complex environmental experiences.	
7: Privacy	Agile working The effects of occupant density, including privacy, crowding and satisfaction	Development of questionnaire Analysis procedure	Repeat relevant details about buildings and participants	1. Break out is a novel typology 2. Mobility affects experience of privacy 3. To characterise the physical manifestation privacy requires typologies and features 4. The components of privacy & crowding is roughly the same as withdrawal	
8: Emotions	Thermal environment, thermal sensation and thermal evaluation (ESE) Models of thermal comfort, w.r.t. ESE and non physical factors Appraisal theory	Development of questionnaire Analysis procedure		Psychological factors that affect perception of thermal environment and their use as a simplified approach to understanding people's thought processes.	
9:Discussion				The challenges posed to sensor systems for monitoring experience of IEQ and how these challenges could be overcome.	
10: Conc.					

Chapter 2

Literature review

Previously

This thesis should support the development of sensor systems in the built environment, especially office buildings.

This chapter

Any sensor system that monitors and evaluates IEQ must have a strategy to characterise the physical environment and the experience and behaviour of occupants. This chapter reviews potential strategies and develops a research framework that addresses some of their shortfalls.

Next

The framework is drawn together into a single aim and a number of objectives.

See also

Keeling, T., Clements-Croome, D., Luck, R., & Pointer, P. (2012). How the sensory experience of buildings can contribute to wellbeing and productivity. Windsor, UK. http://nceub.org.uk

Keeling, T., Clements-Croome, D., Luck, R., & Pointer, P. (2012). A review of how sensory design can influence wellbeing and productivity. CIBSE ASHRAE Technical symposium,

Keeling, T., Appleby, P., Newsham, G., Clements-Croome, D., Nathwani, A., & Hampshire, P. (2014). RESEARCH NOTE - ACOUSTICS. Retrieved from http://www.worldgbc.org/files/2914/1372/1146/140918_Research_note_-_Acoustics.pdf

2.1 Bottom up models of IEQ

2.1.1 The structure of bottom up models

Any system of sensors used to continuously monitor and evaluate building environments so as to determine the health and wellbeing of occupants must be developed from existing approaches to building post occupancy evaluation and existing models of how indoor environmental quality (IEQ) affects occupants. The goal of much research on indoor environmental quality is to build a universal model to predict satisfaction from IEQ. Bluyssen (2008) outlines what she calls a bottom up approach as follows:

- *“Step 1: Identification of sources and other influencing factors.*
- *Step 2: Definition of dose–effect relationships.*
- *Step 3: Establishing threshold values for recognised dangerous pollutants.*
- *Step 4: Assimilating or integrating all factors into end-user satisfaction.”*

Overall satisfaction can be broken down into categories such as thermal and luminous comfort. These in turn can be broken down into criteria such as emission from materials, ventilation rates and pollutant levels. These in turn are broken down into specific indicators including physical measurements and survey questions (Figure 2-1).

Different authors choose different categories (Table 2-1). An almost universal approach is to separate out the different physical components of temperature, lighting, sound and air. Some approaches include specific design elements as separate categories, such as views out and daylight. In contrast to both of these, some authors opt for categories based upon outcomes such as personal control and social support (Leaman & Bordass, 2000; Ulrich, 1991). These outcome focused approaches give greater prominence to the building as it is experienced in its totality as opposed to the individual components of sensory experience.

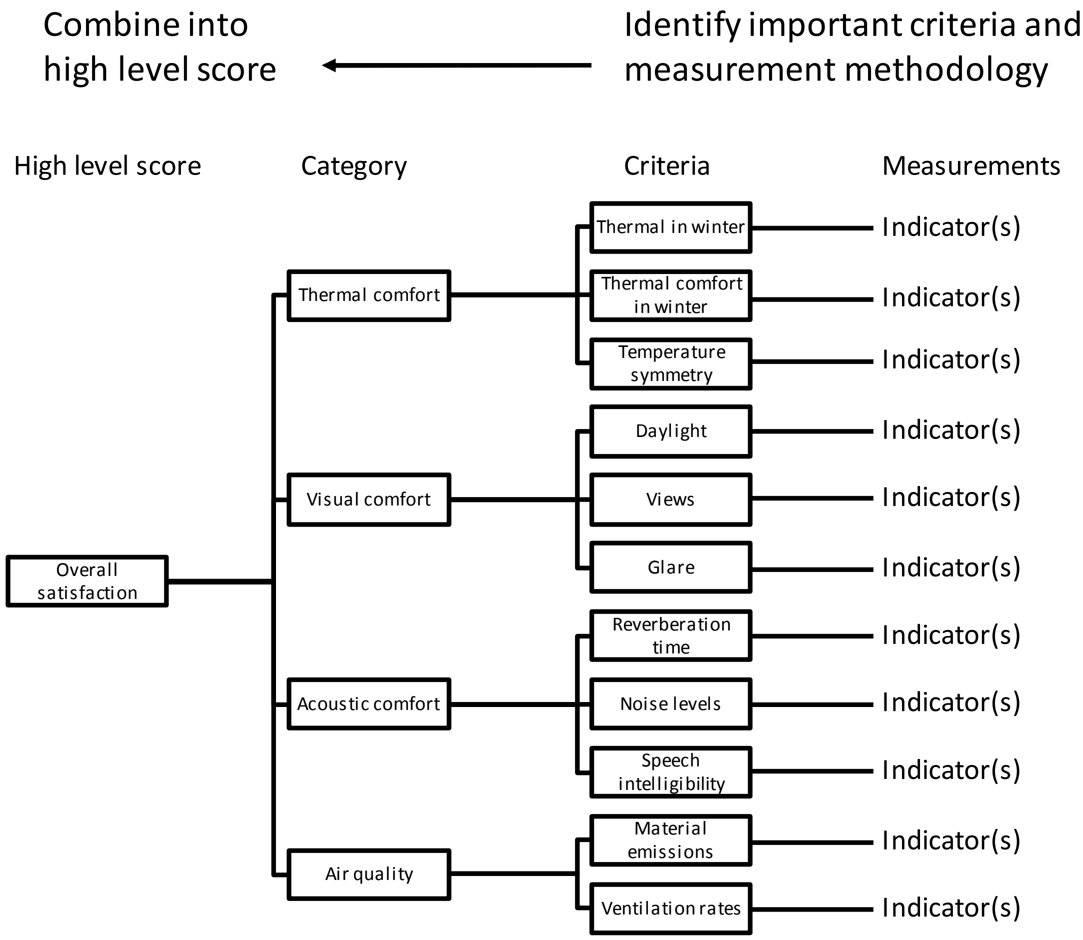


Figure 2-1: Hierarchy of the bottom up approach (adapted from Gadotti and Albatici (2016))

Another consideration is the importance given to spatial factors. Sometimes they are ignored to focus on ambient conditions (Bluyssen, 2009; CIBSE, 2006). When included, spatial factors can be lumped together as a single category (Clements-Croome, 2013a; Pallasmaa, 2005) or broken down into a number of categories (McCoy & Evans, 2005; WGBC, 2014). In summary, there are a number of approaches to choosing categories as follows:

- Components of physical senses (thermal comfort, visual comfort…);
- Key elements of design (views, daylighting…);
- Occupant outcomes (perceived control, social support…);
- Inclusion of a spatial category;
- Inclusion of a number of spatial categories.

Table 2-1: Different systems of categorising the internal environment.

		Focused on ambient conditions									Focused on whole environment			Outcome focused	
	Category	Bluyssen (2009):	ASHRAE (2011):	ISO28802 (2012):	CIBSE (2006)	Sundstrom (1986)	Pallasmaa (2005):	Clements-Croome (2013):	CIBSE (1999)	DELOS (2015):	McCoy and Evans (2005):	Barrett et al. (2015):	WGBC (2014):	Ulrich 1991	Leaman and Bordass (2000)
Ambient conditions	Sound	Sound	Sound and vibration	Acoustic	Acoustic environment	Noise Music	Acoustics	Noise pollution	Noise	Comfort	Ambient conditions	Sound	Noise		
	Light, colour and visual scene	Lighting	Light: daylight Light: electric	Visual and lighting	Visual environment	Lighting and windows Color	Vision	Natural light Glare Access to nature Colour	Lighting Aesthetics and furnishings	Light	Architectural detail Views	Light Complexity Links to nature Colour	Daylighting & lighting Look & feel	Positive distractions	
	Temperature	Thermal	Thermal	Thermal	Thermal environment	Temperature and air	Touch	Thermal environment	Temperature	Comfort		Temp	Thermal comfort		
	Indoor air quality	Indoor air	IAQ	Air quality	Outdoor air supply		Scent	Fresh air rates and dist.	IAQ and air movement	Air		Air quality	IAQ		
	Taste						Taste			Nourishment Water					
Spatial	Ergonomics			Vibration	Vibration	Workstation and supporting facilities	Muscle, bone and action	Ergonomic workplaces	Workstation and ergonomics	Comfort	Resources	Ownership			
	Space allowance											Complexity/ Flexibility	Interior layout		
	Room & building layout							Access to nature	Space planning and layout (open vs cell.)	Mind	Spatial organisation Resources	Connection/ flexibility Links to nature	Amenities and location	Social support	Workgroups Building depth
Psychological	Ownership											Ownership			
	Control								Individual control					Control	Personal control & response time

2.1.2 Ways to measure the environment

There are a vast number of ways to measure the physical environment (Table 2-2) as indicators in a bottom up model. Their presentation here in a single place identifies a number of issues in using them. Many parameters overlap, e.g. dBA and dBB, which are two different frequency weightings assigned to sound levels to account for the sensitivity of the human ear. Some parameters, such as glare, have an obvious good and bad while other parameters are more ambiguous, e.g. colour. Some concepts, such as light levels, lend themselves to a single parameter while others require more complex characterisations, e.g. visual scene. Finally, some parameters are specific to particular outcomes, such as speech intelligibility, while others are more characteristic of the physical phenomena, such as unadjusted sound levels. These different measurements exist to account for the different needs of different spaces types and users. This suggests that bottom up models need to be adjusted for different building and user types.

Table 2-2: Environmental categories and related measurement concepts.

Category	Measurement concepts
Light, colour and visual scene	Illuminance (scotopic, photopic, melanopic)
	Illuminance on retina (vertical), working plane (horizontal) or other surface (SLL, 2012)
	Colour (CRI, colour temp., RGB, CMYK, Munsell…) (Mahnke, 1996)
	Glare, flicker and stroboscopic effects
	Daylight: illuminance, coverage, degree of glare, daylight autonomy, circadian stimulus, view and solar heat gain (Leslie *et al.*, 2012)
	Visual scene: scale (size and distance of window) and content (Ulrich, 1984)
	Look and feel: architectural detail (McCoy & Evans, 2005), or look and feel (WGBC, 2014), consists of decorative style, surface treatment, signage, colour, artwork and ornamentation (McCoy & Evans, 2005). Barrett *et al.* (2013b) call this category stimulation and break it down in to complexity, colour and texture.
Sound	dBA, dBB, dBC, dbD (Hygge, 2007)
	Reverberation time, speech intelligibility and speech privacy
	Soundscape (Long, 2006)
Temperature	Air temperature, radiant temperature, air speed and humidity (Fanger, 1970)
	Mean outdoor temperature (de Dear & Brager, 2001)
	Temperature asymmetries and rate of change (Nicol & Humphreys, 2009).
Air quality	Ventilation rate: l/s per m^2 (floor space) or l/s per person
	Pollutant levels: e.g. VOCs, mould & bacteria, humidity, NOx, CO and CO_2 (ASHRAE, 2009; DCLG, 2010a)
Ergonomics	Desk ergonomics: adjustability of seat height and depth, screen height (DELOS, 2015)
Space allowance	Space allowance: desk size, occupant density, the height and depth of the building (BCO, 2009), the number of people per room or workgroup (Leaman & Bordass, 1999)
Room and building layout	Connectivity: room connectivity (Barrett *et al.*, 2013b), accessibility of gathering places (Sundstrom & Sundstrom, 1986)
	Access to amenities such as shops, exercise, showers and cafes (WGBC, 2014)

2.1.3 Additional considerations

Temporal variations

Many of the indicators in Table 2-2 can be represented as fluctuations over different characteristic timescales (Table 2-3) rather than singular points in time. These timescales are defined by fundamental physics (i.e. tone and colour), building systems (i.e. flickers and buzzes), diurnal and seasonal cycles and the usage cycles of different building components. These fluctuations in different modalities have different characteristic properties and have a variety of different usages. Again this range of potential indicators underlines the complexity of characterising IEQ

Table 2-3: Temporal variations in the environmental factors.

	Tone and colour	Flickers and buzzes	Minutes to hours	Diurnal	Monthly	Annual	Year+
Light	Colour at 500THz	1–120Hz	Movement of daylight	Circadian	n/a	Seasonal SAD	n/a
Sound	Tone 20–20,000Hz	Low level irritation	Composition & music	Important for sleep	n/a	n/a	n/a
Thermal	n/a	n/a		Adaption		Season	n/a
Air	n/a	n/a	Air flow	n/a	n/a	n/a	n/a
Matter	n/a	n/a	Setting		Scenery		Fit out

Spatial variations

Sometimes rather than a building being defined in absolute terms it is specified in terms of outside conditions, as with daylight factors (Tregenza & Wilson, 2011), background noise levels (Long, 2006) and the adaptive theory of thermal comfort (Nicol & Humphreys, 2009). At other times, the range of conditions in a space can be characterised using a uniformity factor (CIBSE, 2006; SLL, 2012). All of the environmental modalities also have a directional element to them. Finally, light can be perceived in terms of a scene (similarly to sound in terms of composition or soundscape; Table 2-4).

Table 2-4: Spatial variations in the environmental factors.

	Outside vs inside	Here vs. there	Directionality	Scene
Light	Daylight factors	Uniformity	Glare	Visual scene
Sound	Background noise levels	Privacy factors	This can be sensed	Reverberation / soundscape
Thermal	Adaptive comfort	Draughts and asymmetries	Radiant temp., draughts	n/a
Air	Fresh air	n/a	Air movement	n/a

Personal and psycho-social factors

There are a number of personal factors that are used to predict interpersonal differences in response to IEQ. Perception of light quality can depend upon an individual's visual acuity, depth perception and colour perception (SLL, 2012). These personal factors vary according to personal psychological factors, age (Barrett *et al.*, 2013a) and other interpersonal sensitivities (Boyce, 1973). There are also a number of personal factors that have been found to affect thermal comfort. These include the clothing of the individual, their metabolic rate (Fanger, 1970), their recent thermal history (Cabanac, 2006) and the climate they are used to (de Dear & Brager, 2001). These factors are either demographic (e.g. age) or modality specific (e.g. thermal history or colour perception).

Sources and material properties

An alternative way to conceptualise the environment is to think of it in terms of sources of energy and the material properties of objects. The interplay of these makes up our sensory experience.

Table 2-5: Ambient conditions in terms of sources of energy and material properties.

Modality	Selected sources	Material properties
Light	Windows, electric lights, fires and computer screens	Reflection, absorption or transmission (Feynman *et al.*, 2006)
Sound	People, traffic, and building services equipment	Reflection, absorption or transmission (Long, 2006)
Thermal	Windows, combustion and equipment such as lighting and computing	Specific heat capacity, thermal conductivity and density (CIBSE, 2006)
Air and pollutants	Windows, printers, food, adhesives & sealants, paints & coatings, carpet system, composite woods & agrofibre and printers (DELOS, 2015)	Emission, adsorption

2.1.4 Combination of environmental categories

When relevant environmental categories have been identified, the problem of which is the most important comes to the fore. The reality of the world is that many different cause and effects occur at any one time and it is hard to predict how these combine. In a hot building, next to a busy road, is it better to open the windows to ventilate the room or close them to keep out the noise? There are a number of ways that these and other categories can be combined (Table 2-6).

Table 2-6: Different ways that bottom up categories can be combined.

Type of interaction	Explanation / analogy
Additive and independent	The effect of two environmental factors is equal to the linear combination of their parts (ASHRAE, 2011)
Synergistic	The effect of two environmental factors is more than the sum of their parts (ASHRAE, 2011)
Antagonistic	The effect of two environmental factors is less than the sum of their parts. This can be considered in terms of diminishing returns (Oseland & Burton, 2012) or in the extreme cancelling out the effect of each other (ASHRAE, 2011)
Prophylactic	Effect on one outcome defends against the effect on another, i.e. reducing humidity lowers the risk of mould growth (ASHRAE, 2011).
Cumulative	Repeated exposure causes greatest harm (ASHRAE, 2011)
Hygiene and motivators	Hygiene factors cause dissatisfaction; low performance on these factors causes dissatisfaction but high performance does not cause satisfaction. Motivating factors cause satisfaction; low performance on these factor does not cause dissatisfaction, high performance causes satisfaction (Herzberg, 1964).
Kano satisfaction model	Basic factors are similar to hygiene factors. Bonus factors are similar to motivating factors. There are also proportional factors, these cause both dissatisfaction and satisfaction (Kim & de Dear, 2012)
One vote veto	Dissatisfaction with a single environmental factor leads to overall dissatisfaction (Huang *et al.*, 2012)

2.2 Alternatives to bottom up models

2.2.1 Top down approaches

One way to overcome the combination issue is to take a top down approach. This starts with identification of user needs rather than low level physical indicators. These user needs can be chosen according to the values of end users, through stakeholder engagement (Bluyssen, 2008) or by developing a repertoire of outcomes that are likely to be desired (Vischer, 2008b). Once these outcomes have been identified, it is possible to work backwards to build a model of how the indoor environment supports them (Vischer, 2008a).

Vischer (2008b) identifies territory, privacy and control as three key psychological outcomes that affect occupant satisfaction. Identifying these needs is the first step in a top down approach. The next step is to understand what factors are important for these needs in a given situation. After this is it is necessary to map the intricacies of the outcome to the physical environment (Figure 2-2).

For example, privacy is a key user need but different users have different privacy requirements, whether it be restriction of information or retreat from social interactions. Understanding the intricacies of people's requirements is an important first step in the top down approach. After this it is possible to identify the factors that influence the user needs. These could be a combination of physical parameters (e.g. sound levels, sight lines, office typologies) and social factors (e.g. management attitudes and policies). The relative importance of these factors may be context specific. Optimising the privacy in a given situation requires an understanding of the relative importance of different factors and the modification of design accordingly. In summary, and in contrast to the bottom up approach of section 2.1.1, a top down approach can be said to consist of the following steps:

- *Step 1: Identify user needs and priority outcomes;*
- *Step 2: Understand how these outcomes apply in a given context;*
- *Step 3: Identify the causes of the outcome:*
    - *Physical parameters*
    - *Space typologies and features*
    - *Social factors.*

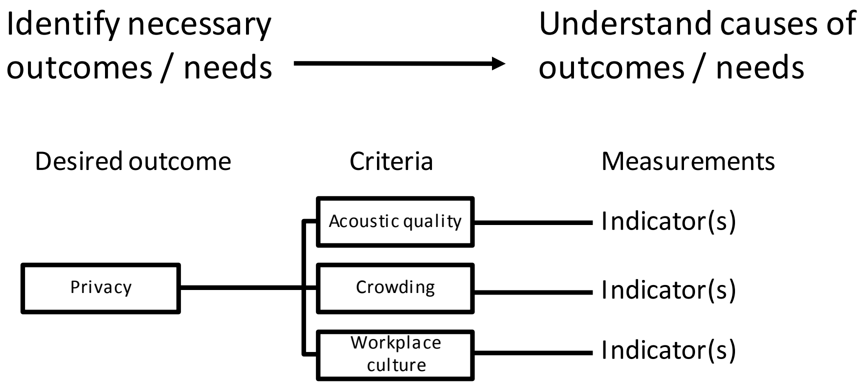


Figure 2-2: Hierarchy of the top down approach.

2.2.2 Hierarchies and categories of outcomes

A number of authors have categorised different user needs and desired outcomes. They tend to categorise outcomes according to different criteria. For example, Maslow (1959) categorises basic needs into physiology, safety, belonging, esteem and self-actualisation. In contrast Vischer (2008a) chooses categories of physical, functional and psychological comfort (Figure 2-3). Among authors there are some similarities between categories but there are also some categories that are vastly different, as Table 2-7 shows.

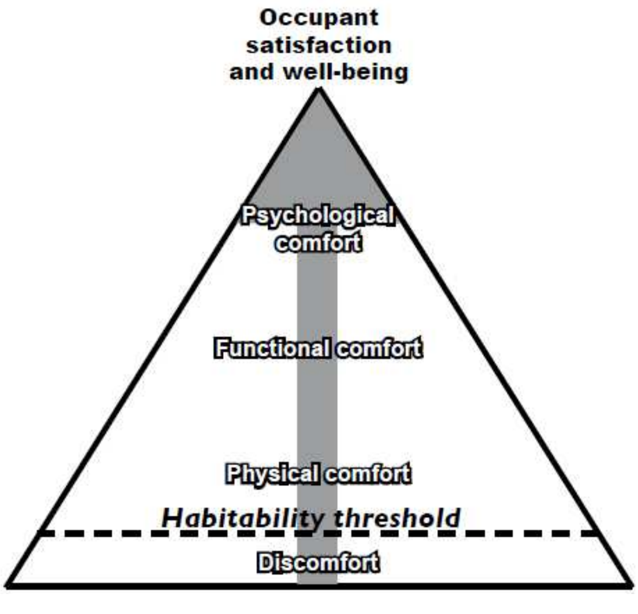


Figure 2-3: Hierarchy of outcomes (Vischer, 2008b).

A category that often recurs is the functioning of the body. Maslow (1959) calls this category physiology and safety, Heschong (1979) calls it (thermal) necessity and Dutson (2010) calls it biological and physiological (she associates it more broadly with how light affects health). This category often forms the base level of a hierarchy of needs.

Table 2-7: Categories of occupant outcomes.

	Individual focused										Multi-level focused
	Maslow (1959)	**Herzberg (1964)**	**Lehman (2013)**	**ISO28802 (2012):**	**DELOS (2015)**	**Croome (2006b)**	**Ruohomaki (2015)**	**Dutson (2010)**	**Heschong (1979)**	**Sundstrom & Sundstrom (1986)**	**Vischer (2008)**
Organisation								Cultural	Sacredness	Organisation	Organisation
Social relations						Social milieu	Social		Affection	Interpersonal relations	Team
Psychological comfort	Self-actualisation	Motivators	Spiritual	Satisfaction	Comfort	Self expression	Pscych.	Pscych.	Delight		Psych. comfort
	Esteem	Hygiene	Intellectual	Acceptance	Mind						
	Belonging & love		Emotional	Preference							
Functional comfort			Behavioural			Choice of work setting	Functional				Functional comfort
Physiology	Safety		Physiological	Sensation	Fitness		Health & safety	Physiol.	Necessity		Physical comfort
	Physiology							Biolog.			

Behaviour is factored independently by only a small number of authors (Clements-Croome, 2006b; Lehman, 2013; Ruohomäki *et al.*, 2015; Vischer, 2008a). The state of the mind is mentioned often; however, it is used with very diverse meanings. For example, some authors focus on motivation levels, while others are interested in the emotions that people are experiencing.

Most authors focus on the individual; however, some also address the fact that buildings can have an effect at an organisational level Sundstrom and Sundstrom (1986); (Vischer, 2008a). Both authors have a category of effect that is at the team or interpersonal level, something that Clements-Croome (2006b) also picks up on. Social organisation is also touched on by the Maslow (1959) needs for self-esteem and love and belonging. However, Maslow's view is of an individualistic need for these factors whereas elsewhere the focus has been on how the environment mediates the function of small groups rather than how it shapes interpersonal feelings.

Finally, the effect of the built environment upon the organisation itself can be important. Sundstrom and Sundstrom (1986) relate this generally to spatial and visual scene factors. Heschong (1979) uses the term sacredness to sum up all those thermal sensations that have cultural meaning. These latter two manifestations are similar to the study of retail atmospherics (Kotler, 1973). They all attempt to understand how a building provides a unifying group identity.

2.2.3 Outcomes for offices

There are a number of specific outcomes that are important for offices. These include base functions such as physiology which can be split into long term health effects and short term sensation (Table 2-8). There are also a number of aspects that are important for individual functioning and task performance, such as having good sightlines and clarity of speech. Above this there is a category of psychological comfort that contains outcomes such as perceptions of autonomy (Knight & Haslam, 2010), control and territory (Vischer, 2008b), social relations and interpersonal feelings (Ruohomäki *et al.*, 2015). Finally, there are principals that relate whole buildings to the functional requirements of an organisation, these include the size and the relationship between departments which can be mapped on to properties of the building such as size and compartmentalisation (Sundstrom & Sundstrom, 1986). However, on this organisational level there is no recognition of group identity and how it applies to office buildings. Which of these outcomes is important will depend upon the type of office.

Physiology is the most universally important to all offices whereas outcomes like visual acuity and speech intelligibility are forms of information transfer and will depend strongly upon what tasks are required.

The suitability of these outcomes for parametric analysis is mixed. Physiological outcomes tend to be more suitable for parametric analysis because the rules governing them are fairly prescriptive and deterministic in nature. Some aspects of functional comfort, such as visual acuity (Rea, 1986) and level of stimulation (Barrett *et al.*, 2013a), are reasonably straightforward to parameterise, whereas others, such as cognitive function and the ability of people to distinguish and ignore unwanted stimuli, are much more dependent upon a great number of complex factors; this is something explored further in Chapter 6. Psychological comfort and social relations are affected both by the environment directly and by how people interpret their environment; this makes them difficult to parameterise. For example, it may be that people's dissatisfaction with open plan offices comes from the combination of spatial, acoustic and visual factors that affect communication channels but it should not be forgotten that private offices are seen as status symbols (Sundstrom & Sundstrom, 1986). These layers of complexity make psychological comfort difficult to tackle with deterministic models formed from physical parameters. Finally, there are some aspects of organisations that can be parametrically matched to buildings, such as the size of the organisation or the degree of centralisation, but others that are much more dependent on individual viewpoints, such as organisational identity and purpose.

Table 2-8: Occupant outcomes for offices.

Categories of outcome	Selected specific outcomes	Description	Ease of parametric analysis
Organisational factors	Functional fit, identity and values	How a building or group of buildings supports the size, structure and other properties of an organisation. Also how it creates an organisational identity.	Mixed
Social relations & psych. comfort	Control, territory, status, privacy / accessibility	The environment can mediate personal and interpersonal feelings and relationships. This is done through a person's interpretation of their space.	Low
Functional comfort	Visual acuity, speech intelligibility, distraction, stress and restoration, cognitive performance	Associated with enabling task performance and completion i.e. visibility, distances travelled, and disabling detrimental activities i.e. distraction.	Mixed
Physiology: sensation	Temperature, light, aroma, taste, sound, kinaesthesia	Sensation is the description of initial perception of the environment, such as cold, loud, bright or stuffy. These sensations are the first line of a person's experience of their environment	High
Physiology: health	Circadian rhythms, Vitamin D metabolism, sensor organ stress, thermoregulation, cardiovascular, musculoskeletal	Physiological effects stem from the energetic properties of sensory stimuli, e.g. the excessive energy of loud noise that damages the ear's sensory apparatus; the balance of forces on the body that affects the musculoskeletal system.	High

2.2.4 Approaches to the relationship between buildings and occupant experience

Bottom up

The bottom up approach assumes that a single state of the environment maps to a single state of the person (Figure 2-4). This mapping implies that the building is some fixed and finished product (Fanger, 1970; Nicol & Humphreys, 2009) supplied to the consumer that has a predictable effect on them.

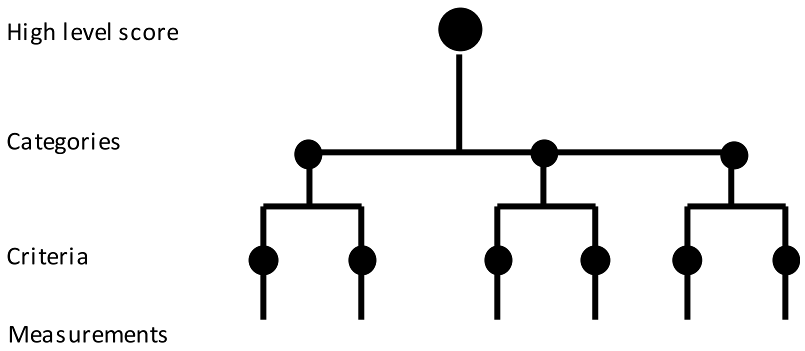


Figure 2-4: Bottom up mapping of physical factors to a single performance score. The focus is to specify optimal environmental conditions.

Top down / gestalt

Vischer (2008a) suggests that, “the place where the behaviour occurs is itself defined by that behaviour”. This describes a viewpoint by which the definition of the user and the building are tightly coupled together (Figure 2-5). She suggests this is close to a gestalt framework and uses the term behaviour setting from environmental psychology. The elements of the building to be studied are defined by the particular experience being studied.

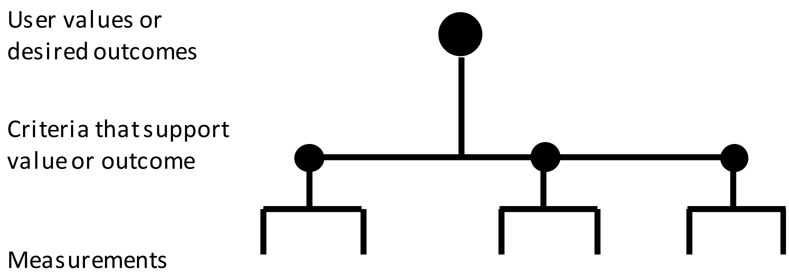


Figure 2-5: Top down / gestalt approach. The focus is to understand user needs and how the building supports them.

Self-regulating systems and the building–occupant interface

As much as buildings shape occupants, so occupants shape buildings (Figure 2-6). Studying the building and occupant as a self-regulating system acknowledges this feedback between occupant and building (Nicol & Humphreys, 1973). This model views the purpose of design as to provide the means to *achieve* comfort, rather to *provide* a comfortable environment per se (Nicol & Humphreys, 2009; Shove, 2003). This sidesteps the need to define universal comfort criteria. Instead, the aim is to maximise the affordances occupants have for control of their environment (Norman, 1998). The indoor environment then becomes one part of a flow of information between buildings and occupants – a flow that can also consists of window signalling (Ackerly & Brager, 2013), energy and IEQ displays (Chiang *et al.*, 2014).

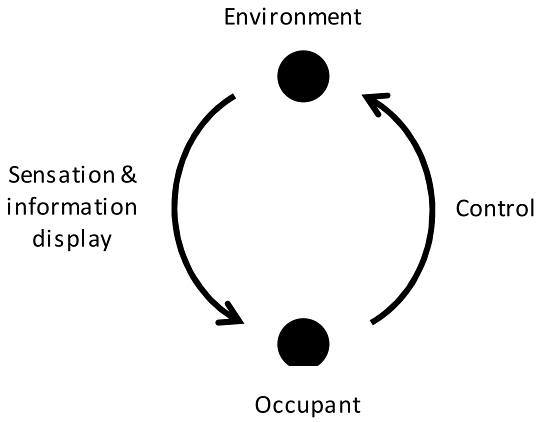


Figure 2-6: Building and occupants as a self-regulating system.
The focus is to optimise useful affordances and improve information flow.

Social construction of reality

The bottom up approach suggests that our experience of the environment can be predicted from its physical manifestation alone. However, this is not always the case; people's experience can be shaped by what the environment means to them (Shove, 2003). Design features that are status symbols (such as executive chairs) are important because of their shared meaning rather than their inherent characteristics. This suggests it is more important to understand the richness of meaning than to count and measure things (Figure 2-7).

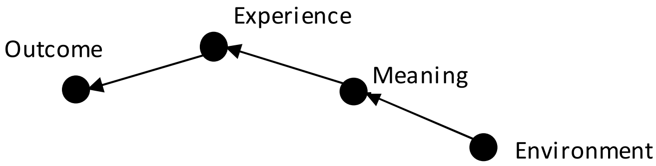


Figure 2-7: A socially constructed view. The focus is to
understand how different people interpret the environment.

2.3 Building performance evaluation

Reviewing approaches to building performance evaluation (BPE) here provides a picture of how theoretical models of IEQ are operationalised in practice. In doing so it provides a practical guide to characterising IEQ that contrasts with the previous theoretical approaches. This provides clues about what a sensor system would need to do to track the IEQ of a building.

BPE comprises the study of the whole life cycle of a building as opposed to post occupancy evaluation (POE), which focuses on the operation of a building and especially that period when a building is first occupied immediately after construction (Preiser & Vischer, 2005). BPE consists of a range of techniques that include surveys and interviews of occupants, combined with measurements and observation of physical space. Often BPE is done to understand energy consumption and inspect energy consuming plant (Deru & Kelsey, 2011). However, in the most general sense, BPE is about understanding how design goals evolved through the design process and whether they were met by the building as it was constructed and operated (Preiser & Vischer, 2005). In this general sense, it is about formulating a definition of what performance is and investigating whether this has been achieved, therefore standard techniques are only used to the extent that there are standard and repeated definitions of building performance, i.e. to the extent that building briefs are similar.

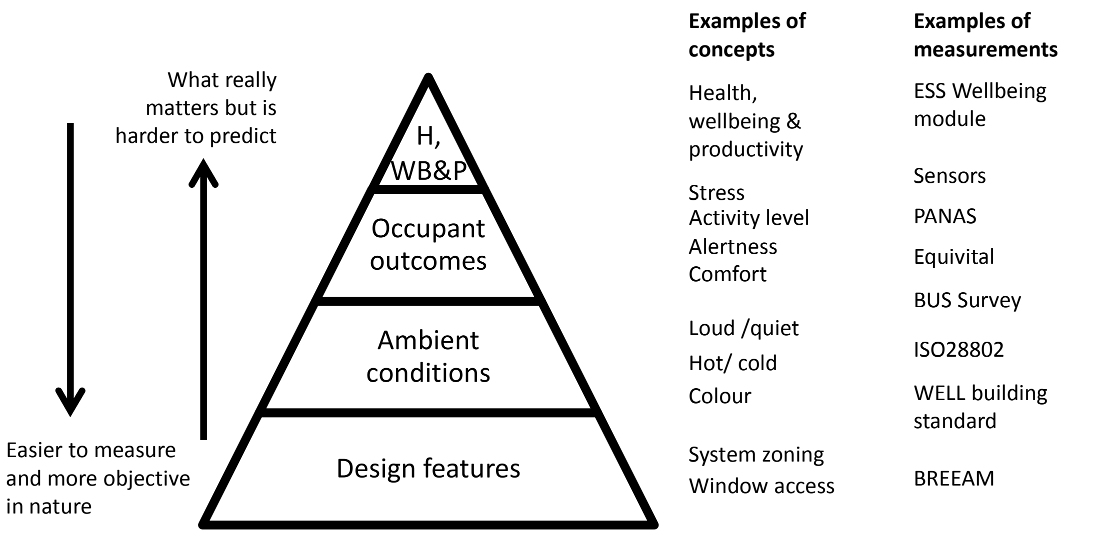


Figure 2-8: Hierarchy of different building performance measurements.

The most objective measures used for BPE are design features (Figure 2-8). For example, BREEAM (BRE, 2014) has a protocol for assessing system zoning in buildings, and the CBE occupant indoor environmental quality survey has a question about the types of adaptive opportunities available to occupants (CBE, 2014). It is possible to assess these design features at design stage because they can be shown on drawings. This makes them easy to measure and compare between buildings. Another important thing to measure is the ambient conditions. However, since these often depend on the external conditions, and have to be measured in use, they are less easy to measure and harder to compare between buildings.

Most POEs measure some form of occupant outcome. However, these suffer from two problems of objectivity. Firstly, many of the measures, such as health and wellbeing, are difficult to define and context dependent. Secondly, it can be difficult to establish a causal link; so for instance, it is easy to measure profit but harder to link it to a specific set of design intervention. This makes them hard to compare between different buildings.

2.3.1 Review of existing surveys

There are a number of survey used to understand an occupant's experience. The Building Usability Survey (ARUP, 2015; Cohen *et al.*, 2001) is commonly used in the UK and there is a similar survey from the Centre of Built Environment (CBE, 2014) that is used in the USA. There are also single use surveys from various academic literature. A number of these surveys are reviewed here, a detailed breakdown and comparison of the surveys can be found in the appropriate electronic appendix.

Overall aims and categories of question

Different surveys ask different sets of questions. Generally questions can be grouped into questions about ambient conditions, spatial configuration and controls.

Questions about ambient conditions asked about temperature, lighting, acoustics, air quality and vibrations. Some questions are general, such as "All things considered, how do you rate the overall comfort of the building environment" (Cohen *et al.*, 2001). Other questions are about specific ambient conditions, such as "Are you satisfied with the surrounding acoustic conditions" (Cao *et al.*, 2012). There are also questions about different aspects of a single ambient conditions, for example (Cohen *et al.*, 2001) asks separate questions about: lighting overall, natural light, glare from the sun and sky, artificial light and glare from lights.

Questions about the spatial configuration focused on aesthetics, I.T., layout, furniture and amenities. The LEESMAN Index asked people to rate their furniture, meeting areas and supporting facilities such as chair, desk, personal storage, audio-visual equipment (Leeson & Oldman, 2011). Agha-Hossein *et al.* (2013) asked about appearance of personal workspace ad well as the overall office, they also asked about layout such as “I consider my workplace satisfactory in the flowing areas: Provision of personal workspace (size, position, etc)”.

There are a number of questions associated with controls, generally they focus on control of lighting and temperature. There are questions about perceived control, such as “How much control do you personally have over the following aspects of the environment..? ”(Cohen *et al.*, 2001). There are also questions about the opportunities for control, such as “Which of the following do you personally adjust or control in your workspace (check all that apply)”(CBE, 2014) (the answer for this question was a list of a number of different control opportunities such as, window blinds and shades, operable windows and thermostats rather than a likert scale). There were also questions about the ability to make oneself cooler in summer and hotter in winter, such as “How easy is it to make yourself cooler in the office”.

Many surveys also asked questions about overall experience of the office focusing on occupant outcomes rather than physical conditions. These includes questions about privacy, ambience, health symptoms, enjoyment and corporate image. These question asked if it was appropriate or satisfactory. For example, “What impact do you think the design of your current workspace has on the following aspects of your organisation: Workplace culture, corporate image”(Leeson & Oldman, 2011) and similarly, “How do you rate the image that the building as a whole presents to visitors” (Cohen *et al.*, 2001). None of these questions define the nature of the perception of the building, in all its complexity, instead they define performance in this category using a one dimensional scale.

Types of answers

The international standard on the ergonomics of the built environment (ISO 28802, 2012) has five categories of response: sensation (i.e. cold /hot), preference (i.e. hotter / colder), annoyance scale, satisfaction, uncomfortable (very uncomfortable to not uncomfortable), acceptability. These are all used to define ambient conditions. Other surveys asked people to agree or disagree with a statement, rate the importance of given feature. Others still sked people about specific design features such as the presence or absence of adaptive opportunities (CBE, 2014). State the level of support provided for activities such as video conferencing, reading and quiet areas and informal meeting spaces(OPN, 2015). Another popular question and answer was to ask for a percentage improvement in productivity that the office was perceived as responsible for.

Temporal coverage

The BUS survey asks respondents to review their experience over the whole time they have been in a building; to do this it simply asks respondents to rate “Temperature in winter” and “Temperature in summer” (Cohen *et al.*, 2001). In contrast the survey used to develop adaptive comfort standards asks about a subject’s experience at the exact time of the survey i.e. “How do you feel right now?” (Nicol & Humphreys, 1973). In contrast the PANAS survey (Watson *et al.*, 1988), that is used commonly in psychology, asks respondents to say how they feel over a selection of different time scales:

- Moment [you feel this way right now, that is, at the present moment]
- Today [you felt this way today]
- Past few days [you felt this way during the past few days]
- Week [you felt this way during the past week]
- Past few weeks [you felt this way during the past few weeks]
- Year [you felt this way during the past year]
- General [you generally feel this way, that is, how you feel on average]

2.4 Research framework

2.4.1 Developing a POE approach that engages with all levels of a hierarchy of outcomes

Although in theory there is a sharp difference between bottom up and other approaches in the practice of POE they are mixed. Survey questions cover both low level sensory experience and high level occupant outcomes although not necessarily in a consistent manner. It would be beneficial to develop a complete set of occupant outcomes that were appropriate for office environments. In fact, there is a layer of the hierarchy of outcomes that is consistently under explored by conventional BPE tools. How a building relates to an organisations is understood in functional terms (Sundstrom & Sundstrom, 1986) but there is little understanding of how buildings affect cultural identity. Thermal experience has been shown to shape culture through shared thermal rituals, customs and practices (Heschong, 1979). Atmospherics studies how retail environments can reflect the brand and identity of the retailer (Kotler, 1973). These point towards the importance of values and identity for organisational sense making. Altogether there is an idea of the ability of the environment to create a feeling or a shared identity for occupants. However, the nature of this and its importance for offices is not well established.

Different outcomes would be suited to measurement by different methods. For instance, it seems relatively straight forward to evaluate a low level outcome, such as thermal comfort, with a temperature sensor but evaluation of a higher level outcome, such as social connectivity, might better be tackled through a range of measurements including space metrics, subjective evaluation and location tracking. Establishing the range of methods suited to high and low level outcomes could help pin point the required complexity of any future sensor system.

2.4.2 Real time access to occupant experience could improve sensor systems

The bottom up approach often differentiates users according to demographic alone. Other approaches emphasise the diversity of individuals, either as part of a dynamic system or as having unique preferences and experiences, that need to be explored in more detail. Any set of parameters used to evaluate IEQ would benefit from being able to account for diverse user preferences and experience.

Modern sensor technology could make this possible, experience sampling (EMA i.e. short surveys administered many times) can provide regular feedback from occupants about their experience (Intille *et al.*, 2003). Physiological sensors can be used to continuously track a person's response to their environment to help identify peak experiences in a changing environment (Tröndle *et al.*, 2014). These present the possibility of sensors providing data not just about the physical environment but also directly about people's experience. This could be used to understand key aspects of people's experience as they happen and forecast their future preferences.

2.4.3 Categorisation and typologies are different from parameters

Some aspects of the physical environment are complex and difficult to summarise in a single parameter. For lighting, it is possible to use background lux levels as a measure of lighting quality but lux levels are a measure of quantity and, though important, this becomes less relevant once a given threshold limit is achieved. Experience of lighting can depend upon a number of distinct attributes including colour, control, visual scene, direction and variability not just the background levels. Because of this trying to reduce lighting quality to a single parameter could be a very difficult task.

The use of such a parameter is even more cumbersome. An analogy is that of music. It may be possible to show that listening to classical music improves performance (Schellenberg *et al.*, 2007). It is a lot harder to reduce the degree of classicalness of a given piece of music to a single number and another step removed to claim that a high score of classicalness will lead to greater productivity. However, this problem of identification and scoring of categories is a common one in IEQ, it is necessary if we wish to measure the performance of a building and so it must be overcome if we wish to use parameters to define and sensors to monitor the quality of the indoor environment.

One way to overcome the problem of complexity and categorisation is to get an observer to judge the quality of the environment rather than trying to measure it directly. The Design Quality Indicator (Gann *et al.*, 2003) is a way of assessing the building that relies wholly on the subjective opinion of different user groups. It overcomes some problems of subjectivity by structuring the assessment of quality around a fixed list of building requirements. A similar approach is taken by Barrett *et al.* (2013b) and Williams (2006), there subjective judgement is supplemented with substantial guidance about how to make that judgement. For instance when judging the quality of display in classrooms there is the following guidance: “The displays are stimulating, well designed and organised, ideally without cluttered noisy feelings” (Barrett *et al.*, 2013b). Still this technique relies on some element of critical evaluation rather than being wholly dependent upon objective measurement. By doing this it overcomes the inherent difficulty of reducing a complex environment to a limited number of parameters. However, it remains challenging as a process for sensor systems because it contains elements of subjective experience.

This is similar in nature to categorising the environment as one typology or another. For instance, judging whether a space should be considered daylit, whether a desk has a view or whether an office is open plan. Sometime assigning a type is straight forward (i.e. for open plan versus cellular) other times it is more nuanced (does a window have sufficient view). Although broad rules can be given about what does and does not constitute a type there will be some element of subjective judgement in attribution.

Here are a number of related problems that need to be overcome if parameters alone are to be used to evaluate the quality of an environment. First types must be assigned. Secondly the degree to which an environment is representative of the type must be scored. To better understand this problem it would be useful to explore how buildings are categorised and how these categories can be broken down. This would help develop an objective approach to the categorisation and scoring of building environments.

2.4.4 The importance of psychological processes

Most of the time in offices the temperature, light levels, noise levels and air quality are roughly right, insomuch as occupants are relatively safe from most physiological side effects. Yet some environments are clearly preferred compared with others. This suggests that psychological not physiological processes are important.

The study of psychological comfort needs different approaches than the bottom up, dose response models often used for IEQ models. The bottom up approach is essentially a dose-response model. It takes a deterministic, bodily stance to understanding multiple effects. Does-response models think of the environment as competing, separable, external stimuli that affect a passive, recipient body. A dose response model requires a simple mechanism to underpin it. When dose A is given in situation B the result is C. This assumes that the system studied is not complex; such that there is little context dependency, few interactions of factors or emergent rules and that there are no unpredictable factors (Clark *et al.*, 2012). In summary use of the dose response model treats IEQ as a simple system when there are in fact many aspects of psychological comfort that suggest it is complex.

The dose response model aims to measure and correlate actual world events (dose A, situation B and result C). This comes from a positivist world view, in which a key aim is to find *"empirical regularities where two or more things occur together or in some kind of sequence"* (p20, Robson, 2002). An alternative, critical realist, approach aims to delve below the *actual* (a term used to describe physical observables) to understand the *real* (a term used to describe the set of underlying causes and mechanisms). Critical realism suggests that it is the mechanisms underpinning the dose response model that should be studied. These mechanisms might be relevant not only for a particular dose response model and by seeking a deeper understanding through the study of mechanisms it is possible to overcome some of the challenges of dealing with complex systems. Therefore any sensor system that tries to uncover psychological comfort must look deeper than dose-response and uncover the reasons behind psychological comfort. The challenge is to understand how the specification of sensors respond to a critical realist stance.

Chapter 3

Aims and objectives

Previously

The research framework identified four key issues that should be resolved to improve IEQ sensor systems.

This chapter

We finalise the aim of the thesis. Then the four key issues in the literature are translated into the objectives of this thesis.

Next

The methodology chapter explores suitable approaches for meeting the aims. It also develops some outline hypotheses.

Aim of work

The literature review revealed a number of barriers that prevent sensor systems being used to monitor and evaluate user experience. As such the aim of this thesis is:

To identify the problems that have to be overcome to improve the specification of parameters used to evaluate the experience of indoor environmental quality.

Development of objectives

There are benefits to both the bottom up and the top down approaches and in fact most POE uses a mixture of both approaches. However, they leave key gaps because they don't recognise a complete set of outcomes. Therefore, **the first objective is to develop a more holistic method for POE**. This will take account of both bottom up categorisation of the physical conditions and occupant outcomes required for general purpose offices. By targeting factors at different levels of the hierarchy of outcomes it will help to establish the range of methods suited to high and low level outcomes. This will help pin point the required complexity of any future sensor system.

Obtaining real time information about a person's experience is different from a post event survey and could help to build up a more nuanced picture of occupants' response to IEQ. Therefore, **the second objective is to develop methods to monitor real time psychological processes for use in evaluating occupant experience**.

Categorisation and scoring of types is a particular challenge for sensor systems and the parameterisation of design. **The third objective to explore how to parameterise the evaluation of categories.** In this light the user requirements for privacy are particularly interesting. It is characterised using a mixture of typologies and parameters, and it involves spatial, sound and visual field information.

It is not enough to say that dose A of building leads to response B in the occupant. The nuance of mappings are needed to predict the effect of buildings. In particular, how thought processes can shape occupant experience (how dose A leads to response B because of thought process C). One of the challenges of any sensor system is how to deconstruct these mappings. Therefore, the **fourth and final objective is to develop methods to understand the mechanisms of the psychological processes of occupant evaluation.** At first consideration thermal experience would appear to map to the ambient conditions in a relatively simple, one-to-one, manner. However, there are a number of psychological factors that can affect this mapping. Exploring how psychological factors affect the mapping, on this apparently low level outcome, will help develop a sensor specification that could account for psychological processes factors and complex mappings.

Chapter 4

Methodology

Previously

Any sensor system that monitors and evaluates IEQ must be specified based on a strategy to characterise IEQ that addresses the physical environment, occupant outcomes and the causal mapping from one to the other.

This chapter

Epistemology and ontology are important for both the development of this thesis and the development of an IEQ sensor system. A deterministic, approach that prioritises empirical results from the natural world, is suited to the use of sensor systems. However, it lacks the deep analysis of people's standpoints to be able to fully understand the social world. The study of IEQ stands at the intersection between the physical and the social world. As such it is suited to neither extremes of positivism or interpretivism. A critical realist approach not only seeks to find common ground but offers a pragmatic approach that is suited to the real world problem solving of the Engineering Doctorate.

Having established this research strategy we explore the specific methods that are most suited to achieving the objectives developed in the previous chapter.

Next

In the chapters of the thesis that follow these methods are developed further and the results presented.

See also

Keeling, T., Clements-Croome, D., Luck, R., & Pointer, P. (2013). Wireless sensor networks for monitoring people and their close environment. In D. Clements-Croome (Ed.), Intelligent Buildings. London, UK: Telford.

4.1 Deterministic models in engineering: expressive versus neutral specification of IEQ

The approach of design guides is to use certain properties of users, and the tasks they will be carrying out in a given situation, to suggest the state of the environment that should be specified. For lighting the user activity suggests the light levels (SLL, 2012). For temperature the average external temperatures, activity and clothing suggest the operative temperature (CIBSE, 2006). The purpose of design in these situations is to lead from known information about building and people and proceed logically to the desired set of internal conditions. This has the prescriptive logic of the bottom up approach.

Design guides recommend neutral environmental conditions because they view the goal of IEQ as removal of environmental stressors to enable the smooth performance of tasks without distraction (Lehman, 2011). This is quite different from the role of thermal experience described by Heschong (1979), where it is integral to the purpose of a space; the point of the sauna is to be hot, the point of a walled garden is to be cool. The approach described by Heschong (1979) uses the indoor environment to express part of the architectural intent. This is quite different from ambient conditions that are chosen for their neutrality and to allow activities to carry on unimpeded. The same can be said of the multisensory experiences described by Pallasmaa (2005) and the detailed history of the senses described by Jütte (2005); both describe an internal environment that expresses an integral part of the experience rather than an environment whose impact is minimised.

The approach that uses the environment to express architectural intent, provides greater choice of what the state of the environment should be. It encourages environments that are dynamic and conditions other than neutrality. Ambient conditions become a part of the architecture that expresses and conveys meaning. The difference between these two approaches is large. On the one had we have an empirical approach that aims for a neutral environment. On the other an interpretive approach that aims for an expressive environment.

The research methods used to develop empirical specifications tend to expose participants to constant uniform conditions and find out whether they're satisfied or how they score on performance tests (e.g. Boyce, 1973; Fanger, 1970). These studies provide plenty of data but fail to provide the rich information about experience that is necessary to understand how ambient conditions become part of the meaning of a place. Literature that does provide the necessary rich and detailed descriptions (e.g. Heschong (1979), Dutson (2010) and Pallasmaa

(2005)) does not use data so it is difficult to know just how hot, how light, or how loud the conditions being described are.

4.2 Research strategies

A positivist approach to IEQ would aim to build a mathematically complete picture of the world around us. This would allow the prediction, with some degree of accuracy, of how a person would feel and how they would behave in any IEQ situation. The bottom up approach to neutral specification of IEQ is typical of this aim to create an ideal mathematical model of the world. Using the terminology of Clark *et al.* (2012), this views IEQ as a complicated but mathematically tractable problem, like sending a rocket to the moon, the underlying maths is complicated but doable.

However, theory and its use doesn't have to be neat and tidy (Sears & Cairns, 2015). Theory can be a tool for comprehending the complexity of real world problems. Here we draw on models of complexity from healthcare, where complex means that outcomes depend on many components, that interact dynamically and are part of an open system (Clark *et al.*, 2012). This makes them difficult to study outside of their contextual setting (Robson, 2002). It also suggests that to evaluate success and effectiveness it is important to understand the underlying mechanisms, as well as to measure interventions (dose) and outcomes (response), Figure 4-1(Clark *et al.*, 2012). For example, it is not enough to know at which temperature people will open a window in an office, it is also important to understand the office politics that govern who opens the window and when.

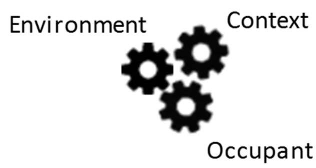


Figure 4-1: Instead of seeing cause and effect that can be clearly separated, a critical realist studies the world as a series of complex interacting mechanisms.

Part of the complexity of IEQ is because it is inherently linked to the study of people and the thorny issue of how they interpret the world around them. An interpretivist approach would prioritise the study of different people's worldviews. It would try to make sense of IEQ solely through the study of people's interpretation of the world around them (Robson, 2002). Arguing that measurements of the physical world were merely part of a person's standpoint and not representative of a reality separate from our thoughts; and in the extreme that there was no reality separate from our thoughts (Okasha, 2002). These are the approach taken by Heschong (1979), Dutson (2010) and Pallasmaa (2005).

Positivism and interpretivism are two extremes of thought. The former developed from the natural sciences, the latter from the humanities. They both lend themselves to the disciplines they emerged from and risk ridicule when their principles are applied outside their original confines. The study of people and buildings sits between the natural sciences and humanities; so should we turn to positivism or interpretivism to study IEQ?

In reality there is not such a great need to choose and maybe there was never such a sharp distinction between the two anyway. It is possible to identify a cycle of enquiry that moves between inductive and deductive approaches to inquiry and in doing so embraces both positivist and interpretivist approaches, see Figure 4-2 (Sears & Cairns, 2015). There are parallels here to the realities of BPE with its mixture of surveys, data gathering and narrative building, collected both as an embedded agent and as a detached gatherer of evidence.

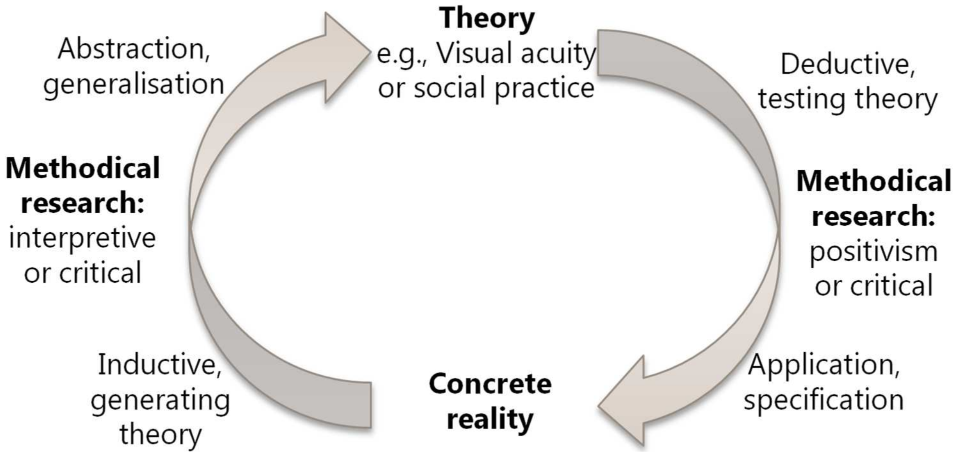


Figure 4-2: Cycle of inquiry (Sears & Cairns, 2015).

The two world views can be reconciled further by critical realism. There the view of reality is essentially layered. Firstly, in terms of an underlying reality (*"the real"*) *of* mechanisms and explanations that shapes the world independent of people. Secondly, the physical world of events and happenings (*"the actual"*). Finally, the events and happenings as people sense and measure it (*"the empirical"*). This suggests that there is both a physical world and structures (i.e. mechanisms) that drive change and exist beyond our empirical senses (Sayer, 2000).

The mechanisms of the real are multiple, for instance they may be biological, sociological or chemical. As such critical realism provides the philosophical space to consider a multitude of approaches to a problem. For example the instances of Tuberculosis on Tyneside were found to be driven by three main factors, poor housing, poor feeding and being Irish (Robson, 2002), clearly one could have studied the genetic and biological mechanisms of Tuberculosis but in this case these were not the mechanisms that were considered useful for understanding and fixing the problem. This encapsulates another principle of critical realism, that the mechanisms of the real are multi layered of explanation. Each layer is emergent and potentially independent from other layers (i.e. the societal structures cannot be understood by at first understanding biological structures). This approach places an emphasis on the study of natural settings and inductive analysis leading to the selection of theoretical mechanisms that are appropriate to the context being studied (Robson, 2002).

This thesis uses a number of different methods to probe the mechanisms of psychological comfort. This helps identify and utilise when an occupant's interpretation of their situation is important and when there is a more prescriptive, dose–response relationship between building and occupant. To understand when a building can be understood through objective measurement of the physical environment and when it may be better to use the occupant's subjective evaluation of their situation. To understand when a bottom up approach can be used and when a top down approach is better.

Chapter 5 is where the critical realist approach is felt most strongly. This study consists partly of observational reports of how the different buildings work and what the experience of being in them is like. This will help uncover both the character of the building and what shapes that character. This is an essential part of this thesis, it equates to the inductive, theory generating part of the cycle of inquiry (Figure 4-2) because it will help to shape our ideas about what is important about the character of a building. This will in turn help to shape conclusions about what are the best set of parameters to capture that character.

Chapter 5 also has positivist aspects. We go to these buildings with a predefined set of parameters and test the degree to which these parameters are useful. However, the selection of what data to analyse further and present in the thesis is guided by what was observed in those buildings. So it is only fair to acknowledge these observations as explicitly as possible. The studies following this are more traditionally positivist, explicitly testing theory using data and statistics and trying less to understand the complexity of different people's stand points. However, even then, there is potential to use field observations to help identify what may or may not be the underlying mechanisms that help explain correlations.

4.3 Methods

4.3.1 Development of field study measurement protocol

Choice of physical measurements

As seen in chapter 2, there are many ways to characterise the environment. It is essential that the space is characterised effectively and as comprehensively as possible. The aim of this thesis is to investigate multisensory effect. Therefore, it is of key importance to measure a broad and comparable set of factors from across the range of sensory perception. To do this a selection of measures from different categories of IEQ will be chosen.

Most ambient conditions have something equivalent to a background level. This makes it useful for comparison between sensory modes. However, this is not the case for air quality or spatial factors. For air quality, CO_2 levels can be used as a proxy for outdoor air rate (Chatzidiakou *et al.*, 2015), it is also an important pollutant in its own right (Satish *et al.*, 2012). For spatial factors, density is the most similar to a measure of background level because it is a continuous number and characterises the average amount of space per person.

In addition to these measures, occupant control of the environment needs to be understood. For this a measurement of actual controls is needed, rather than perceived control. To do this size of zone, control usability, system response time, degree of automation and ownership of space will be noted as appropriate (Table 4-1). Together these measurements cover a range of environmental factors, and a mixture of ambient conditions and design features.

Table 4-1: Physical variables measured for this thesis.

	Whole building measures
Light	Lux levels at working plane, power spectrum
Sound	Background levels, power spectrum
Temperature	Radiant T, air T, air speed, humidity
Air	CO_2 levels, humidity
Spatial	Density of space, room depth and height, number of people in a room.
Controls	Zone size / extent of effect, control usability: Location, system response time, degree of automation, ownership of space

Measurement equipment

Continuous environment data were obtained using sensors that monitor air temperature and humidity, a number of these sensors also measured light levels. These sensors were placed throughout each building in places that would be representative of temperature and lighting conditions. At least two sensors were placed on each floor, one close to the window another in the centre of the space. One sensor was placed outside to measure external air temperature. For all other environmental factors spot measurements were taken. Table 4-2 provides a full breakdown of equipment used.

Systematic rules for the placement of sensors were followed. Sensors were placed at desk height, this is between abdomen and head height for a sitting person, which is ideal for temperature measurements (ISO 28802, 2012). It is also appropriate for measurements of light levels at the working plane. Sensors were placed away from sources of heat and light. In particular, sensors near windows were placed close to the wall to provide shading from direct sunlight. Temperature sensors on desks were placed away from computers and other sources of heat. CO_2 sensors were placed at the back of the desk to minimise the effect of respiration. The microphone was mounted upon a tripod to bring it to ear height. Photos were taken of sensor location for future reference (see appendix).

Table 4-2: Equipment used for measurement of physical environment.

Sensor type	№	Purpose	Calibration
Onset HOBO U12-012	4		
HOBO H8-004-02	6		
TinyTag Plus 2	2	Cont. logging of air temp. & humidity	
Telaire 7001	1	Cont. logging of CO_2	Partial calibration at BSRIA
Onset HOBO U12-013	1	Thermal comfort rig	New
Gigahertz-Optik BTS256	1	Light spectrum and intensity	New
Solo	1	Sound level	Calibrated annually

Temperature and humidity sensors were either new, calibrated at BSRIA or calibrated in the UoR climate chamber. All sensors were within design specified tolerances for temperature. Humidity sensors were ±10%.

HOBO light sensors were uncalibrated.

Some of the HOBO sensors could be connected to a Telaire 7001 to log carbon dioxide levels. The Telaire 7001 was calibrated by BSRIA, it had a systematic error of between +50 to

+75ppm (i.e. readings were between 50ppm and 75ppm higher than calibration chamber levels). This is outside specified accuracy levels but adequate for these studies.

For more accurate measurements of light and colour a Gigahertz-Optik BTS256 Spectrophotometer was used. This could only be used for spot measurements. It could be set up to take regular spot measurements. This was how it was used for the sensors study. This was purchased new especially for this study.

For sound level measurements a solo sound level meter was used inside and outside on a selection of the buildings. This is calibrated annually.

4.3.2 Development of survey

Surveying a complete hierarchy of outcomes

The first objective of this thesis is to explore the range of occupant outcomes. To do this we asked questions aimed at different levels of the hierarchy of outcomes, these covered:

- Overall experience in terms of health, wellbeing and productivity. In particular questions about SBS symptoms, perceived effect of the building on wellbeing and productivity;
- Occupant outcomes, including privacy, emotions, identity and values;
- Component environmental factors, including temperature, light, sound, air and layout.

Identity and values

One of the occupant outcomes we asked about was the identity of the building. For this we developed novel questions about building identity and values. Questions about values were sought from human relations. The Gordon survey for personal and interpersonal values (Hofstede, 1994) met our requirements. We modified this to suit buildings, so that occupants were asked to choose any of the following descriptions that suited their office: “practicality”, “excellence”, “variety”, “decisiveness”, “orderliness”, “goal orientation”, “support and consideration”, “conformity”, “recognition”, “independence”, “generosity” and “leadership and authority”. We felt this was a useful addition that covered in detail an outcome that was previously overlooked.

Privacy survey

We also developed a survey to understand people experience of privacy. This was based upon a number of surveys in the literature. More details can be found in Chapter 7.

Emotions survey

As observed in the literature review, often the goal of IEQ research is to map a set of physical conditions to a set of occupant outcomes. Often there is an underlying assumption of a one-to-one mapping; that it is possible to map a single state of the environment to a single human experience. However, there are cases where psychological factors, such as perceived control, affect occupant evaluation. These cases do not fit easily into a simple division of physical and human factors.

In one branch of the study of emotions there are theories of how psychological factors can influence what emotions people experience. If these could be applied to the experience of building occupants it would demonstrate the importance of psychological factors and provide a systematic approach that could be used to account for them.

Because it is considered relatively straightforward to map thermal parameters to thermal experience, it is all the more interesting to show that psychological factors are highly relevant to thermal experience. This is done in Chapter 8, there the problems of mapping specific to the thermal environment are outlined and the utility of psychological factors is tested.

4.3.3 Methods to access experience in real time

This section reviews wearable sensors and how they can be used to access short term psychological processes. The use of on-body sensors in natural settings is called ambulatory assessment. The Society for Ambulatory Assessment maintains a website with up-to-date resources and available hardware and software (SAA, 2013). Ambulatory assessment aims to encompass a breadth of perspectives about real-world situations and embrace complexity. It suits the critical realist approach because it is embedded in real world situations. In contrast, laboratory-based investigations, are generally stationary and designed to provide in-depth answers to very specific and controlled scientific questions.

Data from wearable sensors can be split into four reasonably exclusive categories:

- **Physical environment**. Data can be collected about the physical environment, this includes temperature, air quality etc, as reviewed in the earlier sections of this chapter.
- **Experience sampling.** Data about a person's subjective experience are most commonly collected through a survey. Advances in mobile computing mean that these can be administered on an ongoing basis and in response to changes in the environment.
- **Behaviour.** Data can be collected about a person's location and acceleration or their activity such as operation of lighting, window opening or of I.T. devices. This can be from sensors deployed especially, or from of internet connected devices such as smartphones.
- **Physiology.** Data include heart rate, skin conductivity and electroencephalograph (EEG). All these data need to be treated with care because they do not provide a direct or complete picture of a person's state of mind, and results can be difficult to interpret.

Periodic sampling of subjective experience (experience sampling)

Getting participants to respond periodically to questions using a smartphone or other device is a useful tool to use alongside traditional retrospective surveys (Intille *et al.*, 2003; MacKerron & Mourato, 2012). Experience sampling applications prompt participants to provide contextual information such as how they feel or their thermal sensation. This can be done either at regular intervals or in response to changes in contextual factors such as temperature or behaviour.

Asking people's subjective experience as they go instead of their reflection after the event, has been shown to generate systematically different responses. Generally, retrospective recall “favors mental representations that fit into idealized self-concepts, social expectations and after the fact information, rather than those that represent actual experiences” (Wilhelm & Grossman, 2010). It also tends to prioritise final states and peak experiences (Redelmeier & Kahneman, 1996). So, in structuring what and when something is asked, it is important to be aware of the difference between short term feelings and long term contextual reflection.

Behaviour

Sensors that track behaviour either monitor movement (i.e. by accelerometers), location or specific actions such as opening windows or using equipment. Common behaviours associated with experience of the environment are opening and closing windows, repositioning blinds, and moving seats. However, it is felt that these occur relatively rarely in office environments and therefore they were not suitable for obtaining the large amount of data about experience that was desired.

Physiological

There are several off the shelf physiological systems that obtain continuous information from participants. Because of the need for continuous information anything that requires the extraction of bodily fluids, such as saliva, is not suitable. This rules out hormonal systems (which would include the measurement of cortisol). Systems that are more indicative of bodily metabolism are not suitable either. Blood oxygenation and blood sugar levels are both indicative of the effectiveness of the operation of the cardiovascular system and metabolic rate. These can be directly affected by building environment. They then in turn effect occupant experience. However, they are primarily measuring the physiological effect of buildings rather than psychological effects.

This leaves three bodily systems that can be used to indirectly access the workings of the mind. The autonomic system is the system of nerves by which the mind controls the function of the organs. Facial muscles, part of the somatic system, can be used to track facial expression and hence emotions. Finally electroencephalogram (EEG) directly measures the electric field at the scalp.

Mapping from a physiological state to a psychological state

In an ideal world, a given physiological state would map to a given psychological state in all circumstances. In reality a single physiological response can have many causes (both of the mind and the body) and a single psychological state can give rise to many different physiological responses. For example, heart rate can be affected by psychological causes such as arousal or physiological causes such as increased activity. Changes in skin conductivity could be because of arousal or because of temperature changes. Changes in breathing rate could be because of activity or speech or arousal. Being able to isolate and identify the causes of a physiological response is essential to using it for research purposes.

For instance, a person's response to a stimuli can be categorised using three basic responses. They will be startled at a stimuli with rapid onset, they will be orientated to a stimuli if it is of interest to them, or they will feel defensive toward a stimuli if they recognise it as a threat. All of these reflexes give rise to a heart rate (HR) and skin conductivity (SCR) response. Therefore, it is impossible to tell between these basic psychological states on the basis of the absence or presence of a particular physiological response. However, mapping from physiological to psychological can be disentangled by looking at the nature of the physiological response in greater detail. Figure 4-3 shows that a one-to-one mapping can be obtained by looking at the rate at which physiological markers change. This enables these three psychological states to be mapped on to the physiological response of SCR and HR.

However, this one-to-one mapping applies only where there is freedom from confounding contextual factors. These contextual phenomena may be psychological factors such as stress and personality or behavioural factors such as activity level, all of which can affect heart rate and skin conductivity. Taken together, this means one must be aware of both specificity of mapping and context effects (Cacioppo & Tassinary, 1990), when using physiology responses to understand psychological processes (Figure 4-4).

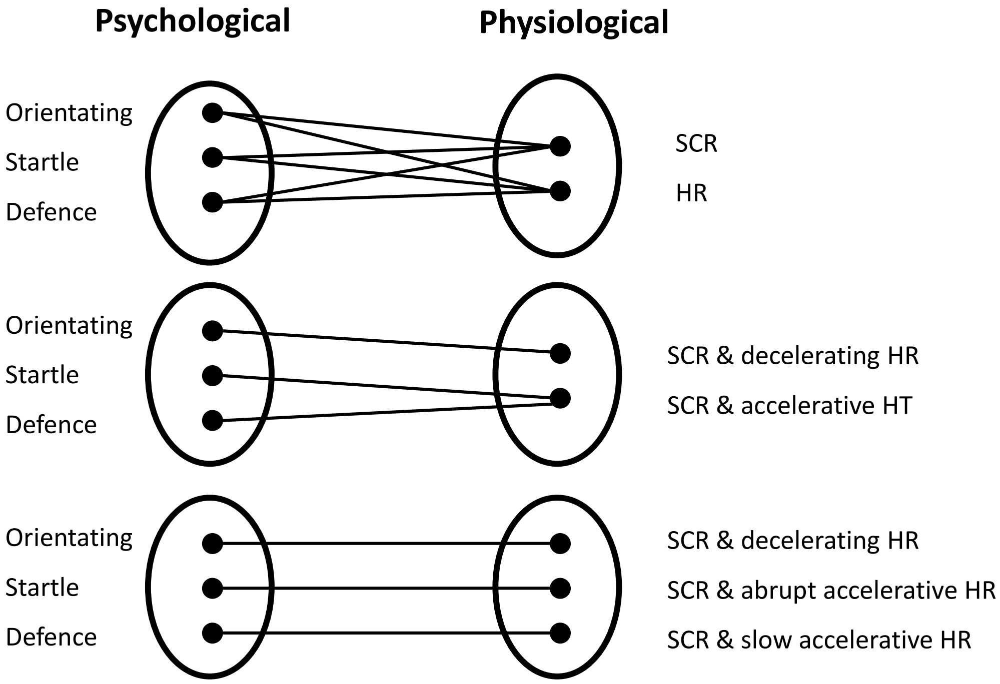


Figure 4-3: How second order changes in physiological response can be used to obtain context specific one-to-one mappings (Cacioppo & Tassinary, 1990).

Theses reflexes are not the only psychological states that can be detected by changes in physiological response. Emotions can also be studied this way. Emotions can be split into dichotomous groupings such as good and bad or passive and active. It is then possible to use psychophysiological methods to distinguish between opposite groups (e.g.:Urry *et al.*, 2009). However, there is little evidence to suggest that different named affective states (such as fear, happiness, guilt) have unique psychophysiological markers (Bradley & Lang, 2007).

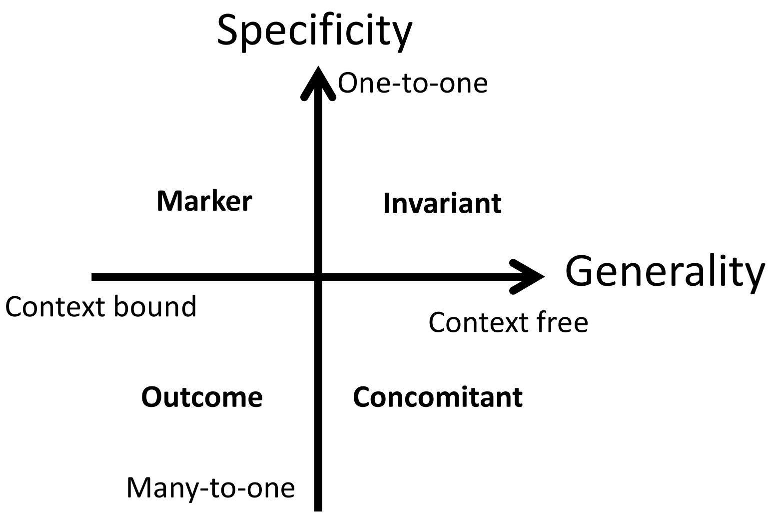


Figure 4-4: Major dimensions and classes of psychophysiological relations (Cacioppo & Tassinary, 1990).

Conclusions about psychophysiology

The use of physiology to understand an individual is not without its difficulties. Some believe the signals from the body are simple and overly reductive of the workings of the mind. Others believe that psychophysiology offers more objective insight than alternatives such as self-reporting. However, it is altogether more sound to see psychophysiology as providing an aspect of what occurs in mind and body, it is neither the whole story nor is it inconsequential (Parsons & Tassinary, 2007). When the strengths and weaknesses of subjective recall, behaviour analysis and psychophysiology are understood they can be used in conjunction to complement each other as required.

Enquiries into both psychology and physiology rely on good experimental design, the psychometric properties of the measures and the appropriateness of data analysis and interpretation. Psychophysiology is especially useful when the psychological processes are not completely available to or accurately represented by conscious recollection or behavioural observation (Parsons & Tassinary, 2007). This makes them useful to monitor people continuously while minimising interaction.

Combining sensor types

To conclude this section on wearables we review a number of devices and experimental set ups that combine data from several different sources. These include combinations of data already covered here and others, such as: sound recording, social interaction, camera/video and experience sampling. For example, the SenseCam and Ebutton (Gauthier, 2011) measure a selection of contextual data such as temperature, acceleration and location information. This information was used to help understand how people adapted to their thermal environment.

Another device was used to investigate user experience of a museum. Tröndle *et al.* (2014) asked visitors to wear an armband that integrated a heart rate monitor, skin conductivity sensor and location tracker. These data were used to map peoples' routes and identify where they had their most intense experiences. Then different people's journeys could be compared. Maps, from many different participants, were overlaid to build up a picture of how different types of people used and experienced the museum (Figure 4-5).

Figure 4-5: A person's journey in a museum. The picture shows a person's route and peak physiological response (Tröndle *et al.*, 2014).

Choosing wearable sensors for this study

Current models assume that similar people respond to the environment in similar ways. Wearable devices produce a large amount of continuous data about an individual across a range of contexts. This could make it possible to draw statistically sound conclusions about a single person's experience and how they respond to environmental change. This could provide information about how an environment will affect one individual compared with another.

The ANS and CNS could both be used to provide continuous data. Systems that monitor the ANS have the advantage of being marginally less intrusive because they are not worn on the head. More importantly, they have a more contained mapping scenario than EEG signals. ANS also does not suffer from the problem of system noise that EEG does. For these reasons the ANS is the most useful data for this study.

Understanding subjective experience is essential to building up a full picture of a person's time in a building. However, experience sampling is not a suitable tool for this investigation. It intrudes into the participant's activities because they have to actively respond to prompts and questions, this is especially problematic for something used in an office environment. However, because of the importance of subjective experience an exit survey will be administered after participants have had their physiology measured.

In offices people are predominately sedentary, therefore not all sensors need to be wearable. Minimising wearables will reduce the amount of intrusion people feel. Because of this, the physical environment can be measured by sensors at the participant's desk, rather than on their body.

Behaviours associated with computer use could be important for productivity. However, monitoring these would be very intrusive to the participant and should be avoided if possible. Otherwise people are generally stationary which means that behaviour is relatively unimportant for understanding the experience of occupants. Although activity level will need to be monitored to remove its confounding effect on the physiological response.

These data can be combined to build up a detailed and contextually rich picture of a participant's experience of the environment. It will allow data from multiple sources to be linked so that the time series of environmental conditions can be compared against the time series of physiological response. This allows the investigation of how the physical environment affects participants physiological response.

Chapter 6 tests whether these sensors can be used for personalised multisensory comfort assessment. It does this firstly by comparing between individuals, looking at whether different people's response to the environment can be predicted and compared with each other. It then uses within person analysis to test whether it is possible to observe an individual's unique respond to different environmental stimuli.

4.3.4 Observation

A key part of our method is that the researcher was in the building during the week of data collection. This helped with data interpretation and guided on the fly data collection. It was only through observing window opening patterns in Building A and E that it was possible to understand that it was different management techniques that led to different temperature patterns. It was seeing the windows being shut at 4pm in building A that led to additional carbon dioxide measurements being carried out. The acknowledgement and utilisation of the situated perspective is a key part of the pragmatic critical realist approach.

It would have restricted findings to carry out the research any other way. However, it is not without its risks and it may have influenced people's response on the survey. Over the course of the week the building occupants may have felt some relationship to the researcher and this may have affected their responses. Where necessary the relationship between the researcher, the data collected and the interpretation of that data has been explored.

In contrast the aim of this thesis is to improve the collection of data remotely without regard for wider contextual information. This could encourage the investigator to take a detached stance from the situation, with an increased reliance on reductive data. It is important that the benefit of convenience and coverage is achieved without a loss of situational understanding. This is a paradox that this thesis hopes to overcome.

4.4 Step by step guide to case studies

Each building studied in this thesis was visited for a week. The physical conditions were monitored both continuously and by spot measurements. Individual participants underwent physiological measurements throughout the week. Measurements lasted about 1 hour for each person. A general survey was sent electronically to all occupants at the end of the week.

Day one

Time	Action
0900–1100	Orientation and introductions. Put data loggers in position
1100–1400	Verify information from plans, take photos, assess controls
1500–1700	1x Sensors study

Day two and three

Time	**Action**
0900–1300	2x Sensors study
1500–1700	1x Sensors study

Day four

As per day 2 and 3, except the survey was launched at the end of the day.

Time	Action
0900–1300	2x Sensors study
1500–1700	1x Sensors study
1830–1900	Launch office wide survey

Day five

Time	Action
1900–1300	2x Sensors study
1300–1400	Send reminder email for survey
1400–	Collect data loggers. Take final photos. Hand out snacks as a reward. Check equipment. Ensure all data collected is filed appropriately.

Overview of sensors study (Chapter 6)

The process for one participant should take no longer than 2hrs. The following steps occurred for up to 10 people per building. It was generally done at 3 slots per day 0900–1100, 1100–1300, 1500–1700. Alternative time were done to accommodate people.

Time (minutes)	Action
0–5	Introduce person to investigation. Sign off on permission. Participant to put on vest with physiological sensors.
5–10	Set up kit around their desk: HOBO data logger with CO_2 sensor Spectrophotometer Sound level logger Time stamp all recordings
10–15	Check with them about position of kit and go
15–75	Leave them to continue work
75–80	Participant takes off vest. Stop all equipment
85–110	Participant completes exit survey

4.5 Methodological rigour

The methodological flexibility that critical realism brings makes it harder to identify good science (Pratt, 2009), it even calls into question exactly what the process of science is (Okasha, 2002). This creates a need to identify how academic theory building differs from everyday thinking (Sears & Cairns, 2015). The methodological considerations identified in this section distinguish academic theory building from everyday thinking (Pelham & Blanton, 2003; Robson, 2002; Sears & Cairns, 2015).

Internal validity / empirical rigour

Internal validity refers to the extent to which causality can be attributed to two observations (Pelham & Blanton, 2003). Or more broadly that conclusions fit the data gathered (Sears & Cairns, 2015). This thesis uses a number of theories to explain the relationship between sets of empirical data. Wherever possible alternative explanations have been considered. For example, in Chapter 7 it is unclear whether mobile working causes changes in privacy perception or whether people self-select to be mobile workers based upon their privacy perception. This is taken into account in the conclusions drawn.

One way to improve empirical rigour is to collect enough data from an appropriate sample size. Where there are probable causal paths it is important to collect data from each step on that path. This maximises the chances of establishing causality given a lack of control over the situation. For example, when monitoring the effectiveness of a heating system it would be wise to collect data about the local temperature, skin temperature, thermal perception, thermal comfort, overall wellbeing and adaptive behaviours such as window opening.

For this study, data have been collected across the range of sensory experience. It also covers design features, ambient conditions, occupant outcomes and health, wellbeing and productivity. This provides a wide base of data about each building which should build up detailed pictures about particular occupant outcomes such as privacy and building identity.

Datasets that can be coordinated with each other, and prior studies, allow corroboration of results. Raw data should be systematically checked so that irregularities can be identified and excluded from analysis if necessary. Results should be presented with an appreciation of absolute accuracy and sensitivity to change of the sensor.

All data collected in this study underwent preliminary checks after collection. A visual check of time series for discontinuities, or erroneous data was carried out. Figure 6-4 shows an example of a time series that would be visually checked for every participant. This exercise revealed errors in some of the physiological data, which led to some data being excluded from analysis.

There are also practical issues that affect data reliability. The memory of the device will be a result of the physical memory, the data that are being collected and the frequency of readings. The robustness of a sensor design should be considered in terms of how a sensor will be used and in what environmental conditions. The complexity of the device, can it be controlled in the field or does it have to be set up in advance. The ability to time stamp a device is important especially when trying to coordinate different hardware. Finally, cost and battery life should be considered. We conducted pilot studies using temperature sensors that had no time stamp facilities, this meant it was difficult to coordinate time series for the sensors study in Chapter 6. For the final study these particular sensors were replaced with devices with time stamps. Future investigations would further benefit from wireless sensors that uploaded data in real time.

External validity / logical rigour

The logical rigour of the argument from core assumptions to detailed inference (Sears & Cairns, 2015) will dictate the extent to which conclusions can be generalised. A critical realist approach suggests we look for useful mechanisms rather than universal truths (Robson, 2002). The value of good research is that it should be informative when applied to a novel context not that it represents some eternal universal truth.

Conceptual validity

It is important that concepts and language are used in a consistent manner (Sears & Cairns, 2015). The meaning of words used should relate back to the concepts used in theoretical models (Pelham & Blanton, 2003). Privacy in particular can have a number of different meanings across the literature. Words such as workstyle originate from industry and therefore can lack precise and universally agreed definitions. Throughout the thesis we have tried to use words consistently and to remove ambiguity where it occurs in the external literature.

Construct validity

This refers to the extent to which items measured represent the conceptual variable of interest (Pelham & Blanton, 2003). For instance, our measurements of the physical environment is limited to what can be detected and recorded by an electronic data collection device (sensor). This may be a poor representation of the sensory experience, and still yet poorer representation of a person's momentary response to their environment. However, for a number of reasons there will always be a desire to use sensors to predict a person's comfort assessment. These differences are something explored further in Chapter 6.

Ethics

Ethical issues arise when data contain information that could be used in a way that does not serve the participant's goals. Data collection processes should consider confidentiality, anonymity, storage and timely disposal of the data. The participant should be fully briefed on these issues before their permission is obtained and they should have the option to opt out of monitoring at any point. Consequently the use of the data will be limited to the scope initially agreed between observer and participant. Any changes in this scope should be agreed by both parties.

For our studies we obtained ethics approval from the University of Reading. We also obtained permissions on three counts. On a building wide basis (i.e. sign off by building manager), from each participant of the survey and from each participant of the physiological measurements. All these are kept on record and further details can be found in the appendix.

At the beginning of the general survey they were fully briefed about the purpose of the questions and how their data would be handled. They consented and were informed they could withdraw at any time. For completing the survey, participants were rewarded with a snack of their choosing.

Before the physiological measurements participants were fully briefed about what was going to be measured, the purpose of the investigation and how their data would be handled. They signed a consent form and were informed they could withdraw at any time. Participants were not rewarded for taking part in this study but they were given their data on request.

Intrusiveness

Closely related to ethics and a key goal of wearable technology is to minimise obtrusiveness. Ideally sensors would be completely invisible to the user. To these ends, there are devices that are the size of plasters or embedded in clothing. There are also many computing devices, such as smart phones, that are unobtrusive not because of their size but their ubiquity. The user's response to being monitored governs how long the sensor can remain in the field and whether they accept the device at all. This response could bias field measurements by making people aware that they're being monitored. Moran and Nakata (2010) identified a number of factors that influence response to monitoring devices:

- **Perceived affordance.** Does the person understand that the device collects data. Either because of user familiarity or obvious affordances (inherent indicators in form and appearance). For instance both a Smartphone and a GPS data logger can be used to track position but even though the GPS may be smaller it could be more intrusive than the Smartphone. The smart phone is understood in terms of the many other things it does so it is easy to forget that it is also a monitoring device. The GPS data logger is a novel purpose built device, therefore would act as a constant reminder of the monitoring.
- **Perceived natural borders crossing.** The degree to which a person feels that any natural physical borders have been crossed (e.g. device is in their home or next to their skin)
- **Perceived device control.** The degree to which a person feels they have control over the monitoring device, e.g. ability to avoid, switch off and remove.
- **Perceived coverage.** A person's understanding of the area or extent of activities 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 the type of information that is extracted and how widely the information about the user is disseminated

- **Perceived trustworthiness.** The degree to which a person feels the observer is trustworthy.

The most intrusive of our methods were the wearable sensors because they were attached to the participants' body. To reduce the feeling of intrusiveness we kept the data anonymous and only used it for research purposes. We also explained the process fully to participants and allowed them to withdraw at any time.

4.6 Summary

This chapter started comparing expressive and neutral approaches to IEQ. There are strong links between these approaches and positivist and interpretivist research traditions. Just as critical realism hopes to bridge the gap between positivism and interpretivism we hope that it can be used to bridge some of the gaps between expressive and neutral approaches to IEQ specification, as well as bottom up and top down approaches. Or rather that there is a way to use these methods, as and when they are appropriate, to develop a holistic set of parameters to evaluate and monitor indoor environmental quality.

To do this a set of methods were outlined that represented a reasonable approach to characterising the IEQ of a building. They included a selection of comparable physical measurements of each component of IEQ. This was supplemented by survey questions that ask about different aspects of user experience. The survey covers satisfaction and control of component environmental factors, occupant outcomes including privacy, emotions, identities and values and it covers overall health, wellbeing and productivity from all building factors together. Methods of accessing experience in real time were reviewed and measurement of the autonomic nervous system was considered most appropriate. Finally, the benefits of a situated understanding through observation were outlined. Together these form the combined methods to explore IEQ at each building that was visited. For the sake of clarity an hour by hour guide for the studies was then provided.

Finally, we covered methodological rigour. In light of taking a critical realist approach it is important to establish what differentiates everyday thinking from academic theory building. Principles from the literature were reviewed and compared with the methods previously described. Particular examples from our studies were used to illustrate our approach to methodological rigour. The next part of this thesis details the application of our methodology in the studies we carried out.

Part 2

The studies

Chapter 5

A post occupancy evaluation using an environmental sensory design approach

Previously

We identified the importance of, and challenges to, using sensors to monitor and evaluate user experience of IEQ.

This chapter

An environmental sensory design approach is used to understand the environmental conditions and occupant experience. There is difficulty with summing up complex issues of environmental quality with single parameters. Numbers such as background lux levels, and simple concepts, such as comfort leave ambiguity about the nature of user experience. For example, buildings that achieve fixed background levels can have environments that are comfortable but not stimulating. We also use 12 independent values to define the perceived identity of a building. This measure is strongly correlated with overall building performance. Finally, we observe the phenomena of group control (as opposed to individual control). The group dynamics observed could have an impact on the suitability of retrofit strategies.

Next

The study in this chapter provides the context for the following chapters. It also provides a situated practical understanding of the buildings that stands in contrast to the abstraction and depth of the following studies. This combination of the practical and the abstract will inform the discussion and conclusions of the entire thesis.

See also

Keeling, T., Clements-Croome, D. & Roesch, E. (2015). Building values, identity and perceived performance (in preparation)

Keeling, T., Roesch, E. B., Clements-Croome, D., & Keelin, A. (2015). Field studies of occupant experience in seven UK offices. SuDBE, Reading, UK.

5.1 Environmental sensory design

The fabric of the building separates and protects occupants from the inhospitable external elements of wind, rain, and sun but not all these should be excluded all the time.

Environmental design recognises that, to create an internal zone, it is useful to work *with* the external environmental as much as *against* it. In colder climates, buildings will be massed and orientated to increase the sunlight that enters and decrease exposure to wind. Noise sensitive locations will be shielded from sources of noise. The environmental design approach responds to the external and internal environmental drivers (CIBSE, 2006). Because this method utilises the environment as a resource it is inherently low energy (which provides a double meaning to the word environmental). Because it connects to a changing external space the internal environment will have a more dynamic and responsive interior that is connected to the natural world outside.

Sensory design has multiple meanings. It indicates design for multiple sensory pathways where the experience depends on a particular sensory combination (Pallasmaa, 2005). It is about the environment providing positive emotional and aesthetic experiences (i.e. being expressive) rather than being neutral (Lehman, 2013). In summary sensory design focuses on the effect on people rather than the performance of building components.

Environmental sensory design must be seen in relation to these two terms. It responds to its environmental and human context, so that it is dynamic and responsive rather than static and predetermined; much like an intelligent building (Clements-Croome, 1997, 2014a). It stimulates occupants intellectually and emotionally (Lehman, 2013), rather than only provide a platform for the smooth function of occupant activities. Conversely most studies of building environments aim to find the set of background environmental conditions that bring satisfaction (ISO 28802, 2012). This approach suggests there is a set of optimal conditions, that might vary with personal factors such as age, clothing, activity or personal history (Boyce, 1973; Fanger, 1970). Given the heterogeneity of office occupants this approach leads to a small number of optimal conditions that are applied in practice. This leads to homogenous internal environments, which is quite different from environmental sensory design.

This has implications for the study of buildings. It suggests that all environmental factors should be studied together. That the dynamics of environments should be tracked. The process by which occupants and buildings interact should be studied. And finally, the occupant emotional and intellectual experience should be understood alongside other occupant outcomes. This study uses environmental sensory design to provide a scaffold of ideas upon which to lay an investigation of internal environments and building occupants. The purpose of this study is to explore the extent to which environmental sensory processes go on within buildings, to describe them and to measure their effect.

5.2 Description of the offices

This section provides a brief overview of the seven buildings studied during summer 2014 (Table 5-1 and Table 5-2). Three buildings were at universities and contained academics and administrators, three were building design consultancies, one was a charity. They had different systems for maintaining ambient conditions and were occupied by different organisations. Three of them were entirely new to the researcher, two were places where the researcher had worked in occasionally and two more were buildings the researcher knew of. Together these buildings provided a diverse range of building types and occupier types, in the hope of finding a diverse range of contexts to understand and make the results more generalisable.

Table 5-1: Overview of buildings.

Bdg	N (Resp. rate)	Occupier	Occupier relationship	Typology	Plan	Visited
A	13 (27%)	Design	Tenant	Open plan	Shallow	2–6 June
B	10 (77%)	Academic	Owner-occupier	Open plan	Shallow	9–13 June
C	62 (23%)	Academic	Owner-occupier	Open / cell	Shallow	23 -27 June
D	34 (18%)	Academic	Owner-occupier	Open / cell	Shallow	30 June -4 July
E	11 (22%)	Design	Self-designed	Open plan	Shallow	7–11 July
F	26 (2%)	Charity	Tenant	Open plan, agile	Deep	8–12 Sept.
G	46 (30%)	Design	Self-designed	Open plan, agile	Shallow	15–19 Sept.

Table 5-2: Occupant density and building systems.
NV= naturally ventilated, MM= Mixed mode, AC= fully air conditioned.

Bdg	Work spaces per room	Occupant density (NIA)	Local density	Lighting	HVAC	Cooling degree days	Min. (°C)	Max. (°C)
A	49	7.5	5.2	Overhead	MM	7	7	20
B	9	8.3	5.9	Overhead	NV	14	10	24
C	Varies	Varies	Varies	Overhead	NV	11	11	22
D	Varies	Varies	Varies	Overhead + task	MM	13	10	23
E	17	14.2	5.7	Overhead + task	NV	10	12	22
F	687	7.3	5.9	Automatic, overhead	AC	11	11	22
G	50	6.9	3.6	Overhead	NV	18	13	26

Building A

This is a mixed mode office built in the 90s. On each floor an open plan office feeds off a single stair core. A single floor contained about 40 people in an open plan room. The room had glazing on two sides, on one side was a reasonably busy central London road, and on the other was a small and inaccessible courtyard space. All windows had blinds, overhead fluorescent lighting was used and there was little task lighting.

The building had been designed to have a mechanical supply of tempered outdoor air to the occupants and be cooled with fan coil units. However, the ventilation system had been turned off because people immediately below the ventilation outlets felt it was too draughty. This led to performance issues that will be described later.

Building B

This university building was built in the 60/70s. It was F-shaped and consisted of lecture halls, labs and small offices. The area studied consisted of three small offices and a researcher room coming off a central corridor. The windows were large tilt and turn with inbuilt blinds. Lighting was manual switching overhead fluorescents. The building had radiators with thermostatic valves (TRVs). In the summer the windows were the source of cooling and ventilation. However, in the research room that had south and west facing windows they were also a source of heat gain.

Building C

An administrative building for the University of Reading. It is beside a large sports field. It was built in the 60s /70s and has a concrete construction. Windows are steel framed single glazed. They are either sash or pivoted on a central vertical axis. The building is organised along a central cores, with a corridor either side. Offices are on the outside of this. It has a combination of old features and visible bolted on infrastructure, such as lighting and computing cables.

The building was heated using old convective radiators and reportedly experienced overheating in winter. There was also summer overheating. This was exacerbated by an east west orientation, difficult to open windows that were shut at night, and unvented glazed stairwells. In addition, the site could seem quite noisy because of occasional buses and delivery vans outside.

Building D

This was the last of the three University of Reading buildings. It was arranged around a ring corridor, with offices on both sides of the ring. The offices were a mixture of private and small offices (less than four people). There were a limited number of research rooms that had more than 11 people in. The rooms were mostly naturally ventilated although some air conditioning had been installed on an ad hoc basis. There was an underused courtyard in the middle, with a large amount of heat rejection equipment.

Building E

This office was a recently completed renovation of a Victorian canal side warehouse. The design was done by the occupying organisation. The main office consists of three floors. The basement was at canal level and has basement vaults at the side opposite the canal. The middle/ground floor is at road level on the side opposite the canal; it had a cutaway section to make it part mezzanine, part ground floor. Opposite the mezzanine there were large double height casement windows that face on to the canal. On the opposite wall downstairs are vaults and, upstairs, a view to a quiet street with large tilt turn windows. There was also a top floor, above these, which felt detached from the floors below. The top floor has large casement windows and a vaulted ceiling, both features gave a light and spacious feel.

The windows were open most of the time. There was sometimes a smell of fumes from the canal boats and sometimes cars could be heard when they drove up the road alongside the office. The building was heated through a wet underfloor system. It had no additional ventilation or cooling. As well as overhead fluorescent lighting there were fixed task lights, one for every two occupants. There were spotlights for the walls that were used as side lights but also to illuminate drawings hung on the wall.

Building F

There were five storeys of deep open plan office (50x50m). In the middle was a full height central atrium. When entering at the atrium one felt like one had arrived at a destination. The feeling is not one of ostentation but of purposeful intentions. The atrium is light and spacious. Reception is at the end, with seating on the wings, and there is a sculptural centrepiece in the middle. It is clad in glass and bare concrete. Two floors were used as case studies. On each the atrium was surrounded by a glazed partition, then service areas, meeting rooms and main access ways, then a partition, then the tenants office. The tenant's office space had a walkway running around the centre and desks on the perimeter side of the walkway.

An immediate problem with this configuration was navigation. The loop walkway is too far away from the external window and the internal atrium is not visible. This makes it very difficult to orientate oneself while walking the office floor. This is countered with some well thought out features that break up the scale of the office. These include different themed meeting areas, desks arranged concentrically as well as linearly, coloured quarters, and unique design elements. However, the feeling of being lost only began to wear off towards the end of the week's study.

Control of the ambient conditions was almost fully automated. Heating, cooling and ventilation were provided by an underfloor air system, supplemented in winter with perimeter air heaters. The offices were lit with overhead fluorescent lights, this was controlled centrally and no switches were visible on the floor. At the perimeter there were sensors to modulate the lighting according to the levels of sunlight. Occupants could open a small number of windows. Floor vents could be adjusted by special request to the facilities management.

Building G

This building was also designed by the occupying organisation. One arrives at the entrance to an art deco building and walks up two flights of narrow period stairs. On the second landing is the entrance behind which is something quite different. There are plenty of quirky, colourful features and many different types of decorative light fitting hanging from the ceiling. These supplement the requisite overhead florescent strip lighting. Multiple long fields of view give a sense of lightness and space. Features are used to add colour. All these elements contrast the narrow entrance way and austere external facade. Because of this the immediate feeling on entering the office was a sense of release.

The building was arranged in an L shape and the organisation occupied two floors. As such it consisted of four large volumes; three of which were used for desk space. The fourth had meetings rooms arranged around a lunch / forum space. In each of the three office volumes there were desks down one side and informal working areas down the other. At each side of the room there were large windows that let in lots of light but not much air. There were a lot of desk fans around the office, some of them quite large and powerful; when it got hot they were used a lot.

5.3 Results

5.3.1 Lighting

Building E was naturally lit almost all of the day. Overhead lights were rarely switched on because of the combination of plentiful natural light and ample task lighting. This was possible because of a shallow plan with large unobstructed windows on either side. One interesting quirk of the building was the directionality of the light, sat on the ground floor by the edge of the mezzanine, it was possible to receive daylight from below as well as above; a unique and beguiling feature.

Building F was deep plan and the lighting system was designed to maintain consistent levels throughout the building. In the central region this was achieved by the uniform arrangement of overhead fluorescents, in the outer regions triple glazed and tinted windows reduced daylight penetration while photosensitive controls adjusted perimeter lighting. This left a feeling of uniformity throughout; it is possible that this lighting design contributed to the lack of orientation.

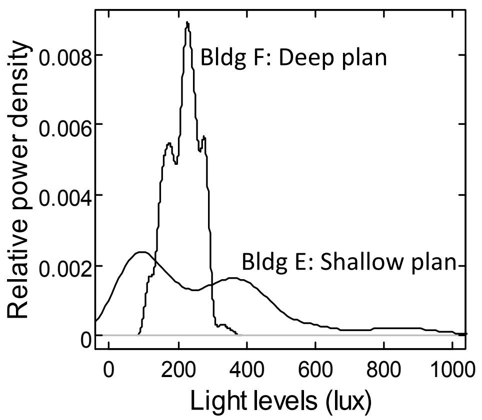


Figure 5-1: Distribution of light levels during working hours at Building E and F.

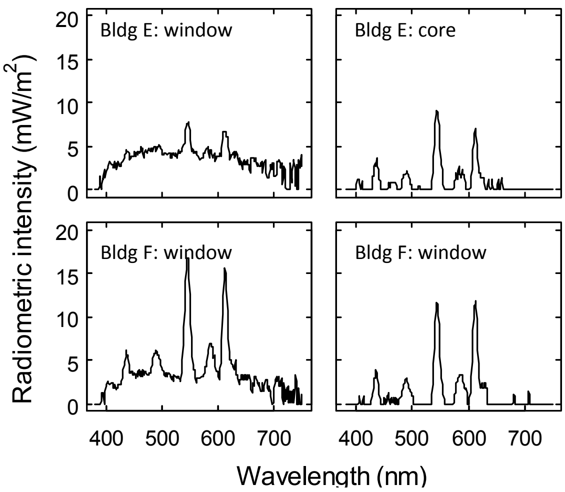


Figure 5-2: Spectrum of light at different locations building E and F.

The difference in lighting can be seen in Figure 5-1 through to Figure 5-4. Figure 5-1 shows that the lighting levels at Building E have greater variation than Building F. Figure 5-3 shows that light in building E would vary from 50 to 350lx at a single location whereas the lighting in building F is highly uniform; light levels at the core of the building hardly change throughout the whole day. This pattern is repeated the rest of the week although on less sunny days the Building E pattern is muted slightly.

The spectrum of light at different locations in the two buildings is more similar (Figure 5-2). Characteristically the light spectrum is made up of the broadband daylight and the narrow bands of fluorescent lights (at 550 and 620nm). In both buildings light in the centre of the building lacks a broadband element whereas light on the periphery is dominated by broadband elements. At Building E the spectrum of fluorescent lighting has much less influence and the broadband daylight is greater than at Building F. This suggests that, at Building F, internal light colour at the window zone is still influenced by fluorescent lighting.

Overall survey results show that satisfaction with the lighting at the two locations is similar but that perceived effect of lighting on performance is greater at building E (Figure 5-4). Some user comments for building F lighting were negative; some describe it as too bright and harsh.

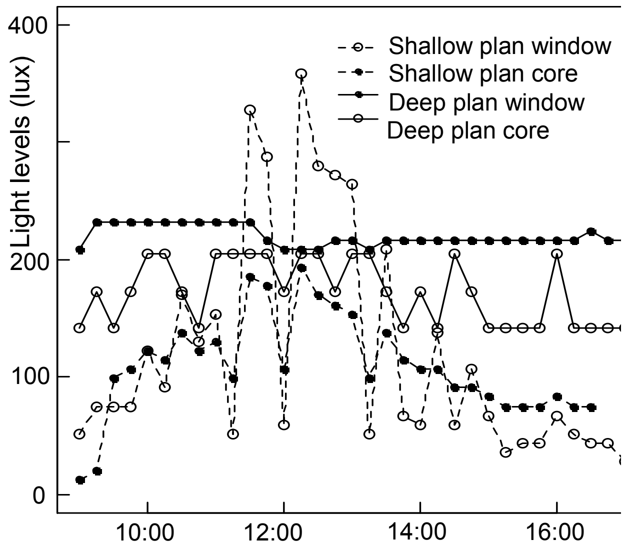


Figure 5-3: Lighting variation over a day, at building E (shallow plan) and F (deep plan).

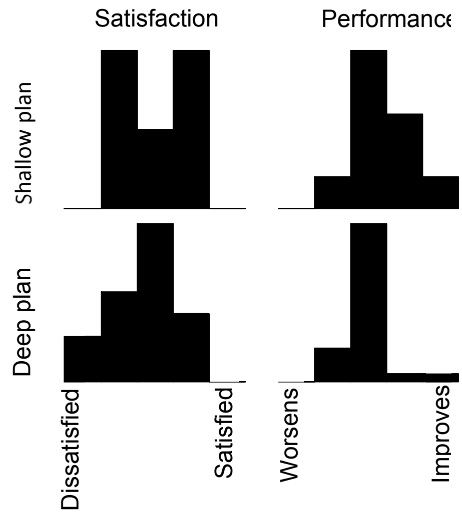


Figure 5-4: Histogram showing distribution of satisfaction and perceived performance enhancement of lighting at building E (shallow) and F (deep).

5.3.2 Temperature

General observations

Figure 5-5 shows the combined air temperature data from all sensors during office hours. It shows that building G and building C are hot, building B is relatively cool. In addition building E and building F have particularly tight temperature control whereas building D and building G have a wider spread. Satisfaction with temperature is greatest at building E, followed closely by G and F. Conversely clear dissatisfaction occurs at building D, C and A.

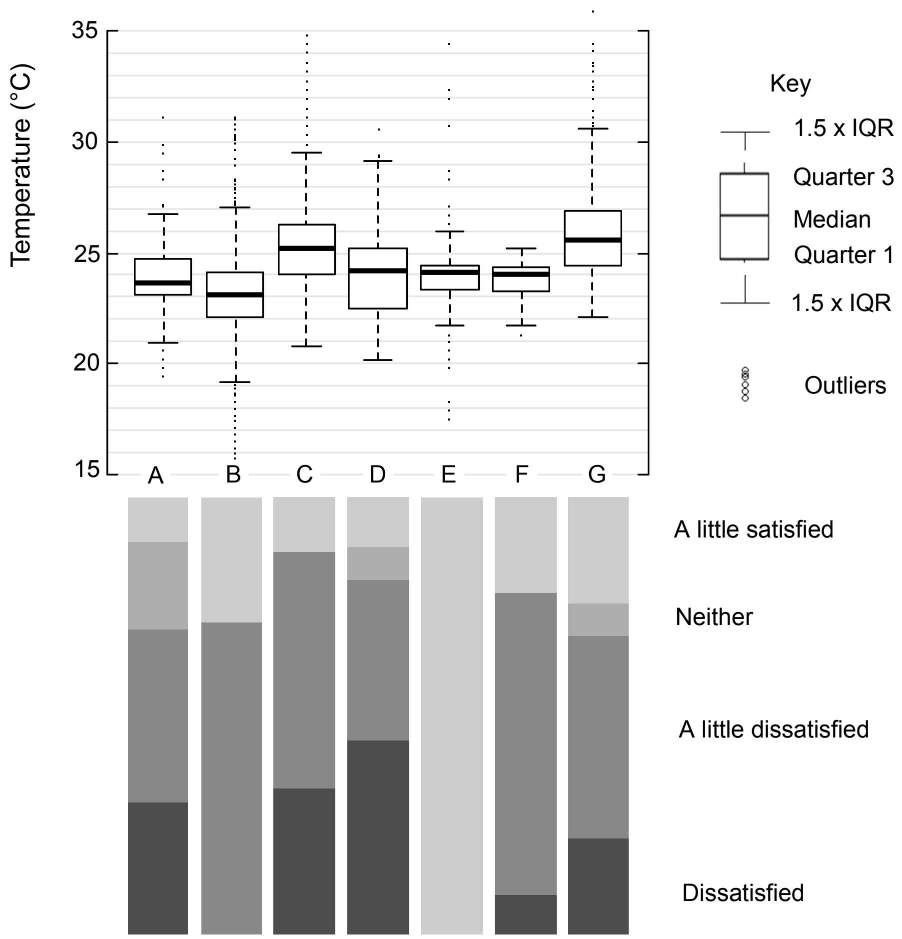
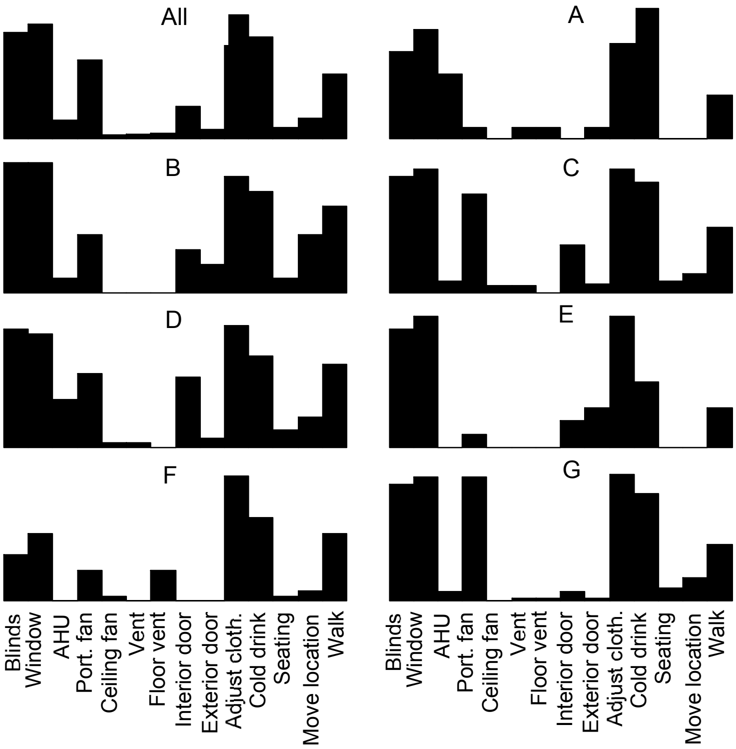


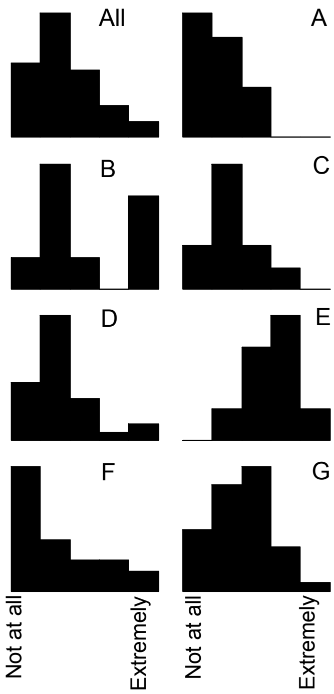
Figure 5-5: The spread of measured temperatures and occupants satisfaction in each office.

Figure 5-6 compares the opportunities occupants use to cool themselves down. These are broadly similar except building F has much fewer opportunities and the use of portable fans varies between offices. Generally, most people in an office considered it difficult to make themselves cooler (Figure 5-7). However, building E, and to some extent G, show the opposite skew; occupants generally found it easy to make themselves cooler. This underlines the importance of access to portable fans in naturally ventilated buildings. It also suggests that people at certain offices had adaptive opportunities available to them but did not think they were effective.



From left to right opportunities are: blinds, windows, air conditioning units, potable fans, ceiling fan, air vent, floor vent, interior door, exterior door, clothing adjustment, cold drink, seating adjustment, location change, go for a walk

Figure 5-6: Proportion of people using adaptive cooling opportunity.



X-axis from left to right: Not at all, moderately, extremely

Figure 5-7: Ease of making oneself cooler in the office.

Satisfaction model

The data suggest that temperature and perceived control but not opportunities are important for satisfaction. To test this a linear model was constructed. The model had satisfaction with temperature as the dependent variable. The independent variables were average temperature, temperature variation, perceived ability to make it cooler and the number of available cooling opportunities (Table 5-3). The model was tested both on a building basis and an individual basis. On a building basis the model had 7 data points, one for each building, with building wide average values used for all variables. On the individual basis there were 159 data points one for each respondent to the survey, although temperature data were still based on whole building averages.

For the building wide model, perceived ability (to make oneself cooler) has a significant effect ($p<0.05$) on satisfaction scores, the other variables do not have a significant effect. For the individual model, both perceived ability and temp variation have a significant effect ($p<0.05$). The coefficients for each model should be equal; however, this is not the case for the perceived ability to make cooler.

Table 5-3: Temperature satisfaction model parameters.

Variable	Source of variable	Method for creating variable	Model parameters with 95% CI	
			Building wide	Individual
Temperature satisfaction (DV)	"During the last week how satisfied were you with the temperature?"	Convert to 1 to 5 score	R^2=0.96 F(4,2)=12.56 p=0.08	R^2=0.97 F(4,144)=5.24 p=0.001
Average temperature (IV)		Mean of all readings	A1=0.0±0.2 p>0.05	A1=0.12±0.2 p>0.05
Temperature variation (IV)		Standard deviation of all readings	A2=0.3±1.2 p>0.05	A2=-0.54±0.4 **p<0.05**
Perceived ability to make cooler (IV)	"How easy is it to make yourself cooler in the office?"	Convert to 1 to 5 score.	A3=1.1±0.4 **p<0.05**	A3=0.30±0.2 **p<0.05**
Available cooling opportunities (IV)	"Which of these would you use to adjust your temperature in the office?"	Count of opportunities	A4=-0.5±0.7 p>0.05	A4=0.02±0.12 p>0.05
Model intercept	n/a	n/a	A0=2.2±6.2 p>0.05	A0=-0.75±5.3 p>0.05

5.3.3 Building-Occupant interactions

Satisfaction with controls

There were a range of controls available to the building users, from fans and windows to light switches. There were also many different modes of control. Building F was the only fully conditioned office. At the other end of the scale was building D, where almost all people were in small rooms of less than four people, some of which had mechanical cooling and all of which had a window. This shows up in the degree to which people felt they had personal control of the temperature, which is much greater in building D than in building F (Figure 5-8). Interestingly satisfaction with temperature control was the same in both buildings, it would seem that people in building F were satisfied despite having less control this is probably because their building had less variations in temperature overall.

Figure 5-8: Satisfaction with controls and perceived personal control (building D and F).

The usability of windows

Many of the buildings had large tilt and turn windows which could have been opened very wide but for various reasons they were not. These windows often open inwards and in Building A objects on the window sills and neighbouring desks restricted them being opened fully. Generally, when operating in turn mode, tilt and turn windows have no fine control and a tendency to swing freely; at Building B this contributes to reduced use. They also intrude into the building a lot (twice as far as a casement window). At Building E these problems were overcome because of the depth of the internal window sill, which had storage beneath it, and the use of a door stop to peg the window back. At Building G they had two layers of windows, the outer window opened along a central vertical pivot, the inner was a tilt and turn window. The windows were too close together to fully open the outer one and there were too many internal obstructions to fully open the inner one. This resulted in the two layers of windows providing much less ventilation than either type would alone. It also made their operation extremely cumbersome.

Other offices had their own issues with windows. Windows at building C were either sash windows that were old and difficult to open or central pivot windows that were restricted by internal blinds. In the smaller offices it was necessary to place desks parallel with the external façade, this meant that desks obstructed windows opening. Building F had a small number of operable windows around the perimeter that were appreciated by those close enough to them. The windows at Building B had inbuilt blinds that could not be raised and therefore it was impossible to get an unimpeded view of outside.

Group control

Buildings A, E and G had floors with approximately 30 to 50 people on and were predominately naturally ventilated. In all these offices windows had to be opened depending upon prevailing conditions of air quality, light, temperature and noise. Opening the windows, or not, required some sort of consensus to be reached between occupants, often without formal rules. Offices A and E had contrasting regimes of control which will be briefly explained here.

In the morning at building A some windows would be open with blinds mostly closed and indoor lighting on. Most of the windows would be open on a tilt basis because there were too many obstructions to open the windows fully. Also there was a reasonably busy road next to the windows. On Friday afternoon at about 4pm the building got particularly hot and two people went around asking people if it was ok to close the windows and turn the cooling on. Because there was no working ventilation except for the windows the carbon dioxide levels of the building increased considerably, from 700–800ppm to 1400ppm.

Meanwhile in building E the windows were fully opened by a single person first thing in the morning most days. On hot sunny days windows were left open. On cooler days occupants (other than the single person who opened them in the morning) would close individual windows especially on the basement side of the building. The windows were partly closed because on this side of the building there were noises and smells from the canal that were not felt so much by people on the ground floor.

In Building E there was a clear leader who came in and opened the windows in the morning. This made it a little cool in the mornings but relieved afternoon overheating. This behaviour maintained a narrow range of temperatures (Figure 5-5). In building A this did not happen, instead they made use of local cooling systems in the afternoon if an overheating problem emerged. If the windows in building A had been operated as they were in building E then perhaps there would have been less need for mechanical cooling. However, the cooling allowed the occupants of building A to minimise their exposure to noise from the adjacent road. The different patterns of temperature in the two offices can be seen in Figure 5-9. The temperature drop associated with the air conditioning at building A can be seen in panel A5 and the temperature drop from opening windows in the morning at building E can be seen in panel E2 and E3.

Both these arrangements can be contrasted with those at Building F where the system was specified at design stage to provide full air conditioning between 20 and 24°C all year round. Following complaints of it being too cold in summer the building manager was holding the summer temperature at the upper end of this range. The building manager would have liked to raise the temperature further to improve comfort but could not do it because he felt compelled by the design specification to keep the building within 20–24°C.

Although building F generally had occupants who were satisfied with their building there were some difficulties. The whole building had 4 zones, one for each of its quarters. Maintaining sufficient temperature on one floor could require under or over conditioning another floor. Also people near air outlets would complain of drafts. Overall though temperature control was good and satisfaction levels reasonable.

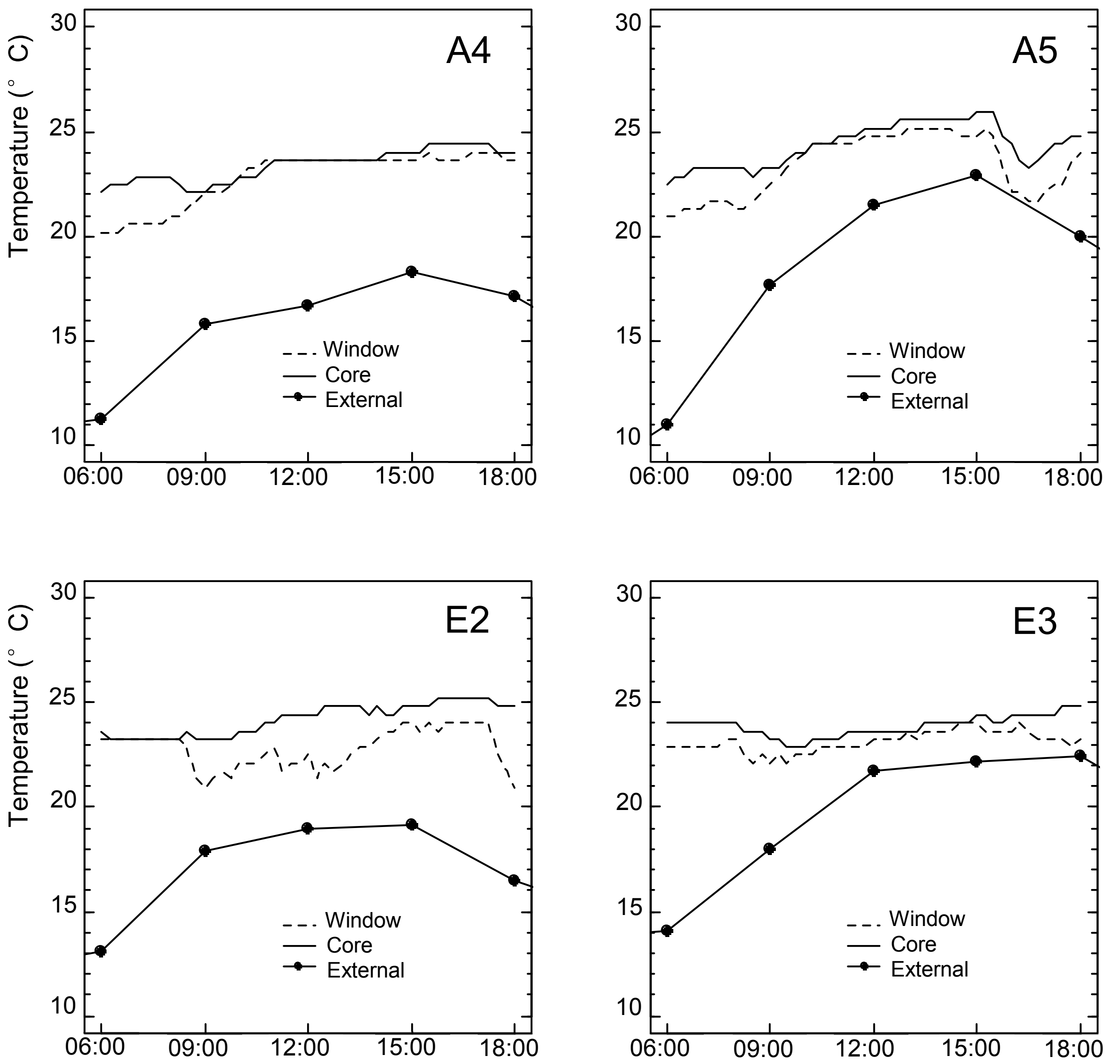


Figure 5-9: Temperature over the course of the day. Figure labels are A4: building A on day 4 etc.

5.3.4 Values and identity

Occupants were asked to reflect on the values of their building and whether these reflected the ethos of the organisation. Specifically, they were asked to choose any words that they associated with the design of their workplace from a list of: “practicality”, “excellence”, “variety”, “decisiveness”, “orderliness”, “goal orientation”, “support and consideration”, “conformity”, “recognition”, “independence”, “generosity” and “leadership and authority”. After this respondents were asked: “Do you feel the office reflects the ethos of the company?”. The words were a form of the Gordon survey for personal and interpersonal values (Hofstede, 1994) modified to suit as descriptions of buildings. The answers to these questions were used to understand if people at the same office chose similar values for the design and if these values differed between buildings (Figure 5-10).

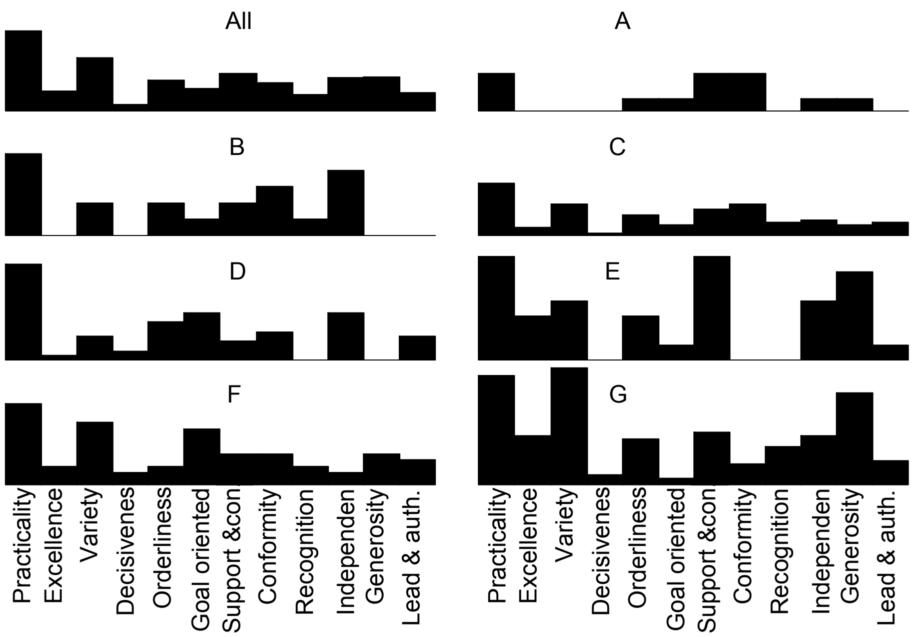


Figure 5-10: Values chosen for each building by occupants.

The correlation between people’s perceived values was measured using the R^2 correlation coefficient. The results in Table 5-4 show that occupants of some buildings responded more coherently than others. Building E and building G responses were particularly coherent whereas building C and building F responses had much less correlation between occupants.

For a given building, those that had a high degree of correlation between values also had a large number of values chosen (Figure 5-11). Some buildings were judged to reflect the ethos of their organisation more than others. It also emerged that for a given individual the more they thought the design reflected the ethos of the company the greater the number of values they identified with the design (Figure 5-12). The significance of this relationship was modelled using a linear model and the gradient and correlation coefficient were both extremely significant (***p***<0.001).

Table 5-4: R^2 correlation of values chosen between by different occupants of each building.

Building	A	B	C	D	E	F	G	All
R^2 correlation between occupant choices	0.19	0.21	0.11	0.23	0.31	0.12	0.24	0.11

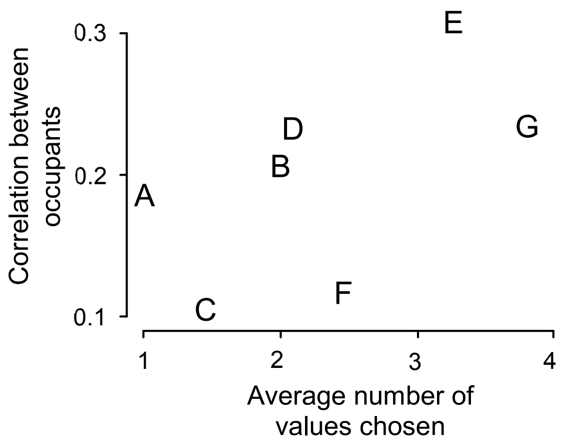


Figure 5-11: The average number of values chosen and the correlation between choices.

Figure 5-12: Comparing how much an individual thought the design reflected the ethos of the company, and the number of values they chose.

Lastly, we tested the importance of identity for overall building performance. To do this we constructed a linear model of identity and overall building performance; this was done on a whole building basis (Figure 5-13) and an individual score basis (Figure 5-14, area of bubble is proportionate to the number of people who had those scores). The score for identity was obtained two ways: for individuals it was the number of values they chose; for buildings it was the average number of values chosen added to the R^2 correlation from Table 5-4. We used the average of the health and wellbeing and productivity score as the overall building performance. For both models there was a high correlation between identity and overall building performance. The model parameters (Table 5-5) show that evaluation of a building's identity has a significant correlation with perceived building performance.

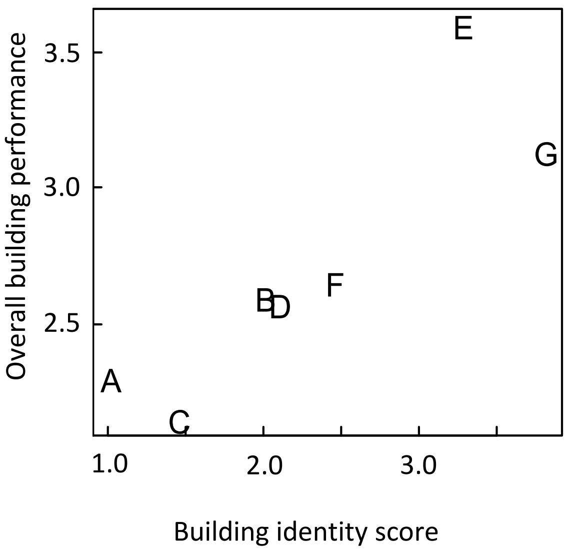


Figure 5-13: Building performance and identity (whole building model).

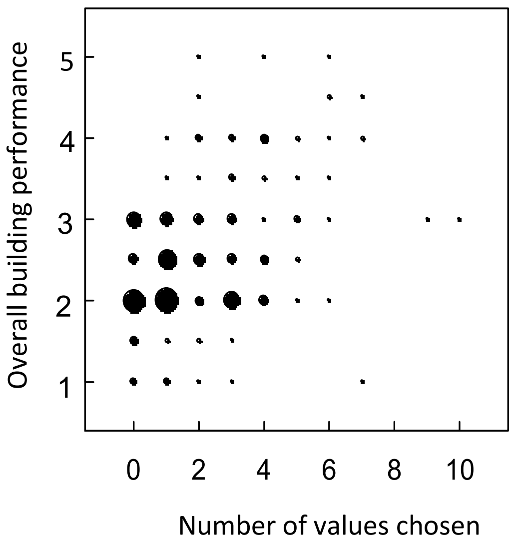


Figure 5-14: Building performance and identity (individual model).

Table 5-5: Model parameters for relationship between building performance and identity.

Model	a1	p-value	R^2	f-statistic	p-value
Building	1.4	<0.001	0.92	F(1,5)=55.5	<0.001
Individual	0.21	<0.001	0.16	F(1,194)=37.9`	<0.001

5.3.5 Overall building performance

It is not possible to see how different factors (satisfaction with temperature, IAQ, light, acoustics, layout and identity) contribute to overall building performance. If a model is made with building wide averages for satisfaction there is seven data points for seven independent variables. This is not enough to find statistical relationships. A model based on individual scores suffers from two weaknesses. First, there is a great deal of correlation between different satisfaction scores (Table 5-6). Second, there are a number of cases that have to be excluded where the survey respondent failed to answer all eight questions.

Rather than building a statistical model the results for the different buildings are displayed in Figure 5-15. This shows that Building E and G have a more cohesive identity. Building A has bad air quality. Building E has good temperatures. Building F scores well on component factors compared with E and G but less well on identity and overall building performance.

Table 5-6: Correlation table for individuals' rating of their buildings (BP = Building performance).

	Temp	IAQ	Light	Acoustics	Spatial	Identity	BP
Temp	1.00						
IAQ	0.57	1.00					
Light	0.30	0.43	1.00				
Acoustics	0.08	0.18	0.31	1.00			
Spatial	0.18	0.26	0.25	0.45	1.00		
Identity	0.10	0.07	0.21	-0.02	0.31	1.00	
BP	0.30	0.32	0.36	0.21	0.50	0.34	1.00

5.4 Discussion

5.4.1 Variation

The lighting levels in Building E varied through time both minute by minute as sky cover changed and throughout the day. This variation was large, at one point going between 50 and 300lx in 15 minutes. It is clear that the variation in lighting adds to the environmental experience in Building E. At Building F, the lighting system provides the recommended light level, at all times and all places (to the extent that the lighting system dims perimeter lights when sunlight is strong). This results in artificial lighting that is described by some in negative terms and is not perceived as improving performance. Overhead lighting at building E is installed to provide the requisite amount of lighting but it is rarely switched on. Users prefer task lighting when its necessary to top up light levels. At Building E, local personal control and daylighting, frees occupants from the uniformity of recommended lighting levels. Given this freedom, occupants choose a lighting regime that is more variable. The temporal variation of lighting leaves satisfaction scores unaffected and improves the perceived effect on performance. This offers some support to the importance of perceived naturalness as a characteristic of lighting as proposed by Haans (2014).

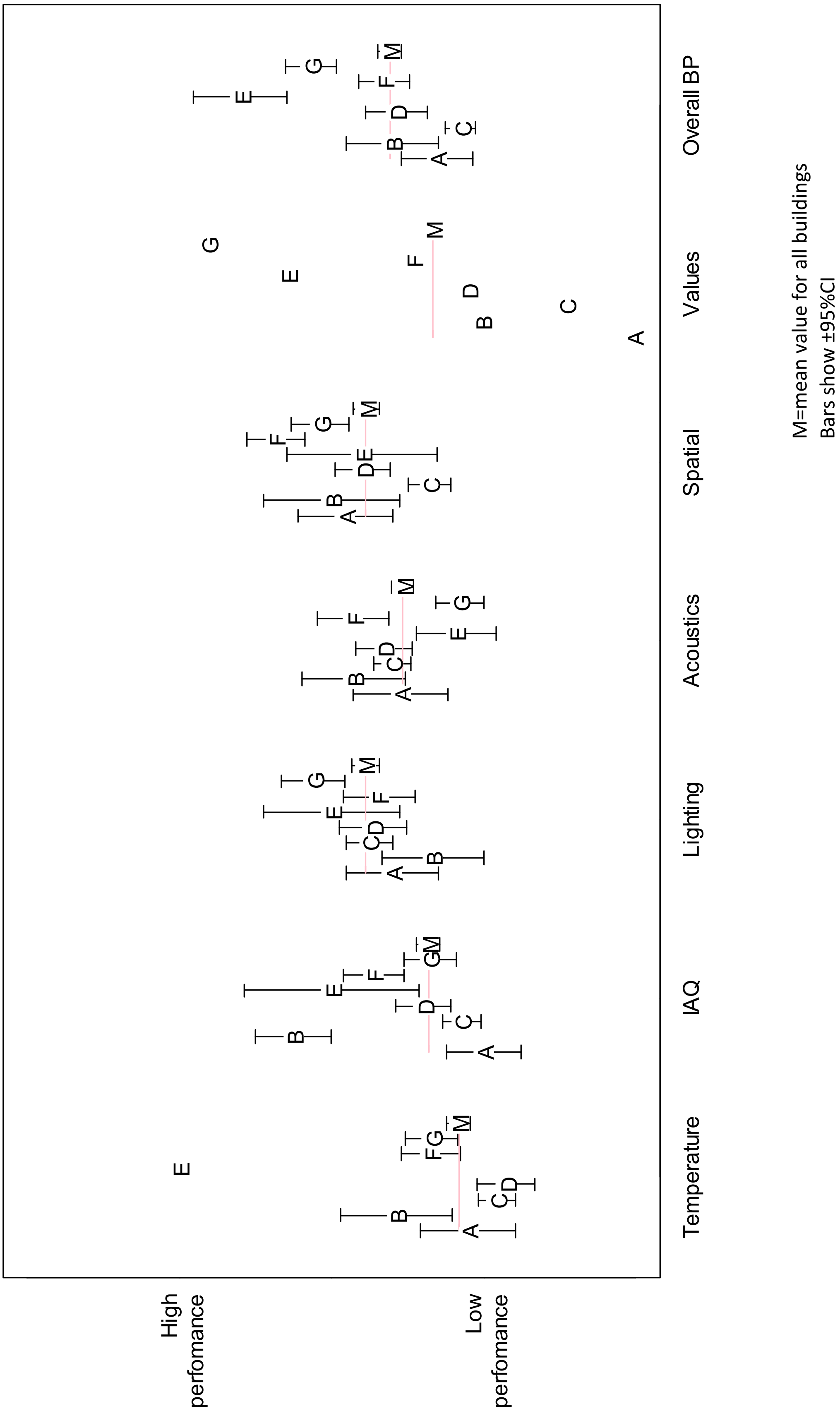


Figure 5-15: Building performance overview.

Conversely for temperature variability is detrimental to satisfaction. Because of the way the data were treated the variability measured at these buildings may be temporal or spatial. Comfort standards recommend no more than a 3°C variation within a single week (Nicol & Humphreys, 2009). This limit is being exceeded in some buildings and it would appear that this is a source of dissatisfaction as predicted by theory.

In these buildings variability is good for lighting but not for temperature. Lighting variations provide clues to the time of day and the state of the outside world. The variations in lighting may be acceptable because they have no effect on the comfort or performance of occupants whereas variation in temperature can lead to difficulties in the effectiveness of adaptive behaviour. This supports work that suggests natural variations are preferable as long as they do not interfere with function (Haans, 2014).

5.4.2 Management and control

We specifically asked two kinds of questions about perceived control. One question was about the number of cooling opportunities (such as fans, blinds and windows) that people had access to ("*Which of these would you use to adjust your temperature in the office?*"). The other question was about the relative ease of adjusting their temperature ("*How easy is it to make yourself cooler in the office?"*). We found it was the ease of making oneself cooler that was important and not the availability of opportunities. This shows that people are not satisfied with controls per se but require controls that work effectively. This is contrary to suggestions that even dummy control improve satisfaction (Zhou *et al.*, 2014). Perhaps dummy controls work in the short term in laboratory settings. Whereas participants of this study know their building and understand the effectiveness of its controls.

Different offices have different modes of operating windows. Operation is driven by internal conditions and social dynamics. Because environmental control affects everyone it becomes a topic of intense scrutiny and uncertainty. Often it is easier for people to take action when conditions have reached a moment of crisis, for example when the building is clearly too hot, or light is causing disabling glare.

Having air conditioning available changes the nature of these crisis points. In the morning at building A occupants choose not to fully open their windows. Consciously or not, they are navigating a trade-off between immediate noise levels from the road and an office that is cooler in the afternoon. This trade-off is less important to them because when it is hot the air conditioning can be turned on. Building E has no air conditioning. There the trade-off is tackled head on. A single person takes responsibility for the environment and opens the windows early. This suggests that the power structures within the office are important for predicting how natural ventilation systems will be operated. This has implications on the effectiveness of behaviour change measures. Understanding the people who tend to take control could help the implementation of behaviour change programmes. Most behaviour change programmes aimed at reducing energy consumption target the behaviour of individuals (Gill *et al.*, 2010; Tetlow *et al.*, 2015), our work suggests that they could alternatively target key individuals and the power structures that govern energy consumption.

There are also implications for system selection. Clearly an office environment that is managed by crisis would be better off automated so that it can be managed with some foresight. Understanding how an office environment is managed may help in choosing the right system. A system that requires active management will be best suited to an office with active managers. Again this suggests a movement away from studying individual control, traditionally studied in thermal comfort (Brager & de Dear, 1998; Hellwig, 2015), to a consideration of the underlying structures that govern how a group operates control over a building. This would require a similar interpretivist methodological stance to Raw *et al.* (2016) and Shove (2003) but with the unit of study as the occupants of a single thermal zone rather than wider society.

5.4.3 Values and identity

The character, identity and values of a building is something that is difficult to measure and most times left out of surveys. The questions we found that delved most into identity were in the BUS survey (Cohen *et al.*, 2001). It has two questions about: “the image that the building as a whole presents to visitors” and satisfaction with “the building design overall”. These provide no information about what the nature of a building’s identities and values. We wanted to define an identity that was based on human values rather than building characteristics. To do this we used an adapted version of the Gordon survey for personal and interpersonal values (Hofstede, 1994). Some translated to buildings better than others. Practicality was chosen most often. This could be because it was first on the list, or because practicality is something a building can obviously do. Decisiveness was chosen least, perhaps because it is hard to see how a building could be decisive. To improve this, values that are rarely chosen could be tweaked to make them more relevant.

Despite any misgivings the value attributes have proved useful. They clearly differentiate between buildings. They could be used to help develop the brief of buildings. With this tool, building design could be systematically matched to the ethos and brand of an organisation. However, their usefulness depends upon the ability to link certain design features to particular values. There is a risk that people choose building values based upon the ethos of the organisation or, worse, plucked out of thin air. It is possible that the range of characters we saw is more reflective of the range of organisations than the range of buildings.

In this small sample, there was no building that had a clear identity different from that of the organisation. This suggests that value identification is strongly linked to the ethos of the organisation. The values and identity of the design can be judged to support the organisation ethos or not. But it is hard for an office to have a cohesive identity of its own. Therefore, this tool can be used to find buildings that are not supporting the company ethos. It can then frame discussions about unifying the values of the building and the organisation. However, it is less useful for finding the values of a building independent of the organisation. Although, this is a small sample of buildings so it is hard to draw final conclusions.

The two buildings (E and G) that stood out as having the most coherent identities were both designed by the company that occupied them. On reflection it seems that architects who design their own office must put a lot of thought in to it. Not only in the initial design of the office but also in to all the modifications required as time goes by. As a result, their buildings have a more considered feel. The feel is of a space that has evolved and undergone continual crafting, a process which has given it a degree of consistency. In our opinion these are the ways they differentiate themselves.

It is exceptional for an organisation to have designed the office that they occupy. Therefore, our conclusions must be treated with a degree of caution. In particular, the correlation between identity and building performance is strongly influenced by these two buildings. However, it is also influenced by buildings A and C. Both of these suffer from a lack of identity and poor overall performance. Does this mean that identity is the elixir of building performance?

As well as having a coherent identity buildings E and G have a population that is deeply au fait with the process of design. Perhaps, they chose more value traits because they engage more with this question. And the additional coherence between their answers could be because, they are schooled to think the same way about buildings, or they discuss the design of their office more than other people might. Perhaps these questions are just measuring a general enthusiasm for the design. To resolve these issues, more buildings should be assessed and surveys should be followed up with a number of in-depth interviews on the matter.

5.5 Conclusions

5.5.1 Environmental sensory design

Variability sometimes improves an environment and at other times it does not. Lighting variations provide clues to the time of day and the state of the outside world whereas temperature variation can make adaptive behaviour difficult. Pursuing singular optimal conditions could be making buildings a monotonous, less natural and less stimulating place to be. A better strategy may be to allow the environmental conditions to vary within a set of functional limits. In terms of a sensor system specification this could be done with a wider bandwidth or a bandwidth that could be adapted to occupant preference (Nagy *et al.*, 2015).

There are many different modes of interaction with a building. It is not enough to say that there is a spectrum of building control from automated to manual. Buildings can have stronger or weaker leadership and they can be managed in a planned way or through crisis. Understanding a particular building and its occupants will help improve retrofit measures and behaviour change programs. Understanding the building control regime comes from observation and situated learning in the field. This is something that sensor systems alone would struggle to emulate.

The construction of the symbolic identity of a building, i.e. the values that it represents, is done not just by the implementation of certain design features nor by the imposition of symbolism from an external source (in this case the occupying organisation). Instead there is sometimes a fit between the identity of a building and an organisation so that they are both suggestive of each other. Where this is not the case the identity of a building is less coherently understood. Our values and identity survey provides a method for identifying when an office's identity is out of sync with the occupying organisation.

Finally, a building's identity is very strongly associated with people's perception of the performance of that building. This suggests that buildings which are perceived as having a clear identity are also perceived as performing well. This shows that the identity and values of a building are an essential component of building performance and it is important to integrate these into building characterisations.

5.5.2 Design implications

This is a brief summary of the practical design lessons that have been explored in this study:

- Windows need to have enough clearance to open, especially tilt and turn;
- Tilt and turn windows can sometimes open in an uncontrollably manner. This discourages people from using them;
- Blinds should not block the opening of windows;
- Designing lighting to a single parameter (i.e. lux levels) leads to an environment that is only a single parameter. This is not necessarily the most stimulating environment;
- Putting desks close to windows maximises daylight access. However, it means that these areas cannot be used for walkways. In deep plan offices having walkways closer to windows might improve navigation. Also desks by windows tend to restrict their usage;
- Although temperature variation can cause dissatisfaction conversely tightly defining the temperature is overly restrictive and counterproductive. It would be better to insist that comfort and satisfaction levels should be maximised;
- Air from floor vents can be draughty;
- Zoning building F in quarters was not enough. In such a large office each tenant area should be zoned separately. This would allow more responsive control.

Chapter 6

Suitability of physiological sensors for multisensory comfort assessment

Previously

The methodology chapter selected wearable sensors measuring the autonomic nervous system (ANS) for this study. This is because these sensors are less intrusive and simpler to use that other options.

This chapter

We retain the broad focus of Chapter 5 by looking at multisensory experience but focus on individuals' experience. In the first analysis, we see how different individuals react to different environments. In the second, we see how a single individual responds to changing sound levels. Both are in the context of a working office.

The first analysis suggests, there are key differences to the senses. It is the combination of these differences that provide the unique richness of multisensory experience.

The second analysis reveals differences in people's sensitivity to sound.

Both these analyses point towards the limit of using background levels of ambient conditions to understand user experience. They suggest that, until sensors can understand and summarise the complexity of user conceptualisation, they will not fulfil their promise of use for multisensory comfort assessment. However, the use of physiological sensors to identify salient experiences provides a possible approach to characterising complex environments.

Up next

Background levels are not the only way to characterise the physical environment. In the next chapter we will focus on privacy, crowding and satisfaction. From this we will see how, typologies and features can be used to characterise the physical environment.

See also

Keeling, T., Roesch, E. B., & Clements-Croome, D. (2017). Suitability of physiological sensors for multisensory comfort assessment (in preparation)

6.1 Introduction

6.1.1 Energy and information

A simple way to characterise the ambient conditions is by measuring lux, dBA and air temperature (ISO 28802, 2012). These all measure the quantity of energy available in the environment. They also provide a one-dimensional account of the background level of each environmental variable. This study explores how these, along with a number of other measures, can be used in combination with wearable sensors, to understand user experience.

In design practice, background levels of the physical environment are used to specify health limits above and below which it is not safe or feasible to work (ASHRAE, 2010; Hygge, 2007; SLL, 2012). They are also used to predict when occupant satisfaction will be maximised. These one-dimensional measures of the physical environment are often used to predict one dimensional scales of acceptable human experience (i.e. discomfort to comfort).

However, background levels and energy balances capture little of the complexity of environmental experience. At very low energy levels it is the information received by an occupant that shapes their experience; so for example, appreciating artwork is a very different interaction with light than glare or sun burn (Dutson, 2010), perceiving a draught is different from having hypothermia (Heschong, 1979). At one extreme, sensation can be thought of as information transfer, because the interaction with the environment has negligible effect on the bodies energy balance. At the other extreme, there is a significant energy transfer that directly affects the physiological regulation of the body. When information processing is important for experience of IEQ then background levels struggle to characterise the complexity of the indoor environment.

It is difficult to describe complexity using one-dimensional scales (i.e. single parameters). For example, one dimensional scales of comfort and satisfaction inadequately describe multi-sensory experience, visual scene and soundscapes (Clements-Croome, 2014b; Ong, 2013). One-dimensional scales have no room for complex experiences that are neither good nor bad but instead have their own quality. A quality that is interpreted according to preference and circumstance.

Table 6-1: The differences between an energy and information interaction with the environment.

Energy	Information
Background levels	Interpretative meaning
Quantity	Quality
One dimensional	Multi-dimensional
Physical & biological	Psychological & conceptual

6.1.2 Multisensory experience

To define multisensory environmental experience singular environmental measures must be combined (Clements-Croome, 2013a). Most multisensory studies aim to understand the interplay of the senses by assessing their effect on a common outcome; we saw in Chapter 2 that there are a number of ways to do this. These approaches all accounted for multisensory experience by weighting of the single senses and summing these into a single one-dimensional outcome. Typically, through a multiple linear regression type approach.

An alternative approach is to contrast the qualitative differences of the senses (Pallasmaa, 2005). Pallasmaa (2005) suggests that it is not possible to combine and sum different sensory experiences, rather it is the balance and contrast of the different senses that makes an experience what it is. For instance, he describes vision as detached and abstract and a snapshot in time, whereas sound is intimate, situated and can only be comprehended in terms of its unfolding in time. For him, understanding the contrasting, interweaving of effects is more important than using a single concept, such as satisfaction, to unify them. This study emulates this approach by aiming to understand the multiple and differing effects building environments have on their occupants.

We do this by taking a field-based (ambulatory) approach that combines experiential investigation with data from wearable physiological sensors. This allows the integration of Pallasmaa's situated interpretive approach with the sort of physiological measurements that would most often require laboratory-based investigation. By collecting concurrent data about, subjective experience, environment and physiology, it is possible to investigate the experience of real world environments (Schnell *et al.*, 2013; Tröndle *et al.*, 2014). Before we develop the detail of our hypotheses it is necessary to explore how these methods have been used in the past.

6.1.3 Measuring occupants: psychology and psychophysiological

This study uses the response of the autonomic nervous system (ANS) because it is linked to alertness, a key attribute for wellbeing and productivity (Cacioppo *et al.*, 2007). Two components of the ANS response were measured: the skin conductance level and electrocardiogram. These were chosen because they can be continuously measured by equipment that is relatively unobtrusive and accurate. Similar equipment has been used to track occupant movement and metabolism (Spataru & Gauthier, 2014). In contrast we are interested in the psychological component of the physiological response.

When people pay attention to a stimulus this causes a response of the ANS. This can cause a change in skin conductivity, muscle action potential (especially the blink reflex), respiratory amplitude and period, peripheral vasoconstriction and heart rate (Thackray, 1972). Loud noises with sudden onset have been studied in some detail. Peak in blood pressure occurs roughly 10s after stimulus onset (Chen *et al.*, 1991). Heart rate (HR) either increases, decrease or both depending upon stimulus type; louder, more sudden noises tend to result in HR acceleration. Peak acceleration in HR occurs approximately 3–5 seconds after stimulus onset, peak deceleration of HR occurs later at about 5–8 seconds (Graham & Clifton, 1966; Graham & Slaby, 1973)(Figure 6-1). The rapid response makes it useful for studying changes in the environment. Changes in heart rate between 2 and 6bpm have been detected (di Nisi *et al.*, 1987; Thackray, 1972), people who self-reported as being more sensitive to noise had a greater increase (di Nisi *et al.*, 1987). These studies have all been carried out in laboratories with highly controlled stimuli and environments. There are many challenges to transferring these methods to an ambulatory setting.

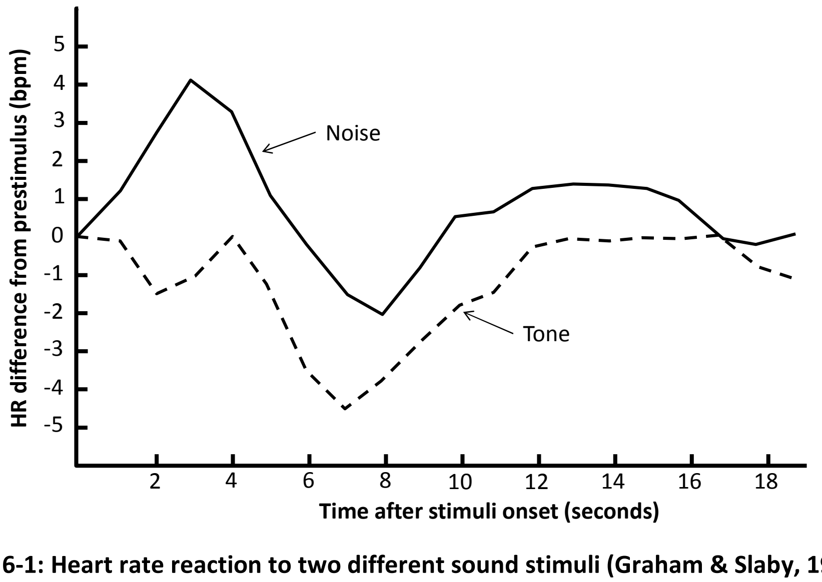


Figure 6-1: Heart rate reaction to two different sound stimuli (Graham & Slaby, 1973).

The physiological data were supplemented with a survey. This improved understanding of participants' subjective experience. The PANAS (positive and negative affect scale) survey is a practical option to do this because it is well established, short and easily adaptable to different time frames (Watson *et al.*, 1988). This was combined with a satisfaction survey.

The PANAS survey is a standard 20 question survey. Positive affect (PA) and negative affect (NA) are not opposites but in fact compose two orthogonal dimensions. High PA suggests enthusiasm, activity and alertness. High NA suggests sadness, lethargy and distress; low NA is a state of calmness and serenity (Watson *et al.*, 1988). Positive and negative affect are both related to important work characteristics (Huppert, 2009) and contribute to productivity (Clements-Croome, 2006a).

6.1.4 The ability of people to distinguish and ignore unwanted stimuli

The cocktail party effect suggests that people are continually screening unattended stimuli to see if conscious attention should be paid to it (Cherry, 1953). More complex speech shadowing tasks are used to understand about the perception of attended and unattended sounds. They require that a listener repeats words that are being played into a single headphone ear, while a separate audio channel is played in the opposing ear. This set up neatly divides attention into attended and unattended sound stimuli (Spence & Santangelo, 2010).

These experiments find that some but not very much semantic content of the unattended recording is recalled. Often subjects would not realise if the language was changed half way through but they would perceive changes in sex of the speaker. People with large working memories were better able to ignore their own name and would later not recall hearing their name. When working memory was limited distraction was greater. People would also show physiological responses to target words that they would later not recall. It is evident from these that come subconscious processing of the signal is occurring and that this is sometimes on a semantic basis (Spence & Santangelo, 2010). This suggests that sound can be distracting because of its semantic content not just its loudness. The degree to which it distracts depends upon the signal, the listener and the complexity of the task they are doing.

6.1.5 Hypothesis development

Comfort is the state of the environment without environmental stressors (i.e. reduced stimuli). This suggests that the presence of stressors, i.e. being outside the comfort zone, leads to arousal, this should result in high PA and low NA (Watson *et al.*, 1988) as well as arousal of the ANS. This has been observed in a number of experiments, the colour temperature of light has been shown to both the PA and NA scales (Knez, 1995; Viola *et al.*, 2008) and prolonged elevated noise levels raise blood pressure (Aydin & Kaltenbach, 2007). These findings suggest that the physical amount of an environmental stimuli results in a response from the participant.

In Chapter 4, section 4.3.3, we discussed the startle, orientate and defence responses of the ANS, all of which occurred in response to a stimulus. This suggests that when an environmental event occurs, i.e. a stimulus of some sort, then there will be an ANS response. However, beyond loudness (Graham & Clifton, 1966; Graham & Slaby, 1973) it is not clear what exact physical characteristics of a stimuli cause an ANS response. Experiments on noise were carried out in highly controlled environments, so that there was a clear difference between stimulus onset and offset, the stimulus was also significantly louder than background noise levels. In our field environment there will be no clear onset of stimuli, the volume will be variable and there will be the potential for semantic effects on stimuli processing (Spence & Santangelo, 2010). Given this there will be three types of physiological and psychological response. Responses caused by no measured stimuli. Responses caused by the size of environmental stimuli e.g. volume of noise and brightness of light. Responses caused by environmental semantics, i.e. information exchange and complexity. From this, we broadly hypothesise that the extent to which background levels are useful for interpreting results will depend upon the importance of complexity and information exchanges in a situation.

For this study that broad hypothesis is split into two specific ones. The first hypothesis relates to analysis where, session averages of all environmental factors are compared with session statistics of personal factors. This was carried out between-subject, so each person was compared to the group. We compare environmental factors (air temperature, humidity, CO_2 levels, lux levels, colour temperature and sound levels) with personal factors (skin conductance variability (SCV) and heart rate variability (HRV), positive affect, satisfaction level). Our broad hypothesis would suggest that where environmental stimuli are outside the comfort zone for prolonged periods during the session a response in personal factors should be seen. However, semantic stimuli within the comfort zone will also cause a participant response which will add unpredictability to the measured personal factors. This semantic distortion will occur most strongly where there is greater potential for environmental stimuli to convey meaning, i.e. noise levels.

Table 6-2 shows the hypothesised relationships (H1). Where no effect is predicted it is because we expect that background levels will not be sustained outside the comfort zone for prolonged periods during our observations (i.e. humidity and CO_2 levels) or because the effect of environmental stimuli will be conflated with the effect of semantic stimuli (i.e. noise levels). Further to this a larger than normal increase in SCV is expected with elevated temperatures (Gagge *et al.*, 1967).

Table 6-2: Hypothesised effects of the building environment upon satisfaction, PANAS and physiology.

Dependent variables	Independent variables					
	Lux level	Colour temperature	Sound level	CO_2 level	Air temperature	Relative humidity
HRV	Effect	Effect	No effect	No effect	Effect	Effect
SCV	Effect	Effect	No effect	No effect	Large effect	Effect
PA	Effect	Effect	No effect	No effect	Effect	Effect
Satisfaction	Effect	No effect	Effect	Effect	Effect	Effect

The second analysis tests the physiological response of individuals to different noises stimuli. This was carried out using a within-subject's design. To do this we broke down an individual's session into approximately 30 to 70 events and compared these events with each other. It is hypothesised that the greater the relative loudness of the event, the larger and more likely the startle response, and therefore the larger the heart rate and SCV response (H2).

6.2 Methods

Procedure

The environmental conditions were measured at the participant's desk. At the same time they wore a sensor vest that measured their skin conductivity and heart rate (Figure 6-2). This was done for an hour while the participant continued working as normal. They were asked to choose a time when they would be predominately working, alone at their desk. However, they were also free to get up, move around and have conversations if needed. After the hour the participant completed an exit survey about their experience during the session.

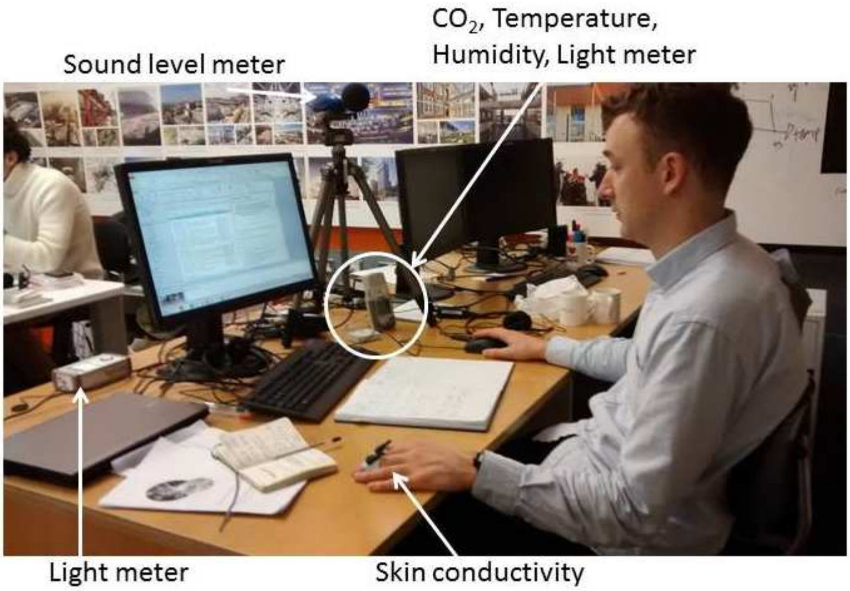


Figure 6-2: Study set up, showing environmental and physiological measuring kit.

This method required the coordination of time series from several different devices. Each time series had a unique clock and frequency of measurement. Manual time stamps were inserted at the beginning and end of each session. This coordinated all of the time series to within ±1second. This temporal accuracy is sufficient because it is shorter than the response times of the physiological signals measured (Cacioppo *et al.*, 2007) and shorter than the averaging periods used in our analysis.

After each session data were uploaded to a PC. Then combined and processed using specially written scripts for R software (Figure 6-3). Novel parts of these scripts are explained later.

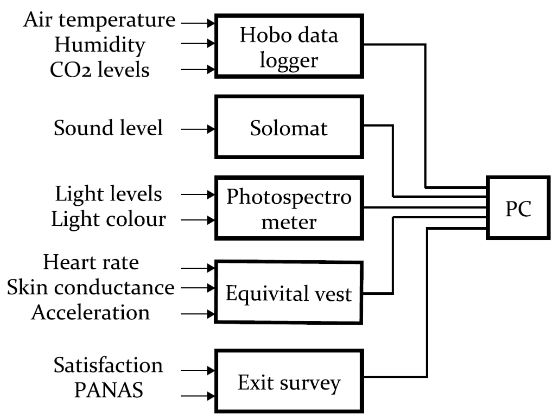


Figure 6-3: Schematic of physical and physiological data collection.

The buildings

Participants were selected from the seven buildings detailed in chapter 7 plus a further building (labelled H) that did not undergo the fuller post occupancy evaluation. The additional building was from the same organisation and in a similar location as building A. The range of settings provide a sharp contrast to more controlled laboratory tests; this is imperative for demonstrating wearable sensors as a useful building performance evaluation tool.

Participants

We recruited participants (27 male, 23 female, age range 18 and above) by email and on an ad hoc basis while present in their building. In certain instances a full quota of data was not obtained because of the failure of one device or another. Further to this full sound level measurements were limited to ten individuals because of equipment availability.

Similar studies used similar number of participants. Schnell *et al.* (2013) used 36 participants to explore the effect of the external environment on heart rate variability (HRV). Tröndle *et al.* (2014) used 576 participants to map how each experienced different museum spaces. In contrast Debener *et al.* (2012) tested an ambulatory EEG device on just 16 participants. Our analysis would have benefitted from a greater number of participants. It is insufficient for making conclusions about the general population but suitable for drawing conclusions about the specific building populations studied. So, given the time involved with setting up the equipment and processing data we have a reasonable number of participants. It also reflects what would be required in a commercial BPE that aims to make building specific diagnoses.

Materials

The physical conditions were monitored continuously for the session. Air temperature, humidity and lux levels were logged every second using an Onset HOBO U12 data logger. Connected to this was a Telaire 7001 sensor to measure CO_2 levels. When available a Solo sound-level meter was used to measure background sound level at a rate of 10 measurements per second. A Gigahertz-Optik BTS256 photospectrometer was used for measurements of the intensity and spectrum of light, this device took readings every minute. The apparatus was placed around the participant’s desk. This was done so that they would obtain accurate readings and not obstruct the participants’ work.

The physiology measurements included heart rate, skin conductivity and acceleration. This was done using an Equivital vest (Liu *et al.*, 2012). Electrocardiogram (ECG) signal was measured at 256Hz, skin conductivity and the accelerometer at 25Hz. ECG data were converted by the Equivital software into an RR (interbeat interval) value and an associated confidence level for this conversion (0 to 100%). The software converted the output from the accelerometer into an estimation of one of three movement levels: stationary, moving slowly and moving fast. Skin conductance level (SCL) was used in its raw form.

At the end of the session the participants answered a short survey. This included the PANAS and their satisfaction with ambient conditions (five-point scale: Satisfied, A little satisfied, Neither, A little dissatisfied, Dissatisfied). They were asked to only consider their experience during the measurement session.

The apparatus used to acquire the data for this study was clumsy. It required the coordination of data from several different systems, the data had to be downloaded manually. General convenience and coordination of time series would be improved if we had used a wireless systems that transmitted to a common receiver in real time. However, there is no single piece of proprietary kit that does this.

Another drawback is that the vest for physiological measurements was put on the torso and underneath clothing. The system would be much easier to handle if physiological data were gathered by an arm mounted device. Tröndle *et al.* (2014) used such a system and this was one of the reasons they were able to obtain such a large number of participants. However, their system was still bulky and could not have been used in conjunction with using a keyboard. It is recommended that future wearable sensors BPE develop both a fully coordinated wireless set of sensors and, if possible, a device that attaches to the wrist or leg rather than the torso. This would improve handling times and decrease the intrusiveness of the device (Moran & Nakata, 2010).

There is also scope for altering the types of sensors used. There are an increasing range of wearable sensors currently on the market. Blood oxygenation may be good for monitoring the effect of IAQ. Electroencephalography (EEG) may be useful for studying combined effects of environment on stress, and restoration. A future BPE kit should have a range of different sensors so that the most applicable sensors could be selected for the purpose required, or the full set could provide a more complete picture. This study did not use these because they are more intrusive (they require attachment to hands or face). They also do not measure the autonomic nervous system (ANS) so do not provide the data necessary for this study.

Data overview

Data for the session were clipped to reduce start and end effects. Looking at a single participant's data for the hour (Figure 6-4) it is possible to note patterns in how the data change. Temperature, humidity and carbon dioxide stay relatively steady for the whole hour, where they change it is generally a steady slow shift in one direction. Light levels also change at a slow continuous shift; though there are times when changes of greater than 100lx happen within a couple of seconds. These time series can be contrasted with sound levels that change much more rapidly, moving from 45dBA to 65dBA and back again within seconds.

In contrast, all physiological data fluctuate at high frequencies. Heart rate has a base rate and varies up and down, with some rapid changes in places, but less so in others. Skin conductivity exhibited two trends, both a steadily moving average and, in some participants, a number of extreme spikes in response.

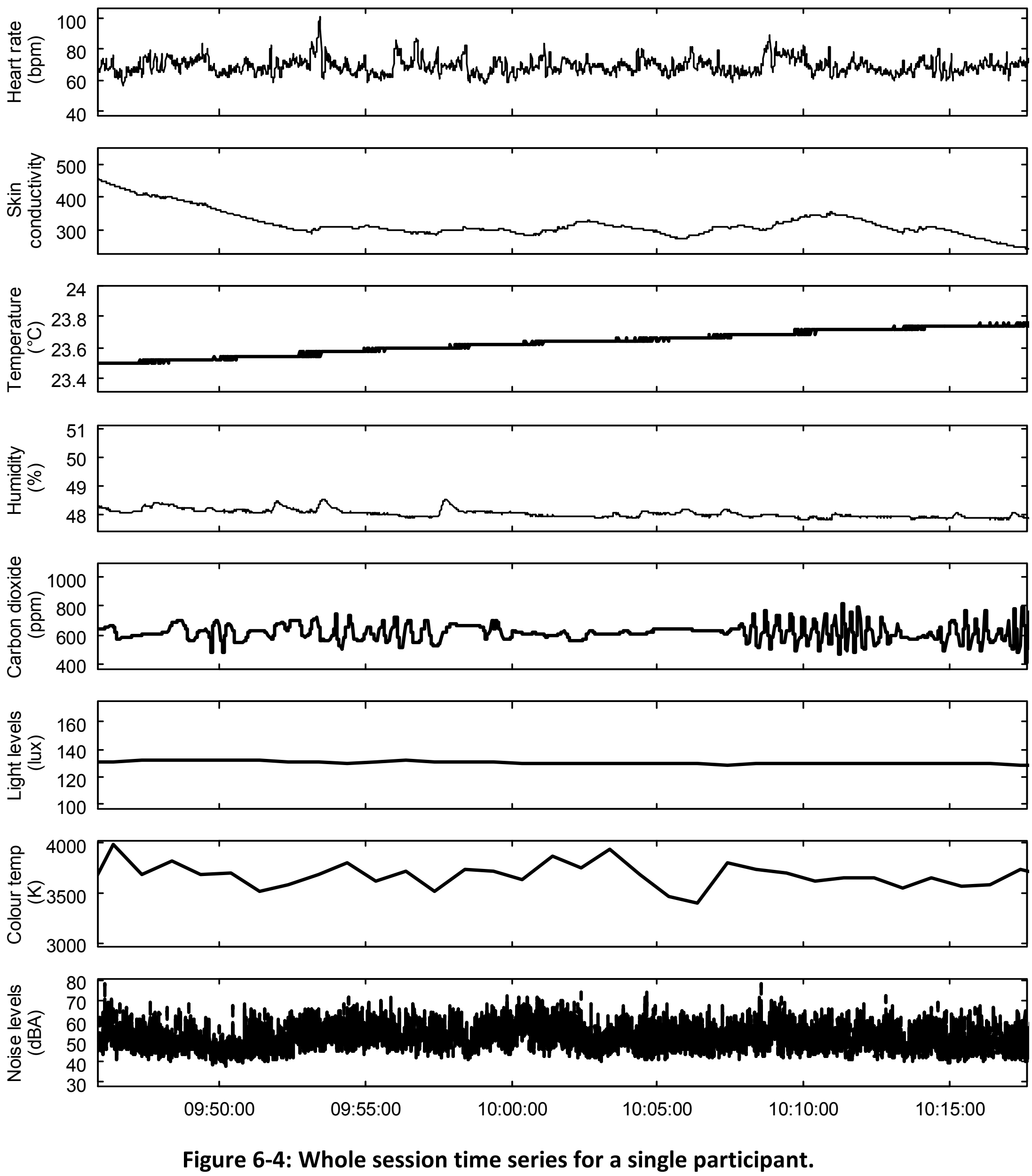


Figure 6-4: Whole session time series for a single participant.

The average values of data from each session were compared between participants (Table 6-3). There were three people for whom heart rate data were not properly recorded. Consequently they had a low average heart rate confidence (<50) and their average heart rate was misinterpreted by the software. There were also three people for whom skin conductivity did not record. These data were excluded from further analysis. Negative affect (NA) scores had a highly skewed distribution therefore they were not used for further analysis.

The environment was completely uncontrolled in these investigations. Average air temperatures ranged from 20 to 30°C; participants were free to adapt their environment to achieve comfort. Light levels ranged from 100 to 2,000lx and colour temperature from 2,800K to 6,000K. CO_2 levels ranged from 450 to 1,000ppm. Humidity from 30% to 65% (Table 6-3). Average sound levels for a session ranged from 50 to 58dBA. Average CO_2 and sound levels were the only variables that remained within their design limits across all sessions.

Table 6-3: Summary of participants' session averages.

Measure	Min.	1st Qu.	Median	3rd Qu.	Max.
Light levels (lx)	138	375	574	764	1,855
Colour temp. (K)	2,686	3,174	3,879	4,528	5,872
Sound level (dBA)	50	51	52	54	58
CO_2 level (ppm)	462	542	619	697	932
Temperature (°C)	21	24	25	26	29
Relative humidity (%)	33	43	47	50	60
Mean RR interval	262	752	822	979	1,226
HRV	2,183	9,400	16,920	33,600	157,100
Mean SCL	-1	165	362	707	2,258
SCV	0	3,491	12,870	50,910	156,100
Mean HR confidence	37	89	96	98	99
Variance in HR confidence	1	1	17	121	499
Positive Affect	11	22	25	30	37
Negative affect	10	11	12	16	31

Heart rate variability (HRV) was obtained by taking the variance of the RR interval for the whole session (Berntson *et al.*, 1997). A large HRV indicates arousal of a person's autonomic nervous system (ANS) (Cacioppo *et al.*, 2007). Skin conductance variability (SCV) was obtained by taking the variance of skin conductance level for the whole session. This indicates activation of the sweat glands, which can be part of the sympathetic response of the ANS or thermoregulatory response (Cacioppo *et al.*, 2007). These method were chosen because of their simplicity, which suits interpretation and use in industrial contexts.

Session statistics, for HRV, SCV and PA score, were compared with demographic factors to check for correlation (Figure 6-5). The value of ***p*** displayed on each graph shows the probability that scores are the same using either the f-test or t-test statistic. Despite there being a range of organisations and locations, there was no significant difference between buildings. Gender had a significant effect on HRV and PA score and age had a significant effect on PA score.

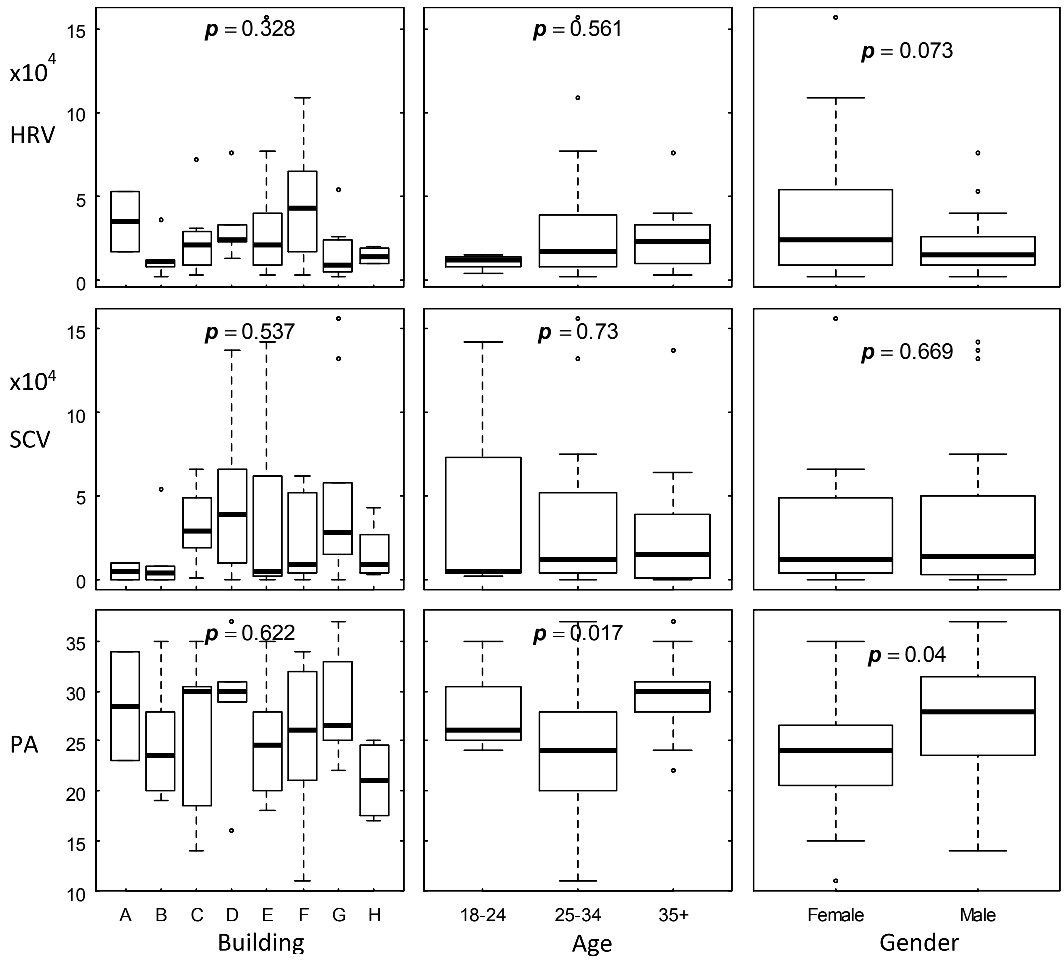


Figure 6-5: Between participants comparison of physiology, positive affect and demographics.

6.3 Development of analysis method for within-subject analysis

6.3.1 Overview of method

The within-subject analysis selects and compares a number of events from a single participant. The benefit of this form of analysis is that the results are all from one person, so there is no problem of interpersonal differences. This within-subject analysis provides insight into the unfolding of events in three key time series: sound levels, heart rate (HR) and skin conductivity level (SCL). These can be seen in Figure 6-6 and Figure 6-7.

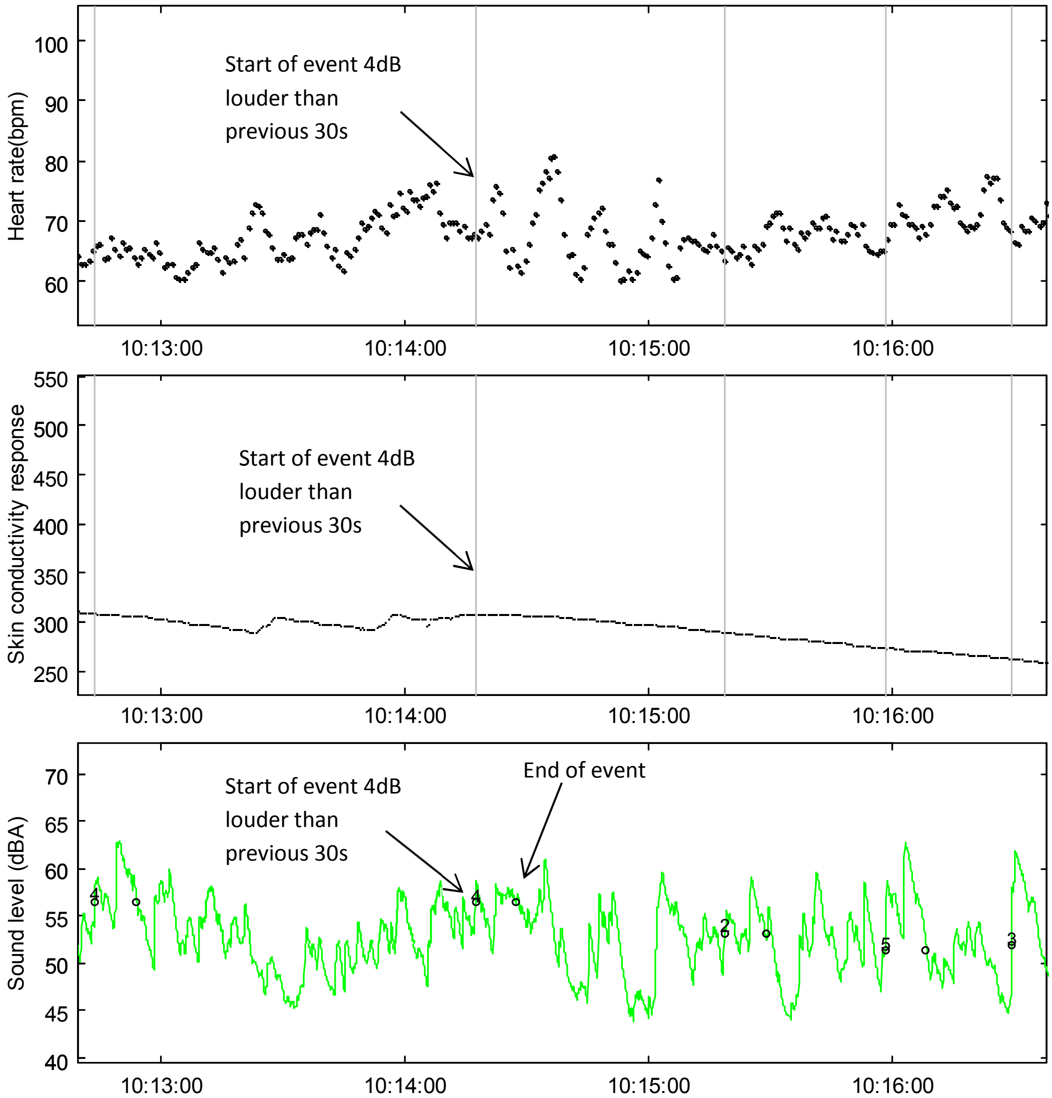


Figure 6-6: Time series for heart rate, skin conductivity and sound level for a participant. The details of a single 4dB event are annotated.

For the analysis we used R Software (R Development Core Team, 2016) because it allowed us to write a special algorithm to identify sound events. Events were defined as periods (10 second long) when background sound levels were louder than they had been in the previous thirty seconds. Events were identified by going through the entire time series and comparing the average sound level of a 10 second section with the preceding 30 seconds. This can also be described as comparing the relative loudness of P_3 (the event) to P_1 (the preceding thirty seconds) (Figure 6-8).This results in the identification of many overlapping events. The number of events can be reduced by choosing the loudest when two overlap. This identifies approximately 30 to 70 events per session. The timing of these events are then used to look at the corresponding physiological response.

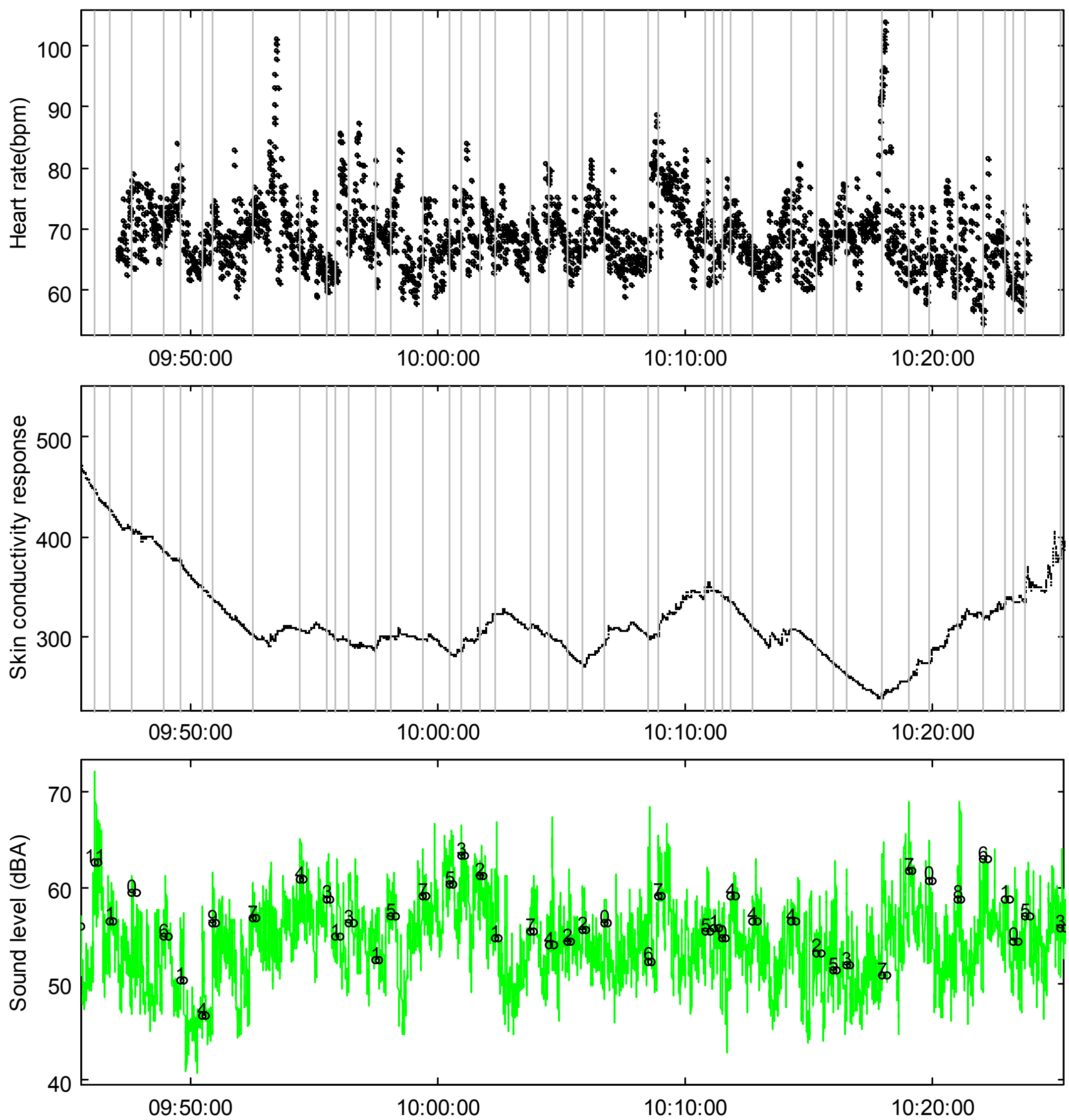


Figure 6-7: Time series for heart rate, skin conductivity and sound level for a participant (whole session). Showing all events size and timing.

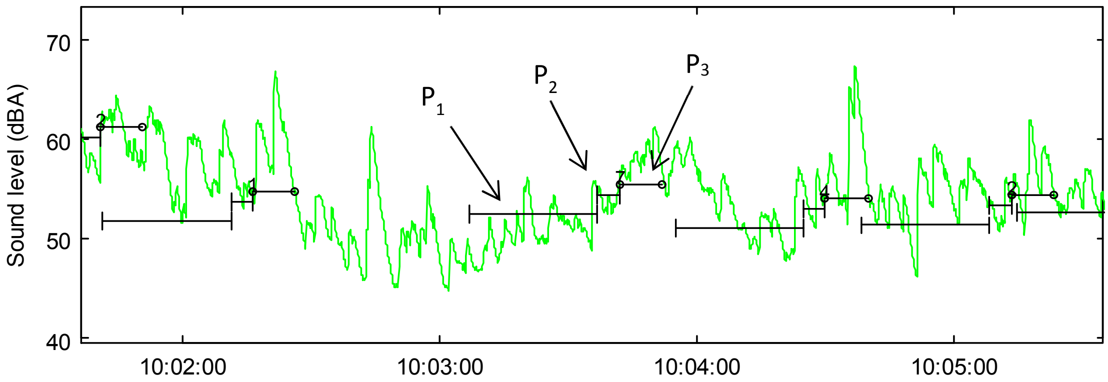


Figure 6-8: Example of time series analysis method. P_1 = reference background level, P_2 ensures segmentation, P_3 = foreground level for comparison.

An alternative approach would have been to segment the time series into a number of arbitrary lengths and compare the data in these (Tiesler & Oberdoerster, 2008). However, that approach seeks to understand the effect of general background levels upon occupant stress (Tiesler & Oberdoerster, 2008).We prefer our approach because it observes specific events rather than environmental averages. It is similar to laboratory analysis of event related potentials (ERP) (Alain *et al.*, 2001; Boksem *et al.*, 2005; Luck, 2005). ERP was developed to understand how environmental events were processed by occupants. In summary our approach looks at whether background noise levels can be used to understand an occupant's reaction to single events rather than whether background levels are a general stressor.

6.3.2 Evaluation of method

This method identifies many sound events in a single participant's data. Then it compares the loudness of these events with the physiological response. This technique has various strengths. Firstly, it makes it possible to compare the same person's response to different noises, this removes the large inter person variation in physiological response. Secondly, the technique can be used to focus analysis on short lived environmental events; this removes physiological noise when no environmental event is happening. Lastly, this technique allows the detailed study of single individuals; therefore it could be used to identify people that are more sensitive to environmental change than others.

There are inherent differences between the time series of the physical conditions and the physiological measures. During this study, temperature, CO_2 levels and humidity have their progression characterised by slow shifts rather than sudden fluctuations. Light levels and colour temperature are generally similar but may undergo a small number of rapid shifts during a session. In contrast sound levels fluctuate rapidly throughout the session; as does the physiological response. This makes sound levels and physiology well matched and therefore suited for within-subject analysis. To identify as many events (>30) for the other physical variables would require a much longer session or the introduction of artificial stimuli.

It is difficult to reliably define a protocol for identifying when environmental events occur and how big they are. This is because real life events have neither a definite onset nor a definite size. Sometimes events are missed, by our algorithm, and other times the identification of an event seems spurious. Regarding event size, sometimes two events can appear similar when the times series is visually inspected but have quite different sizes attributed to them. Despite this there are times when the algorithm works well, many of the significant peaks in sound level are recorded as events and often the estimation of their size seems a reasonable approximation. Undoubtedly though, future studies could improve on this

However, even if the algorithm for event identification were perfect, it would still rely on the use of dBA. Therefore it would not identify those sound events that are salient for reasons other than their pressure level. To track and characterise these events, some other aspects of saliency must be coded into the analysis. This could be achieved by recording audio for the session and manually assessing the saliency of different events. Or we could introduce reference sound events for comparison. Such an approach, of introducing events, would suit the investigation of other sensory perceptions, that did not change so rapidly.

6.4 Results for between-subject analysis

Each point on Figure 6-9 is a summary statistic for a single participant's session. For humidity the satisfaction score is for air quality, for all other variables it is with their respective sensory perception. The inferential statistics on the graphs are obtained from applying linear models to the data: "***p=***…" is the probability that there is no link between the variables; "R^2=…" is the correlation coefficient.

After running 18 tests of correlation between the different variables there is a significant relationship between only three of them. Two of these are with the average temperature; skin conductivity variation and positive affect are greater at higher temperatures. The third is between light levels and skin conductance variation; higher light levels are associated with an increased skin conductance. The correlation between temperature and light levels was tested and it was found to be not significant. These results mostly run counter to H1.

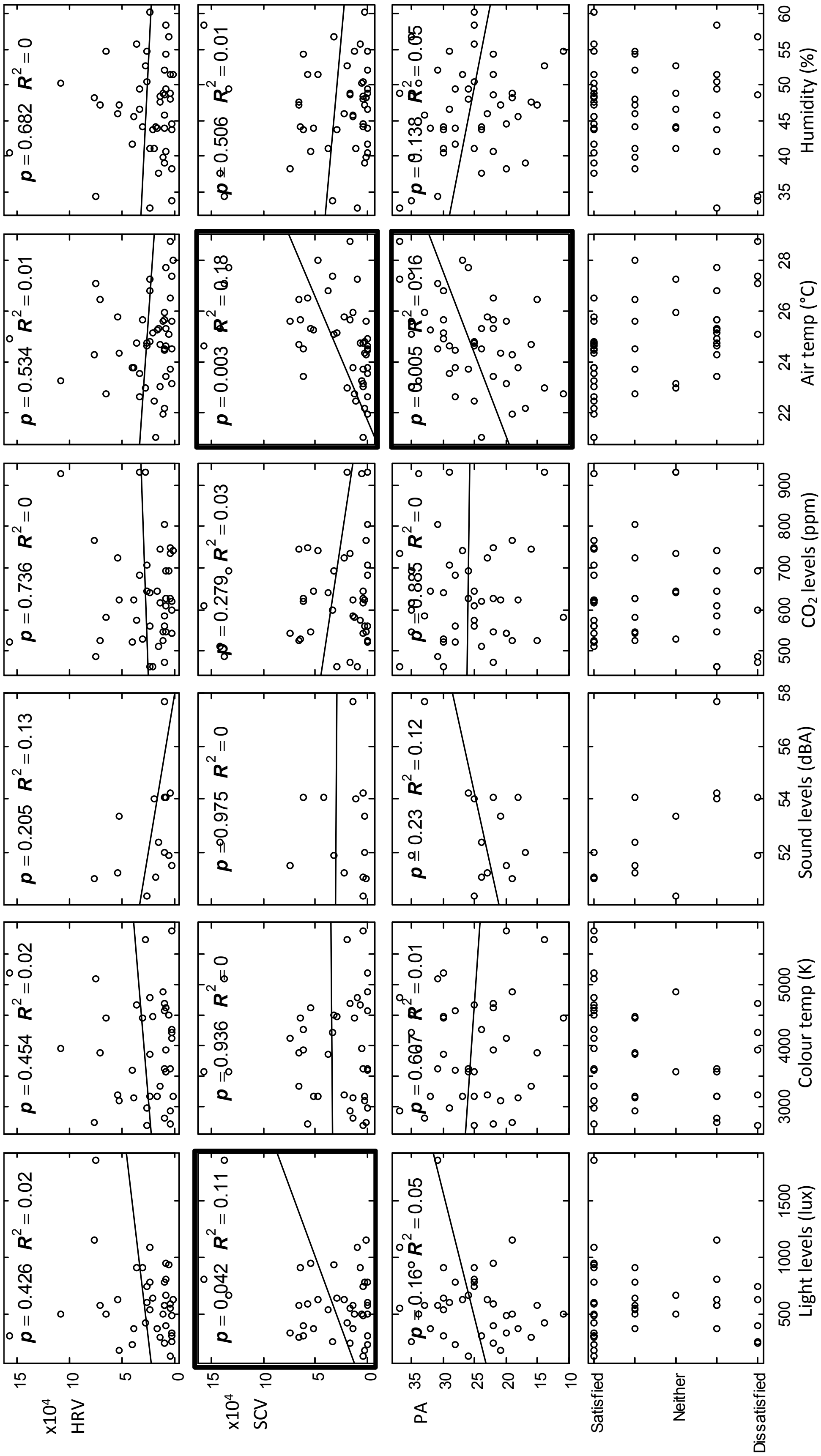


Figure 6-9: Between participants comparison of physiology, positive affect and building environment.

6.5 Results for within-subject analysis

Hypothesis 2 predicted a correlation between the relative loudness of an event and the size of the physiological response. Figure 6-10 shows a selection of results, each graph is the data for one selected participant. The statistics displayed on the graphs are obtained from applying linear models to the data: "***p=***…" is the probability that the gradient of the regression line is zero (i.e. no correlation); "***R²***=…" is the R^2 correlation coefficient.

Some participants show a clear correlation between the loudness of the event and the raising of heart rate. The probability of no significant relationship ranges between *p*=0.006 and *p*=0.5 for the ten participant where full data were available; three have p<0.05. R^2 coefficients vary between 0.02 and 0.17. This suggests hypothesis two holds for some individuals but not all.

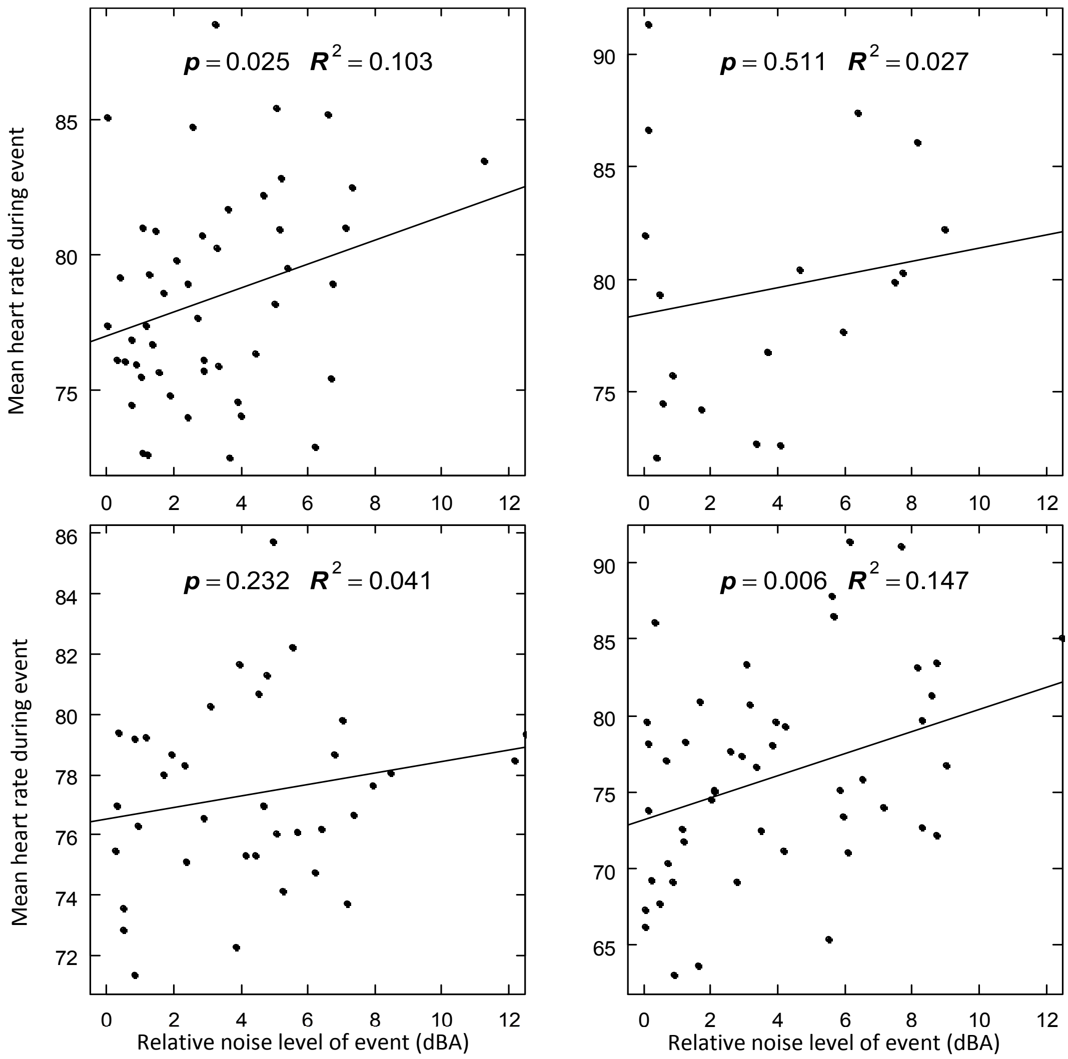


Figure 6-10: Correlation between heart rate and sound levels for selected individuals.

When comparing skin rate variability and relative loudness the relationships between events is not so clear (Figure 6-11). Each graph is data for the same participants as Figure 6-10. Some quiet events have large skin conductivity response whilst other louder events have very little response at all. Because of this the natural log of the SCV was used for analysis. The R^2 correlation is generally lower for SCV (0 to 0.17) and the probability that there is no relationship between the factors higher (0.01 to 0.98). The correlation is significant for only two participants out of the ten. This suggests that hypothesis two does not hold as well with regards to SCV.

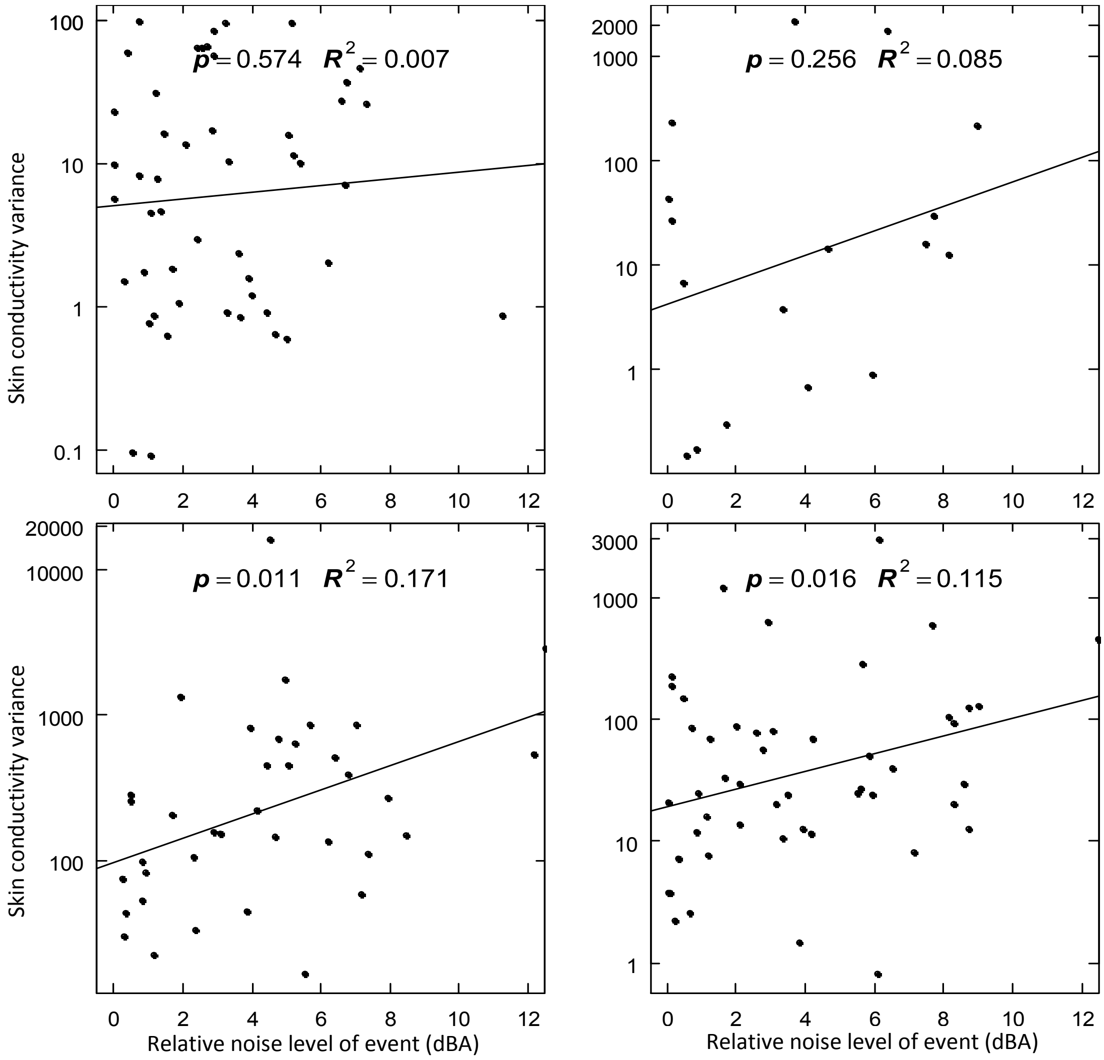


Figure 6-11: Plots of skin conductivity variance and sound levels for selected individuals.

6.6 Discussion

Between-subject

The between-subject analysis showed some correlations between the environment and occupants. However, these were generally different from those hypothesised. Some of the missing correlation can be explained by the narrow range of environmental conditions encountered. For instance, changes within the range of CO_2 levels and humidity measured in this study (IQR = 155ppm, 7%rh) are barely perceptible.

Background light levels showed a small and weakly significant relationship with skin conductivity variance. The significance is only just below 0.05 and there is no correlation between light and any other indicators. Nonetheless this suggests that background light levels did impact user experience. This adds supports to work that shows high light levels can be alerting and stimulating (Cajochen *et al.*, 2000).

Temperature showed the greatest pattern in the between-subject analysis, correlating with both skin conductance variability (SCV) and positive affect. The increase in SCV was a particularly strong correlation. This reproduces results that show skin conductivity increases at higher temperatures (Gagge *et al.*, 1967). This suggests that the source of the SCV correlation is the direct effect of the temperature on the physiological response.

The increase in positive affect is more remarkable. Most other studies suggest that alertness and performance reduce at higher temperatures (Griffiths & Boyce, 1971). Although more recent studies show warmth linked to positive outcomes such as increased interpersonal behaviour (Williams & Bargh, 2008) and high external temperature correlating with increased subjective wellbeing in the UK (MacKerron, 2012). Both our results re-iterate that background levels are important for a person's experience of temperature; this is in contrast to the results for sound and light levels. This supports the idea of qualitative difference between the senses (Pallasmaa, 2005).

Within-subject

The within-subject analysis showed that, for some individuals, heart rate is a useful method to track their response to different sounds and that this can be done in situ. This supports hypothesis two. This method was adapted from methods used in schools (Tiesler & Oberdoerster, 2008) and to study sonic booms in laboratory settings (Thackray, 1972). Our work suggests the method can be used to study workplaces in situ. However, most occupants did not show a clear physiological response to events, this could have been because of limitations of the method or because they were less effected by the noises. Furthermore, if bonferroni correction had been applied then no results would have been significant.

The data, especially that of SCV, highlighted the non-linearity between the size of physical stimuli and the physiological response. This made it hard to infer a correlation between the two. The data also show that there is not a one-to-one mapping between the relative loudness of a sound and the physiological response. It is apparent that not every noise causes a response and not every response is caused by a noise. However, despite the simplicity of the models used, some of the variation in physiological response can be explained by relative loudness. This supports work that shows that loudness is but one facet of what makes a noise salient (Spence & Santangelo, 2010). It also emphasises the difficulty of translating concepts and methods used in the laboratory to ambulatory studies of real world noises (Wilhelm & Grossman, 2010). The use of physiological sensors to identify salient environmental experiences suggest a way of overcoming the problem of characterisation of complex environments (complex characterisations). Instead of characterising IEQ by its physical manifestation it could be characterised by the type of physiological response it produces. Such a system could be used to engage machine learning to determine the most suitable environments for different people and tasks (Eadie *et al.*, 2016).

Background levels and multisensory experience

Background light levels and physiological response show only weak correlations in the between-subject analysis. This could be because background light levels are only one feature of the visual field (Dutson, 2010). However, with temperature, background levels are clearly of major importance as they have a strong correlation with both positive affect score and skin conductivity variance. This suggests that using a single parameter, such as background level, to characterise experience is suitable for temperature but not so suitable for sound and vision. This suggest that everyday experience of the thermal environment is more simple compared with the complexity of visual and acoustic experience. This is despite the complexities of temperature experience observed by Heschong (1979). This could be interpreted as evidence for the standardisation of thermal experience (Shove, 2003) as much as an innate tendency to have a simpler relationship with the thermal environment.

This balance between complexity and simplicity of our sensory experience can be related back to the balance between information exchange and energy exchange. The range of the physical conditions measured in this study illustrates the qualitative difference between everyday experience of the senses. In the office environments studied, the range of sound levels can only have an informatic effect on occupants. They can be distracting and annoying but they are unlikely to damage hearing. The range of light exposure measured here would also be within the informatic range and not high enough to have an energetic impact. Although it is possible that there were a small number of light conditions that were bright enough, with a sufficient colour temperature, to activate non-visual cells (Ámundadóttir *et al.*, 2015). In contrast, across all the buildings visited, there is a wide enough range of temperatures to stimulate an energetic exchange between occupant and their environment. This indicates that the reason background levels are so important for temperature is that, the energy content is as important as the information content, whereas for the other senses this is not the case. This suggests that those that use background levels to characterise acoustic and visual experience (Cao *et al.*, 2012; Huang *et al.*, 2012) are not taking the right approach.

Pallasmaa (2005) describes temperature as encompassing and embracing, while vision is detached. This is picked up in our data, which show that background levels are most useful for temperature, likely because it is the energetic exchange that is so important for thermal experience. This energetic experience goes on throughout an individual, so in some sense it is encompassing and embracing. In contrast the sensory experience of light is predominately an informatic one that happens at just two point in our bodies, this could contribute to the feeling of detachment that Pallasmaa (2005) suggests for vision.

There are further differences, described by Pallasmaa (2005), that have been observed in this study. He describes the temporal nature of sound as differentiating it from vision. Our data show the physical variables evolve differently in time. These differences, lead to different ways to summarise their physical manifestation and their effect on user experience. This suggests that sensor systems for the two could be quite different. Our work here suggests that temperature is suited to a simple background level measurement while something more complex like the experience of light and sound might, in the future, be understood by pairing environmental sensors with physiological sensors.

6.7 Conclusions

This study demonstrates important differences in the sensory experience of light, sound and temperature. Unique to this study we have highlighted the importance of the balance between energetic exchanges and information processing. There is always some mixture of both energy exchange and information processing. However, in different contexts one may be more important for understanding experience than the other. Because information processing is more complex than energy exchange, sensor methods must be vastly improved if they are to be useful for understanding complex and information rich experiences.

The within-subject analysis provides a unique insight, it enables the continuous tracking of rapidly unfolding events. This allows the researcher to compare the effect of different events against each other. It is most useful when used alongside contextual information, in this case the sound levels. Here it helped to distinguish which environmental events are salient and which are less so. This combination of environmental and physiological data could overcome the problem of complex characterisation because the physiological data can be used to categorise the nature of the user experience and the environmental data.

Multisensory perception requires the processing of information about the environment. To understand this, we must understand how occupants conceptualise their environment. What they find to be salient and how they think about the world around them. Because this is based upon complex information processing and conceptualisations it is difficult for measurements of energy levels to detect. We have shown that combining environmental and physiological measurements can give us an indication of what is salient and this may be useful for overcoming the problem of complex characterisation. This is taking a behaviourist approach because it does not attempt to understand the underlying thinking process (Davies, 2016), there is no idea of the reasons that one IEQ experience is more salient than another. In the following chapters the issue of understanding the thinking will be explored in greater detail.

Chapter 7

Typologies and features are effective ways to characterise offices and predict privacy effects

Previously

We showed that the problem of complex characterisation might be overcome by pairing environmental and physiological sensors to identify salient experiences. However, would still leave us with little appreciation of the underlying thinking processes that might shape experience.

This chapter

Occupant experience is studied in terms of perceptions of privacy, crowding and satisfaction. Privacy is a particularly relevant case because it is multisensory, focused on occupant outcomes and concerned with spatial constraints. For privacy the physical environment can be characterised using a continuous parameter (occupant density), a range of typologies or different design features. This study uses these different ways to characterise the physical environment in the seven offices. These are used to understand the effect of agile working on occupant experience. We believe that by looking at the relationship between features, typologies and parameters we can understand something about how people conceptualise complex environments.

Next

The next chapter will unlock a different aspect of the thinking process by exploring how psychological factors shape occupant experience.

See also

Keeling, T., Clements-Croome, D., & Roesch, E. (2015). The Effect of Agile Workspace and Remote Working on Experiences of Privacy, Crowding and Satisfaction. Buildings, 5(3), 880.

7.1 Agile working, privacy and satisfaction

7.1.1 Agile working

An increase in agile workspace and remote working has changed the way that work is done and offices configured. However, little is known about how these changes affect the experience of privacy, crowding and satisfaction. Experiences of privacy are diverse; it can be thought of in terms of the desire for withdrawal, control of information flow and control of interactions (Sundstrom & Sundstrom, 1986). These are important health and wellbeing issues for building occupants (Clements-Croome, 2006a, 2014b). Therefore, understanding how agile workspaces and remote working affects occupants' experience is important.

There is little peer reviewed coverage of agile working. In commercial literature the term is used to describe a variety of concepts including a mode of worker (an agile worker) and also a type of office design (agile workspace or agile offices), see Table 7-1. There is a range of alternative words that are of importance and describe overlapping concepts. To avoid confusion, this study uses the term agile workspace to describe a particular type of office design. This study uses the term "remote worker" and "mobile worker" synonymously to describe people who work in places other than their assigned desk space. Finally when talking of both mobile workers and agile workspace together the term agile working will be used.

Table 7-1: Overview of terminology used in commercial literature.

Term	Definition
Agile working	Working in different ways especially without a fixed desk (Ramidus, 2015).
Workstation setting	A word for the various places to work in an agile workspace. As in agile workspace has "a greater variety of workstation settings." (BCO, 2013)
Workstyle	The arrangement and set up of the office , encompassing the different ways of work (BCO, 2013).
Mobile working	
Remote working	
Co-working	Different organisation working in the same building (Ramidus, 2015).
Activity based working	Choosing workstation setting according to the work activity carried out at any one time (Morgan Lovell, 2014; Ramidus, 2015).
Flexible working	Having flexibility of when to work (Ramidus, 2015).

Traditionally open plan and cellular offices are composed of uniform assigned workstations, formal meeting rooms and support space. In contrast agile offices have a variety of additional work station settings such as shared desks, informal meeting space, collaborative space, break out space and contemplative space (BCO, 2013; Herman Miller, 2015; Littlefield, 2009; Morgan Lovell, 2014). These alternative work settings have developed from the hive, den, cell and clubroom patterns of work identified by (Duffy, 1974). Agile workspaces often facilitate working from unassigned desks, desk sharing is common and there are a variety of available work settings to choose from (Ramidus, 2015); however, this is not always the case. Although agile workspaces could consist of cellular or open plan offices they generally tend to be open plan. These unique aspects suggest that these new ways of working need to be examined.

In tandem with agile workspace has come the remote, or mobile, worker. Mobile workers have greater flexibility in where they work because of the use of mobile communications and computing. Generally the mobile worker has an office building that acts as a base but also works from a variety of other locations such as their home, cafes and other offices (Duffy, 2007). Mobile workers can be found in traditional offices not just agile workspaces. They are defined by the degree to which they work from locations other than their main offices. How this is operationalised for this study will be explained in more detail further on.

The move towards agile working is in part driven by a need to intensify space use and in part from a drive towards greater collaboration and interaction (Oseland *et al.*, 2012). Its benefits for collaboration and interactions have been explored elsewhere (Oseland *et al.*, 2011; Parkin *et al.*, 2006). There is a tendency to focus on the trade-off between interaction and privacy and assume that the intensification of space naturally leads to poorer privacy. However, there are features of agile workspaces that support both increased privacy and improved collaboration. The aim of this study was to focus on perceptions of privacy, crowding and satisfaction to better understand the effect of agile working on this trade-off.

7.1.2 Characterising space to understand privacy and crowding

Studying privacy and collaboration are just two ways of understanding how spatial constraints affect occupant relationships. To understand how space affects occupant relationships it is necessary to characterise key features of the building environment. This is often done in terms of occupant density, partly because it is a key measure of space utilisation. At its simplest, a definition of density is a measure of “a number of units in a given area”, where the area is defined by a fixed length or more tangible limits such as the walls of an office (Cooper & Boyko, 2012). However, there are a number of ways to characterise and conceptualise the spatial environment (Table 7-2).

Table 7-2: The different ways occupant density and spatial constraints are conceptualised.

Experience of densification	Factors	Practical measures to improve experience
	Desire to retreat	Contemplative space
	Desire to control information	Provide a way to stop being overheard or block out distractions
	Desire to control interaction	Do not disturb signals
Crowding	Number of people that a person encounters	Reconfigure buildings so encounters are more selective
Large groups	Building environments for large groups: poor system zoning, group decision making, party to long range effects	Reconfigure building so work groups and environmental zones are smaller

There have been a number of studies that have looked into the effects of density in general and particularly for office spaces. Each of these offer slightly different approaches to characterising the spatial environment according to how it affects interaction between people. Lee (2010) compared typologies of office: enclosed private, shared private, open plan with high cubicles, open plan with low cubicles and open plan without partitions. (Leaman & Bordass, 2000) conclude that it is the number of people in a work group that is important for productivity. (Kupritz, 1998) compares open plan offices with and without partitions. (Sundstrom & Sundstrom, 1986; Sundstrom *et al.*, 1982) studied nine physical parameters: number of enclosed sides, workstations in room, private office, distance to nearest workstation, workstations visible, workstations within 25ft (7.6m), floorspace allowance, distance to common entrance and finally a person’s visibility to supervisor. (Fried *et al.*, 2001) measure the number of co-workers within a 15ft (4.6m) radius. (Valins & Baum, 1973) looked at two different typologies of student resident, comparing 17 room corridors with 3 room suites. This range of approaches indicate that the experience of the spatial environment and its effect on occupant relations cannot be understood using simple metrics of units per given area; instead typologies and features of space should be used instead or as well.

7.1.3 Conceptualising the outcomes of spatial constraints

Sundstrom and Sundstrom (1986) define three separate components to the common concept of privacy: retreat from people, control over information and regulation of interaction. As well as using this conceptual breakdown of privacy (Kupritz, 1998) separates the properties of buildings into field characteristics and barriers. The former, such as corridors, break out spaces and neighbouring desks, intrude on privacy. The latter, such as partitions and doors, are moderators of privacy. These privacy factors and feature types are a useful structure with which to conceptualise spatial experience.

Crowding is used to describe circumstances and consequences where social stimulation becomes stressful. Baum and Epstein (1978) explain the phenomena by using models of attentional capacity. They suggest that overload due to excessive noise, information or the need to make decisions can lead to stress and require coping mechanisms such as withdrawal. The concept of crowding is similar to the need for retreat from people (Sundstrom & Sundstrom, 1986). In their study of college dormitories Valins and Baum (1973) showed that people who experience crowding retreat from social contact. Interestingly this suggests that too much interaction can encourage withdrawal because people experience social overload.

The number of people in a given room, has a particular effect on occupant experience. Leaman and Bordass (2000) associate this with negative consequences because it leads to lack of environmental control. Firstly, because it is difficult to consistently map system zones with prevailing environmental conditions and occupant activity. Secondly, occupants must consider many more people when taking decisions about their environment. Lastly, long distance effects such as glare or distant noise are harder for individuals to deal with. This view associates density with the effect it has on occupant control of building systems.

7.1.4 Hypothesis development

It is evident that there is no simple, unified way of thinking about spatial constraints and density (Table 7-2). Studies conceptualise the density problem differently depending upon their particular goals, none of these studies look at how mobile workers in particular experience privacy. All of these concepts could be moderated by the mobility of the worker. To rationalise this study we focus on privacy, crowding and satisfaction. Henceforth, we develop hypotheses to explore how mobile working and agile workspaces moderate experiences of privacy. Because there is a lack of literature to draw upon the hypotheses have been developed based on what we consider reasonable assumptions, that have been detailed below.

Hypotheses:

H1: Compared with open plan, occupants of agile workspace will experience:

- H1A: less need for retreat because they have a range of spaces to access;
- H1B: less need to control information because they have a range of spaces to access that have improved levels of information control;

- H1C: the same need to control interactions because the workspace will not affect the level of contact with others.

H2: Workers with increased mobility will experience:

- H2A: reduced sensation of crowding and reduced need for retreat because they have less contact with their fellow workers;
- H2B: the same need for information control because they will experience the same set of distractions while in the office;
- H2C: reduced need for control of interactions because they have less contact with their fellow workers.

7.2 Methods

Participants and buildings

This study investigates the effects of agile working on the experience of privacy, crowding and satisfaction. For this, three different typologies of office were identified: traditional cellular offices, with assigned seating, formal meeting rooms and some small open offices; traditional open plan, with assigned seating, formal meeting rooms and a small number of uniform break out spaces; and agile open plan workspace with assigned seating, formal meeting rooms and a large number of varied break out spaces.

Participants for this study came from all seven of the buildings; N = 179 people answered the survey; (N=62 male, N=114 female and N=3 no gender). All of them were 18 years of age or older. Not all participants answered all questions but, because analysis was between participants, incomplete cases were retained. Response rates were about 20±5% except for two outliers of 2% and 77%. Sample size is considered more important than response rate because this study is about differences between typologies not the performance of individual buildings. The sample size in this case was large enough to provide statistical differences between the three typologies being compared.

Buildings C and D both fit the cellular office type described above. Their spaces ranged from private offices to rooms with more than 11 people in them. Across buildings C and D a third of the participants were in offices of greater than 11 people. Buildings A and E were both open plan, with formal meeting rooms and one or two small tables for break out. Buildings F and G were open plan with assigned desks but they also had a large number of varied meeting spaces in addition to formal meeting space. Building F had a large expanse of open comfy seating that was away from workstations, it also had a number of break out spaces closer to workstations containing sofas, chairs and tables. Building G had a variety of booths close to workstations and some touch down desks that could be used instead of a person's primary workstation (although these were increasingly being used by new starters). Office B had a small main room and three private offices, it had predominately unassigned seating; it was excluded from the typology analysis because it did not fit easily into one of the three types.

For this study spatial factors are highly important (Table 7-3). Occupant density varied between 7m^2/per and 14m^2/per(NIA). The local density varied between 3m^2/per and 6m^2/per. Occupant density was calculated by taking the net internal area of the floor plate and the number of workstations (BCO, 2013; RICS, 2007). Local density is taken by sampling a small number of workstations and taking only the space around the workstations required for seating and immediate access.

Table 7-3: Overview of buildings. Showing office type and occupant density.

Building	N (response rate)	Occupier	Typology	Plan	Work spaces per room	Occupant density (NIA)	Local density
A	11 (22%)	Design	Open plan	Shallow	49	7.5	5.2
B	10 (77%)	Academic	Open plan	Shallow	9	8.3	5.9
C	54 (20%)	Academic	Cellular	Shallow	Varies	Varies	Varies
D	30 (16%)	Academic	Cellular	Shallow	Varies	Varies	Varies
E	10 (20%)	Design	Open plan	Shallow	17	14.2	5.7
F	25 (2%)	Charity	Agile	Deep	687	7.3	5.9
G	39 (26%)	Design	Agile	Shallow	50	6.9	3.6

Questionnaire development

The questions probed the different facets of privacy and crowding (Table 7-4). Questions 1 to 8 were about how the office supported different types of activity. Questions 9 to 11 were about occupants' experience of their work area. Question 12 was about overall satisfaction with layout. Questions 13 to 15 were about occupants' behaviour. After this there were three open questions, then demographic questions.

Analysis

The answers to questions 1 to 15 were translated into a linear numerical score. For questions 1 to 11, 1=Not at all, 5=Extremely; for question 12, 1=Dissatisfied, 5= Satisfied; for question 13 to 15, 1=Not at all, 6=Throughout the day. Average scores for each typology were then compared using ANOVA. Often the scores for the agile workspaces were either similar to open plan offices or cellular offices. Where they are similar to one and not the other this has been highlighted.

Table 7-4: Survey questions used for this study.

No.	Question	Possible responses
In general how do your current work arrangements support…		
1	…being able to have confidential conversations?	
2	…working alone?	
3	…working without visual or acoustic distractions?	
4	…being aware of what colleagues are doing?	
5	…unplanned interactions with colleagues?	
6	…being able to work with confidential documents?	
7	…getting away from colleagues?	
8	…controlling who comes to talk to you?	
Rate your personal work area…		
9	…private?	
10	…too close to colleagues?	
11	…crowded?	
12	During the last week how satisfied were you with the layout?	Dissatisfied / A little dissatisfied / Neither / A little satisfied / Satisfied
How often…		
13	…do you try to shut off or get away from your colleagues at work?	
14	…do you need to block out visual and acoustic distractions?	
15	…would you like to control who talks to you?	
16	What do you do to manage these issues?	
17	What conditions, or features, of your office cause these problems?	Open response
18	What conditions, or features, of your office improve these problems?	
19	Please enter your age?	18–24/ 25–34/ 35–44/ 45–54/ 55–64 /65+
20	Please enter your gender?	Male / Female
21	When were you in the building this week?	Mon / Tues / Wed / Thur / Fri
22	Where else do you work?	At home /At other offices /At cafes and other ad hoc places /While on the move/ Other
23	How many people do you share an office with?	Private office / 2–4 / 5–10 / 11+

The degree of mobile working of each participant was characterised in two ways. First by the number of days, that week, that the participant had been at the office. This was translated into a number between 1 and 5 which could be used in a linear regression model. The second way to characterise occupant mobility was by the number of different places a participant worked other than their main office. There were five different alternative locations to choose from, as detailed above. This was translated into a number between 0 and 5 according to the number of other places the participant worked at during the week of the study. For both methods, 15 linear regression models were tested to compare questions 1 to 15 with the level of mobility. This was used to see whether people who were more mobile, had different attitudes and experience than people who were less.

7.3 Results

7.3.1 Results summary for all buildings

Looking collectively at all the offices, generally they were thought to be good for interaction and not so good for privacy (Figure 7-1). People reported that their office space supported interaction and awareness of colleagues. Offices were reasonably supportive of confidential conversations, confidential documents and working alone. They were not so good at reducing visual and acoustic distractions and being able to get away from colleagues. They were particularly bad for controlling interactions.

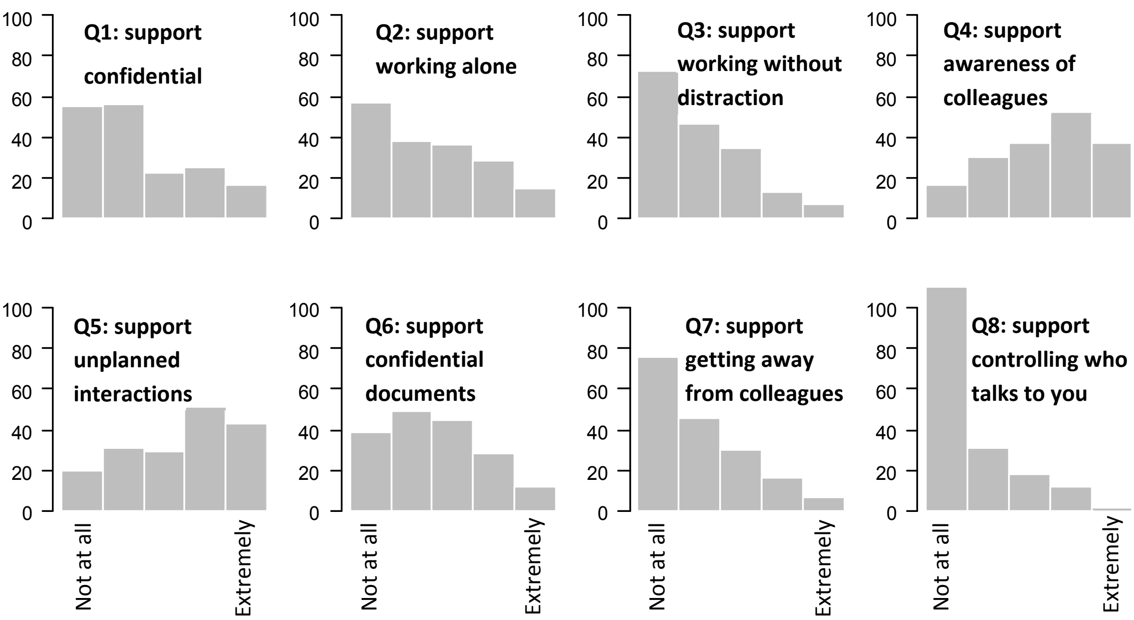


Figure 7-1: How participants from all offices felt different behaviours were supported.

Participants had a mixed opinion of their work area (Figure 7-2); they thought it was neither private nor too crowded. Their concept of privacy was not opposite to crowdedness; most people rated their work area both unprivate and uncrowded. Neither did participants think they were too close to colleagues. Linear regression models confirm that people's response for too close, crowded and satisfaction with layout were all highly correlated; however, their perception of privacy was independent of these three responses. This suggests that whereas the perception of crowding is closely related to the number of people in a place the perception of privacy is not.

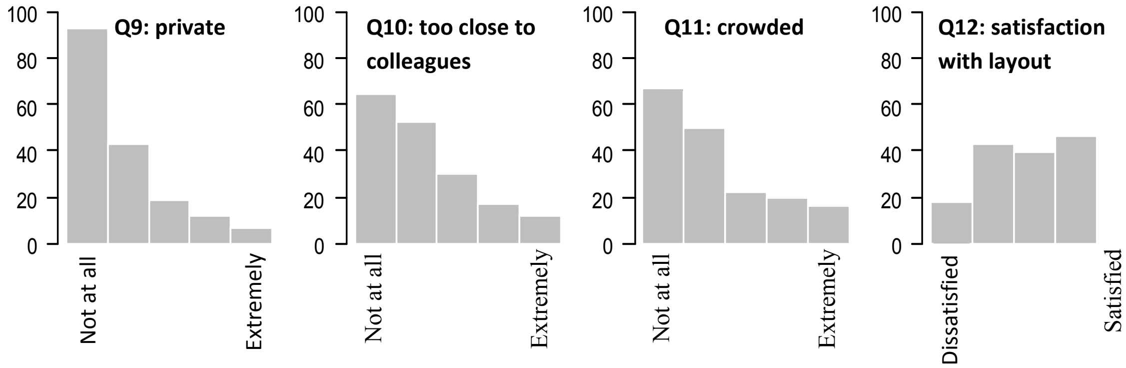


Figure 7-2: How participants from all offices felt about their personal work area.

Figure 7-3 shows the frequency with which participants would like to carry out different types of privacy behaviour. People feel that they do not need to get away from colleagues as often as they would like to block visual distractions and control who comes up to them. The need for retreat is felt less strongly than the need to control distractions and interactions.

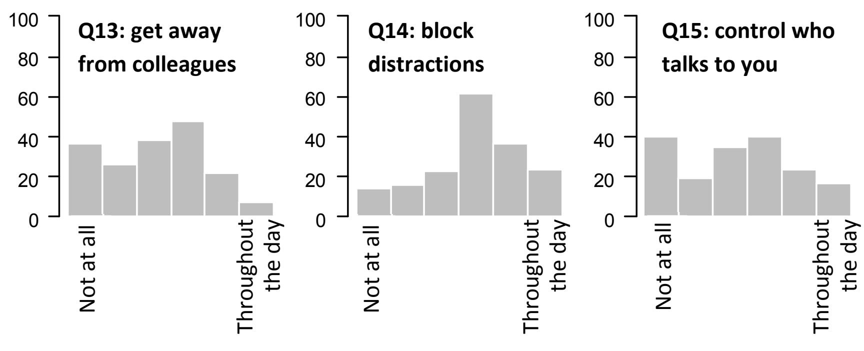


Figure 7-3: How often participants from all offices need to carry out privacy behaviours.

7.3.2 Office typologies

Table 7-5 shows the different responses to questions 1 to 15 for the three different office typologies. For each question an ANOVA test was done to see if the averages were different for different typologies. When two scores are similar to each other and different from the other one, the two similar scores are highlighted in grey. For this a p-value of <0.1 was used instead of 0.05 because several tests were just short of the 0.05 significance level and the purpose of the highlighting is to show the similarity and differences between typologies as well as the significance of individual results.

Table 7-5 shows if agile workspaces had a score similar to cellular offices or to traditional open plan offices. Overall it can be seen that agile workspaces are unique. They are similar to cellular offices for questions related to control of information (Q: 1, 3, 6, 14). They were similar to traditional open plan offices for questions related to control of interactions with colleagues (Q: 4, 5, 8, 15). All types of office were roughly the same in terms of retreat from colleagues (Q: 2, 7, 10, 13).

Agile workspaces were felt to be particularly good for having confidential conversations and as good as cellular offices for working with confidential documents. They were also considered to be as good as cellular offices for working without visual and acoustic distractions. However, they were considered less private than cellular offices. Interestingly people in open plan offices felt less desire to control who talks to them than people in cellular offices.

In summary, all types of office were roughly the same in terms of retreat from colleagues (Q: 2, 7, 10, 13), which is counter to H1A. Agile workspaces are perceived as better than open plan offices for control of information (Q: 1, 3, 6, 14); this supports H1B. They were perceived as similar to traditional open plan office for control of interactions with colleagues (Q: 4, 5, 8, 15), which supports H1C.

Table 7-5: The experience of privacy, crowding and satisfaction in different types of offices (1=Not at all, 5=Extremely or Many times a day).

Experience of density	Cellular and small office	Open plan	Agile workspace	F-test	MSE	p-value
	M=2.31 (*SD*=1.41) 95%*CI*=0.26	2.00 (0.83) 0.32	2.71 (1.28) 0.28			
	2.59 (1.51) 0.28	2.05 (0.94) 0.36	2.58 (1.11) 0.24			
	2.17 (1.84) 0.22	1.52 (0.87) 0.33	2.13 (1.12) 0.25			
	3.10 (1.33) 0.25	3.57 (1.21) 0.46	3.70 (1.09) 0.24			
	3.02(1.39) 0.26	3.48 (0.93) 0.35	3.76 (1.24) 0.27			
	2.62 (1.37) 0.25	2.05 (0.92) 0.35	2.74 (1.03) 0.23			
	2.07 (1.33) 0.25	1.57 (0.75) 0.28	2.16 (1.01) 0.22			
	1.83 (1.18) 0.22	1.40 (0.68) 0.26	1.48 (0.81) 0.18			
	2.17 (1.37) 0.25	1.43 (0.68) 0.26	1.58 (0.73) 0.16			
	2.26 (1.31) 0.24	1.90 (1.09) 0.41	2.13 (1.06) 0.23			
	2.33(1.45) 0.27	1.90 (1.34) 0.50	2.18 (1.08) 0.24			
	2.49 (1.00) 0.19	2.88 (1.02) 0.39	3.20 (0.93) 0.20			
	2.96 (1.45) 0.27	3.05 (1.40) 0.53	3.16 (1.48) 0.33			
	3.96 (1.49) 0.28	3.90 (1.30) 0.49	3.85 (1.41) 0.31			
	3.58 (1.58) 0.29	2.67 (1.53) 0.58	2.87 (1.66) 0.36			

7.3.3 Time spent in office

People who come into the office fewer times in a week; generally rate the features of their office, and experience their office, the same as those who come in more during the week (Q: 1–12). Linear regression models between the time spent in the office (1–5 days) and these questions (1=Not at all, 5=Extremely) had no significance.

However, as seen in Figure 7-4, linear regression models between the time spent in the office (1–5 days) and the need for privacy behaviours (1=Not at all, 6=Throughout the day) show some correlation. Mobile workers have different requirements for privacy behaviours (Q: 13–15). The mobility of the worker does not affect the need to get away from colleagues (H2A) neither does it affect how often they wish to block acoustic and visual distractions (H2B). However, there is a clear correlation between mobility and the degree to which control of interactions is needed (H2C) (Table 7-6). These results show that the less a person is in the office, the more they want to control who approaches and interacts with them. This result goes against H2A, supports H2B, and is the opposite effect than predicted by H2C. This suggests that mobile workers find it difficult to adapt to the office when they are there.

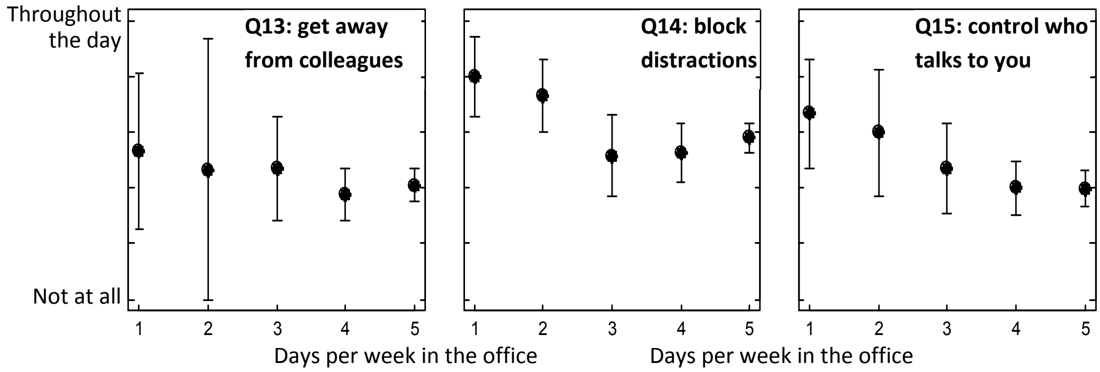


Figure 7-4: Privacy behaviours changes for people who spend fewer days in the office.

Table 7-6: Linear model between days in the office and privacy behaviours.

Measure	a0	a1	*p*-value	R^2
get away from colleagues	3.59	0.12	0.31	0.007
need to block out distractions	4.40	-0.12	0.28	0.008
like to control interactions	2.30	-0.27	0.03	0.03

7.3.4 Number of alternative work locations

People who worked in a greater variety of (non-office) locations rate the features of their office the same as those who come in more during the week (Q: 1–12). Linear regression models between this measure of mobility (0–5 other places worked at during the week) and measures of experience of privacy and crowding (1=Not at all, 5=Extremely) have no significance.

However, as Figure 7-5 shows, people who work elsewhere do have different requirements for privacy behaviours (Q: 13–15). This was confirmed by testing the linear correlation between measure of mobility (0–5 other places worked at during the week) and privacy behaviours (1=Not at all, 6=Throughout the day). There is a significant correlation between mobile working and the desire to get away from colleagues and control interactions (H2A and H2C). There is not a strong correlation between mobile working and wanting to block distractions (H2B)(Table 7-7). This supports H2B, and suggests an opposite effect than that predicted by H2A and H2C. This suggests that mobile workers experience differently the perceptions of interactions but not the perception of distractions from environmental stimuli.

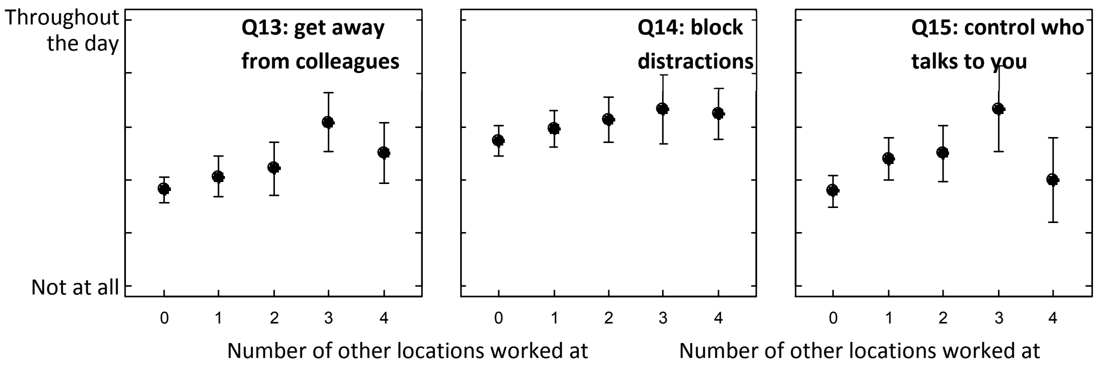


Figure 7-5: Privacy behaviours changes for people who work in a greater number of places.

Table 7-7: Linear model between number of work locations and privacy behaviours.

Measure		a0	a1	*p*-value	R^2
	get away from colleagues	3.59	0.12	0.01	0.04
	need to block out distractions	4.40	-0.12	0.10	0.02
	like to control interactions	2.30	-0.27	0.004	0.05

7.3.5 Possible co-correlations

A linear regression model showed that there is a highly significant negative correlation between the two measures of worker mobility ($p<0.001$). An ANOVA showed that different typologies had no significant difference in mean days in the office ($F(2,137) = 0.7$, $MSE=0.76$, p-value = 0.50) and a nearly significant difference between the mean number of other places worked ($F(2,215) = 2.0$, $MSE=0.94$, p-value = 0.14)).

Age, gender and work role were investigated to see if they had a significant effect on any of the averages recorded. They all showed an effect on Q8, while age also had an effect on Q9. Gender and work role had no significant effect on the number of days in the office but both had a significant effect on the number of other places the person worked at. Age had no significant effect either on days in the office or other places worked at.

7.3.6 Field characteristics and barriers

Field characteristics that exacerbate problems

Participants were asked what conditions and features of their offices caused privacy and crowding problems. Environmental noise was reported as a problem, in particular external vehicular traffic and a lack of background noise to mask activity in the office. Noise from neighbouring areas was also a problem, including: toilets, corridors, tea points, break out space and reception areas.

Forms of communications were a problem. Too many phone calls bothered some people. People shouting across the office was mentioned, as were people with particularly loud voices. Finally, some people felt that work cultures, interactions and “friendly offices” contributed to a lack of privacy.

Finally, particular building features were seen as problematic, including, lack of sound insulation and sound absorption material, the co-location of different types of work activities, lack of space for private conversations and the size of desks. Sight lines were another problem mentioned: looking away from the group meant that one’s computer screen was overlooked, looking into the group meant one was distracted by goings on.

Field characteristics that improve the problem

Having somewhere else to go, such as high-sided seating and quiet rooms, improved the situation. So did the ability to signal to colleagues when distractions were unwelcome.

Coping mechanisms

There were many different coping mechanisms. These included changing one's environment, either by altering it such as using blinds or closing windows or moving to another space entirely; signalling to other people that interruptions were not wanted, either by telling people directly or using headphones; changing oneself, by going out for a walk to take a break, making oneself "just concentrate harder", or taking calls away from their usual workstation. Finally people schedule work time so that difficult work was done during quiet times, such as the early morning or evening or in a quiet place such as at home.

Not all these mechanisms can always be employed though. Open door policies were reported as problematic. In some offices it is frowned upon to listen to music through headphones. Other people identified a lack of alternative space to work from. All of these stopped people employing their preferred coping mechanism.

Comparing features across typologies

Table 7-8 compares the presence and relevance of different features across the three office typologies. They are categorised according to those that worsen building performance, those that improve building performance and the techniques used to manage privacy. Their relevance to the different office typologies studied has been recorded on the right hand side of Table 7-8, relevance was judged by the researcher from their knowledge of the buildings studied and the participants' responses to the open questions. The greater the number of stars a feature is given the more relevant it is considered to be for a particular typology.

The responses suggest that some of the features distinguish between typologies. These are items such as communication methods that is a problem for the open plan and the agile space but not for cellular offices. Another such feature is having high-sided seats in meeting areas and alternative work locations. These features can contribute to the definition of typologies (in this case cellular offices and agile workspace respectively). Other features are equally relevant to all typologies. These are items such as external vehicular noise and scheduling work for specific times of the day. The features that are equally relevant to all typologies can be used to open up sub-typologies of offices. For instance, open plan offices with external vehicular noise is a different sub typology from open plan offices without external vehicular noise.

Table 7-8: Features that affect the perception of privacy and crowding.

	Relevance of feature to given type of office ("*"Low "**"Medium "***" High)		
Features	**Cellular**	**Open plan**	**Agile**
Poor field characteristics			
External vehicular noise	**	**	**
Lack of masking noise	***	**	**
Internal noises: toilets, corridors, tea points, break out space, reception area and co-location of different types of work activities	**	***	***
Communication methods: loud voices, shouting, phone calls, overly friendly	*	**	**
Physical characteristics: sound insulation and absorption material. A lack of space for private conversations. Size of desks. Sight lines.	**	***	**
Good field characteristics			
Alternative locations to work from	**	***	*
Methods to signal when privacy is needed (alternative locations, signage)	***	**	***
High sided seating	*	*	**
Coping mechanisms			
Changing the environment (opening and closing windows, blinds and doors)	***	**	**
Changing oneself (taking a break, taking phone calls out of the office)	**	**	***
Signalling need for privacy	***	**	***
Scheduling work for specific times (such as end or beginning of the day)	**	**	**

7.4 Discussion

This study raises a variety of points about agile working. It has shown that agile workspace is a distinct typology; the experience of which is different from traditional open plan and cellular offices. This differentiates it from the various typologies identified by other authors (Kupritz, 1998; Lee, 2010; Sundstrom *et al.*, 1982). We have shown that these typologies are defined by characteristic features that are unique to them. There is also a range of typology crossing features that can be used to define sub-typologies. These results extend the work on typologies carried out by other authors because it suggests that a knowledge of features and users are required as well as typologies. In addition to the findings about typologies it has been shown that mobile workers actually have a greater desire for privacy than their less mobile colleagues.

Mobile working was predicted to not change occupants' need for information control while reducing their need for control of interactions and their need to retreat from co-workers. This seemed plausible because worker mobility would provide opportunities for the latter two. The hypothesis held for the need for information control. However, contrary to what was expected mobile workers have an increased need for control of interaction and need to retreat. This suggests that mobile workers tend to feel the negative effects of density more than stationary workers. This could be because those who work at the office less often find it difficult to adjust to the high levels of interaction that occur in offices, or that their fleeting appearances encourage a greater number of disturbances. If this is the case it would have important impacts for how offices should be designed. Offices where mobile working is encouraged may wish to improve methods for controlling interactions.

However, the causation could be opposite, and people who have a worse experience of privacy may be driven to work away from their office more. This behaviour was reported a number of times in the open response question, when people described working at home and outside office hours as one way that they managed privacy issues. It is a serious problem if distraction and lack of privacy are forcing people out of their place of work.

It should be noted though that the R^2 correlation coefficients of the regression model were low (Table 7-6 and Table 7-7). So even though there was a significant relationship found, the results here should be used with some caution. It can only be said to apply over large groups of occupants and there may be other, as yet unknown, factors that could confound the relationship observed.

Another weakness is the measure of worker mobility used here. Firstly most of the people surveyed had assigned desks therefore their mobility is not as high as it could be. Secondly for the people surveyed their mobility varied with a range of other factors therefore it is possible that findings may be attributable to a co-factor such as job role or organisation type. Future investigations should prioritise inclusion of highly mobile workers to further test their experience of density and ensure other factors are more tightly controlled.

The results here support the idea that agile workspaces are a distinct typology separate from traditional open plan and cellular offices. The experience of privacy and crowding for their occupants has some aspects of both open plan and cellular offices. They are similar to cellular offices because they improve the ability to work with private documents and free from visual and acoustic distraction; both of these are forms of information control. They are similar to open plan offices because they improve awareness of colleagues and enable signalling to control unplanned interactions; these are both forms of interaction control. Finally, they are about the same as both cellular and open plan; in the degree to which occupants can get away from colleagues when greater focus is needed. Although for many questions about getting away from colleagues, agile workspaces are rated better than either cellular or open plan offices, the difference is not quite significant. In summary it would seem that agile workspaces are similar to open plan regarding their control over interactions, similar to cellular in terms of control of information and almost unique in terms of their ability to provide quiet places away from colleagues. Apart from the lack of significance in one of these conclusions the results confirm the hypotheses (H1) about the agile workplace typology.

Agile workspaces are perceived as different because they have distinctive features that the two conventional typologies do not. They make it easy to leave one's desk to make phone calls and to have small meetings. Combined with specially designed furniture this results in less noise and disturbance for those engaged in solitary work. They also provide somewhere else to go to work as required. This not only allows people to avoid sources of distraction but sends a clear signal that they do not wish to be disturbed. It is these features that make the experience of agile workspaces different from the other typologies.

A weakness of this study is the applicability of typological profiling, drawn from a sample of just six buildings. In the typological analysis there were only two buildings for each type. This gives a reasonable possibility that some other unique factors may be able to explain the differences seen between the offices. In addition the cellular offices studied here had some open plan elements; although they did appear to offer their occupants a distinctly different experience. However, generally the two conventional typologies formed extreme cases, and agile workspaces were similar to either one or the other. There was no score where agile workspace was the odd one out and the other two types had similar scores. This is a very particular pattern and makes it less likely that other factors would line up in such a way. However, the range of organisational cultures observed in the six buildings was diverse. It could be these differences that are driving the differences in experience of privacy.

This work also shows that the division of privacy into three primary elements (of information control, interaction control and withdrawal (Sundstrom & Sundstrom, 1986)) is useful and supports analysis and understanding. However, it should be considered whether the category of information control could be further split into distractions from the real world (environmental noises and movement) and the virtual world of computers (emails, electronic alerts and notifications). The strong correlation that we found between feeling crowded, thinking yourself too close to colleagues and satisfaction with layout suggests that the concept of crowding (Baum & Epstein, 1978) is similar to the concept of need for retreat from people (Sundstrom & Sundstrom, 1986).

Some of the features of agile workspace cut across all three of these primary elements; for example having an alternative location to work from, can provide both a place to withdraw to and allow control of interactions. While some features of agile workspaces, such as high-backed chairs, help to control information flow but do not necessarily allow for improved control of interaction or need for withdrawal. Agile workspace is composed of a number of unique features, each of these affects a different element of privacy; when combined these features set agile workspace apart from conventional offices. To measure the physical configuration of an office a sensor system must be able to recognise component features and typologies and also have an appreciation of how they inter relate.

Having agile space does not change the density of workstations or the features of the immediate vicinities of people's desks. It changes an area remote to where people work, it changes how people work. That this can have an effect on experiences of privacy and crowding shows that a density metric is not sufficient to understand privacy requirements. To fully understand the experience of a spatially constrained office it is necessary to understand the configuration of an office and what it enables users to do. This suggests that any sensor system would have to have a wider appreciation of office dynamics and not just measure the physical attributes. There is a need to link changes in spatial configuration with changes in behaviour and occupant experience, to understand how they are part of a larger whole.

There will always be financial pressure to increase occupant density. Generally this is considered a bad thing for peoples' experience. Nobody likes the idea of being crammed into a building, closer and closer to one's neighbour. However, it has been shown that this all important space efficiency metric is not the only factor that is important for privacy, crowding and satisfaction. By understanding important and salient design features it may be possible to alleviate some of the negative consequences of density while still reaping the benefits.

7.5 Conclusions

This study has answered the specific hypotheses and it has also contributed to knowledge about the relationship between measurements of density, spatial constraints and feelings of privacy, crowdedness and satisfaction. The experience of privacy and crowding in agile workspaces is distinct. They are similar to cellular offices when considering the perception of information control, whereas they are similar to open plan offices when considering the control of interaction. This suggests that agile workspaces renegotiate the trade-off between interaction and privacy. They improve interaction, as documented elsewhere (Ramidus, 2015), and improve aspects of privacy. We have shown that they do this because they offer features, such as a variety of space, that can be used for both private work or collaborative endeavours. This suggests that designers can use specific interventions, such as ensuring space for private conversations and alternative space to work from, to reduce some of the negative experiences of density.

Occupants with increased mobility were found to have an increased desire for privacy. This was counter to what was expected. It suggests that either privacy issues are pushing people to work out of the office or that increased mobility increases the need for privacy in the office. Both of these suggest that privacy and mobility are intimately linked and that design for mobile workers should take greater account of crowding and privacy issues, especially the need for control of interactions. However, the measures of worker mobility used in this case could be improved.

It is very interesting that agile workspaces improve privacy but mobile working makes it worse. This suggests that, to get the best out of agile workspaces, close attention should be paid to the improvement of privacy in the office. Firstly, to ensure that agile workspaces do not encourage counterproductive over mobility, and secondly, to ensure that side effects of mobile working are alleviated.

This work reiterates that density metrics are not the only important factor for understanding the experience of privacy and crowding. Typologies and features of the office are also important. Any sensor system must be able to both identify features and typologies, and further to this, combine user data to build up a complete picture of the experience of privacy.

Chapter 8

Uncovering the psychological factors that shape thermal experience

Previously

The previous studies have narrowed in focus from buildings, to multisensory environments, to privacy, here we look at thermal experience. At the same time the studies have looked at using sensors to evaluate background levels, complex characterisations and then the underlying thought processes that shape environmental experience.

This chapter

Here we look at another aspect of the thought process, we take appraisal theories of emotions and show how they can be used to understand the underlying psychological processes that shape an occupant's thermal experience.

The physical environment leads to a thermal sensation, this is evaluated by building occupants. Commonly, thermal sensation is expressed in terms of hot, warm, neutral, cool and cold; while thermal evaluation is conceptualised in terms of comfort or satisfaction. For this study, we asked people to recall a thermal event and choose how they felt from ten different emotions. We then successfully used four different psychological factors to predict which emotion was reported. This is a novel method for accessing an occupant's subjective experience of IEQ and a systematic method to analyse the psychological factors that affect subjective experience.

Next

The results of all four studies are drawn together in a discussion and conclusions are drawn.

See also

Keeling, T., Roesch, E., & Clements-Croome, D. (2016). Cognitive appraisals affect both embodiment of thermal sensation and its mapping to thermal evaluation. Frontiers in Psychology, 7.

Keeling, T., Roesch, E. B., & Clements-Croome, D. (2016). The psychological factors that affect the mapping of thermal sensation to thermal evaluation. 9th Windsor Conference

8.1 Introduction

8.1.1 Thermal environment, thermal sensation, and evaluative response

Treating thermal comfort as a problem of *energy balance* lends itself to building design practices based on physiology. However, adaptive comfort theory (de Dear & Brager, 1998; Nicol & Humphreys, 1973) contributes scope for a range of *psychological factors* to be considered as well. It indeed seems intuitive that some part of thermal comfort involves the occupants' thermal expectations and preferences, and this in turn may be constitutive of the overall experience (Clements-Croome, 2013b). The aim of the present study is to reveal a mechanism whereby the thermal environment is perceived and internalised by occupants and to show that this evaluative process shapes thermal experience.

For the purpose of the present investigation, thermal experience is broken down into three components. First, physical environments, such as air temperature, air movement, etc., constitute the medium within which occupants operate. Secondly, thermal sensation is the interface between the occupant and the environment, which is predominately described using the ASHRAE thermal sensation scale which runs from cold, through cool, neutral, warm, to hot (ASHRAE, 2010). Thirdly, an occupant's evaluation of their thermal environment can be used to describe the process of reflection upon the sensation. Conventionally evaluation criteria of satisfaction, comfort and acceptability are used.

We look at the psychological factors that shape how thermal sensations are perceived and evaluated, by grounding our investigation in the field of emotion psychology. Particularly, we are interested in the way that four psychological factors ("appraisal dimensions") may shape the criteria of acceptability, comfort, thermal sensation and the ensuing emotional experience, which result from the exposure to a particular thermal environment, or thermal event. We aim to render explicit the relationship between the occupant's psychology and their thermal experience, and hope to inform building design practices by situating occupants at the centre of the space they occupy.

8.1.2 Models of thermal comfort

Models of thermal comfort attempt to predict evaluation or sensation dependent upon the physical environment. For instance, both the *energy balance* and *adaptive comfort* approaches relate the indoor thermal environment to evaluation (of satisfaction and comfort) (ASHRAE, 2010; de Dear & Brager, 2001; Fanger, 1970). The universal thermal climate index relates outdoor thermal environment to thermal sensation (Fiala *et al.*, 2012). These theories focus on the relationship between thermal environment and either thermal sensation or thermal evaluation. In their basic usage, they overlook processes that map a person's thermal sensation to their thermal evaluation (Figure 8-1).

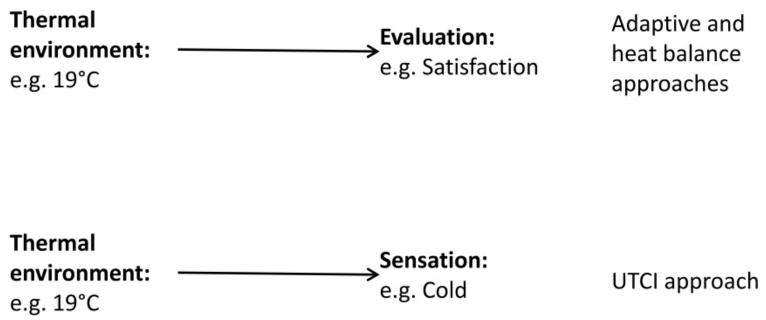


Figure 8-1: Thermal models tend to focus on the thermal environment and either sensation or evaluation. They tend to overlook the relationship between sensation and evaluation.

Physiological models of thermal experience describe the energy flows within the body. They split the body into several layered sections, each with different thermal properties, which are used to predict the energy balance and temperature throughout the body (Fiala *et al.*, 2012; Schellen *et al.*, 2013). Then by understanding these body temperatures and their rates of change, thermal sensation can be predicted (Fiala *et al.*, 2012; Kingma *et al.*, 2012). This still leaves the problem of relating a given thermo-physiological state to an evaluation of the thermal environment. Most often, the above mentioned theories will assume that thermal neutrality is desired and equates to maximum comfort (Fanger, 1970).

Alliesthesia provides one explanation why a neutral thermal sensation, or any other single thermal sensation, will not always lead to the same evaluation. As such, it provides a theoretical approach to understanding the relationship between sensation and evaluation. It suggests that when a person is overheated they will find a cold sensation pleasant, whilst when a person is overcooled they will find a hot sensation pleasant (Cabanac, 2006; Parkinson & de Dear, 2015). However, alliesthesia relies on a physiological approach to explain the mapping between sensation and evaluation. In contrast, we aim to demonstrate a psychological approach.

A final perspective pertains to the psychological effects that certain environments may have on individuals, yielding particular states (Farshchi & Fisher, 2006); in the field of psychology, embodied cognition, which posits that cognition is shaped and influenced by the bodily experience of the environment, make radical propositions. It has been shown, for instance, that experiencing physical warmth promotes interpersonal relations (Williams & Bargh, 2008) and experiencing social inclusion can affect a judgment of temperature and desire for hot and cold experiences (Zhong & Leonardelli, 2008). Secondly, moral decisions have been shown to affect temperature perception (Taufik *et al.*, 2015). Taken together, these findings suggest psychological factors can affect bodily sensations directly.

In the work presented here, we are interested in the overall experience of thermal comfort. Emotion psychology bridges the psychological antecedents of an event to the unfolding of psychological and physiological responses to that event. In the field of building design, adaptive comfort theory is the theoretical tradition that provides the most insight into psychological factors, and we therefore seek to enhance this understanding of occupants' experience with insight from psychology.

8.1.3 Appraisal theory: factors that affect the evaluation of sensations

A fundamental question in the field of emotion psychology concerns the fact that two people may be presented with the same situation and yet have different subjective experiences. A growing body of results suggests that the appraisal of the situation mediates the sensation and the ensuing evaluative response (Arnold, 1960; Scherer *et al.*, 2001) Figure 8-2. It is this subjective appraisal process that influence and shapes the unique emotional response to a particular stimulus, giving rise to a wide range of emotions. In the context of thermal experience, two people can feel the same temperature, but evaluate the situation differently depending on whether it is appraised as conducive or obstructive to their respective needs. For instance, two people could be in a cold office, and one may feel happy because the temperature wakes them up and creates the optimal conditions for work, whereas another person could feel upset because the cold sensation disrupts their ability to focus.

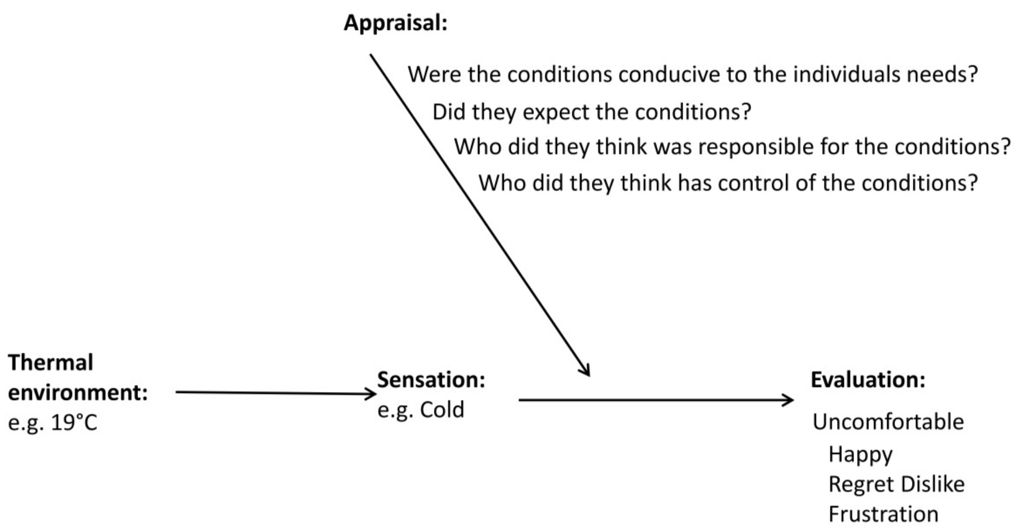


Figure 8-2: Appraisals mediate how sensations are evaluated.

The example above exposes the relationship between appraisals and the evaluation that follows. In this example, a single appraisal dimension of conduciveness is used to evaluate a thermal situation. One person appraises the situation as conducive to their goal and experiences positive emotions, while the other appraises the same environment as obstructive and thus experiences negative emotions. These appraisal processes occur at a subconscious level, which influences the overall experience. Appraisal theorists attempt to characterise the quality of relevant appraisal dimensions and make predictions for the ensuing emotions (Arnold, 1960; Scherer *et al.*, 2001).

We propose to use appraisals as proxies for understanding how participants' past experience will affect their conceptualisation of a given environmental stimulus or scenario. This experience is reduced to a limited number of fixed appraisals, and one of the simplest appraisals is whether a stimulus is consistent with a person's motives and desires or not; if it is, then the resulting emotion is likely to be positive, if not, then the emotion is likely to be negative.

Further appraisal dimensions can be used to predict which positive or negative emotions will be experienced. For instance, another common appraisal is what or who is responsible for the cause of the experience. If a person appraises that they are themselves responsible (for a negative outcome), the theory predicts they will experience regret. If someone else or unavoidable circumstances (e.g. the weather) are believed to be the cause, then anger, frustration or resignation would be experienced. Together, these appraisal dimensions can help predict specific emotions (Scherer *et al.*, 2001).

The value of appraisal theory for the field of building design is that it provides a framework to understand how people's conceptualisation of a situation affects their experience. This sheds light on the mapping between sensation and evaluation. Four appraisals, which are implicit in adaptive comfort theory and explicit in appraisal theory, may be useful to our aim. These are goal conduciveness, causality for the situation, perceived control, and expectation (Roseman, 1996; Scherer *et al.*, 2001; Smith & Ellsworth, 1985). Used together they predict a range of positive and negative emotions (Table 8-1). We suggest that these four appraisals are similar to concepts that have been found to be important to the adaptive theory of thermal comfort. In the next section, we draw on the above-mentioned theoretical traditions and review four hypotheses we formulated to explore the mediating effect of appraisals on the ensuing experience of thermal comfort.

Table 8-1: Emotions mapped to different appraisal combinations (derived from Roseman, 1996; Scherer, 1999).

		Goal conducive		Unconducive	
		Expected	Unexpected	Expected	Unexpected
	C			Resigned	Frustrated
	O			Anxious	
	S			Indifferent	
	C			Dislike	
	O			Anger	
	S			Dislike	
	C				
	O				
	S				
Respons-ibility	Control				

8.1.4 Hypotheses

We focus our investigation on four psychological factors that are present in both Adaptive Comfort theory and the Appraisal theory of emotions, either implicitly or explicitly, and on related effects over thermal experience. The purpose of this comparison is to study the predictions from both sets of theories and highlight aspects that could be operationalised in design practice. The psychological factors of interest here relate to the information processing units that may serve in the evaluation of a given thermal environment by a given occupant. Although it is believed that such evaluations may be performed over continuous sets of criteria, we restrict our investigation to discrete, extreme situations to formulate working hypotheses.

Conduciveness: relates to the extent to which a given thermal event will serve or obstruct an occupant's goal. High conduciveness implies that the event supports the occupant's present goals, whereas low conduciveness implies that the event does not support or even hinders their goals in some ways.

Causality: relates to the extent to which a given thermal event has been caused by either unavoidable circumstances, the occupant themselves or other occupants. By unavoidable circumstances, we mean natural conditions, e.g. a sunny day, or changes in the environment that affect occupants, e.g. a malfunctioning radiator. An example of a situation caused by the occupant themselves or others may be the opening of a window, or a voluntary change in the setting of the thermostat (Leaman & Bordass, 2007).

Perceived control: relates to the extent to which the occupant perceives they have control over their environment (de Dear & Brager, 1998). This aspect is particularly relevant, because practical provisions are formulated in building design to recommend the number, type and access mode for such control interfaces. For obvious reasons, the amount of control available will vary depending on the environment, and we expect a wide distribution of responses.

Expectations: relates to the extent to which the occupant was expecting a given thermal event (de Dear & Brager, 1998; Ole Fanger & Toftum, 2002). High expectancy means that the occupant was expecting the event to occur, low expectancy that they were not expecting it.

We thus formulate the following predictions, which drove the elaboration of our questionnaires and the ensuing analyses of the data. In our interpretation of the results, we compare the predictions from both sets of theories (see Table 8-2).

Table 8-2: Summary of hypotheses.

Models / Hypotheses	Adaptive Comfort theory	Appraisal theory of emotions	Ensuing affect and emotions
1) Conduciveness	High → Comfortable Low → Uncomfortable	High → Neutral Low → Cold	High → Joy, Pleasure Low → Displeasure
2) Causality	Circumstances → Comfortable Others/Self → Uncomfortable	Circumstances → Neutral Others/Self → Too hot, too cold	Circumstances → Resignation, anxiety Others/Self → Dislike, anger
3) Perceived control	High → Comfortable Low → Uncomfortable	High → Neutral Low → Too hot, too cold	High → Anger, anxiety Low → Resignation, frustration
4) Expectations	High → Comfortable Low → Uncomfortable	High → Neutral Low → Too hot, too cold	High → Resignation Low → Frustration

8.2 Methodology

Participants and buildings

As part of a wider field study focusing on evaluating the relationship between environmental factors and psychological experience, occupants of seven office buildings responded to our survey (N=166). The wider field study consisted in the monitoring and recording of environmental factors during a typical work day. The set of buildings was constructed so as to offer a wide range of heterogeneous environments (open space, closed offices, etc). The sample size is similar to other appraisal studies (Folkman & Lazarus, 1985, N=136-189; Roseman, 1996, N=182; Scherer & Ceschi, 1997, N=112). Respondents were a range of ages and genders (Table 8-3) and from seven different buildings (Table 8-4). Participant were rewarded with a snack of their choice. The study was approved by the University of Reading Ethics Committee, in accordance with the Helsinki Declaration of 1975, as revised in 2000. Written consent was obtained from participants.

Table 8-3: Summary of participants.

Demographic	Count
Total number of participants	166
Female	105
Male	57
Undisclosed	4
18–34 years	84
35 years and over	77
Undisclosed	5

Table 8-4: Overview of buildings. NV= naturally ventilated, MM= Mixed mode, AC =fully air conditioned.

Building	N (resp.)	Occupier	Typology	Plan	HVAC
A	9 (18%)	Design	Open plan	Shallow	MM
B	9 (69%)	Academic	Open / cell	Shallow	NV
C	46 (17%)	Academic	Open / cell	Shallow	NV
D	29 (15%)	Academic	Open / cell	Shallow	MM
E	9 (18%)	Design	Open plan	Shallow	NV
F	25 (2%)	Charity	Open plan	Deep	AC
G	39 (26%)	Design	Open plan	Shallow	NV

Questionnaire development

Tapping into the subjective experience of an individual is a major challenge, because the mere attempt to ask a question is likely to disrupt the unfolding experience altogether. To eliminate this disruption, we chose to use a recall survey, in which participants were asked to recall a salient event in their recent past and to answer a number of questions about that event. This also allows us to access a much greater range of experiences than if it was necessary to be present at the time of the event, measuring the thermal environment as the experience unfolded. The reliance solely on user reported data, with little or no measurement of the physical nature of the stimuli, is common in psychology (Fontaine *et al.*, 2007) and is appropriate here because of this study's focus on the relationship between participants' sensation and their evaluation.

The recall survey started with a prompt for the participants to recall an event in detail. To do this they were asked to:

> *"Imagine a specific time when you have been aware of the temperature in your office and it has given rise to strong feelings. Describe what happened leading up to the event and how you felt."*

After this, a number of questions were asked about each of the four appraisal dimensions. Details of the questions and how they were combined can be found in the appendix. These were used to understand:

- Whether the participant felt the event was conducive to them (appraisal 1);
- Who or what they thought caused the event (appraisal 2);
- Who or what they thought controlled conditions in their office (appraisal 3);
- How much they had expected the event to happen (appraisal 4).

To finish the survey, there was an open response to describe feelings and a closed list of emotions to choose from: frustrated, resigned, dislike, indifferent, angry, anxious, liking, joyful, regretful, proud, or, none of these. Then three questions were asked about the participant's thermal experience, using a thermal sensation scale, a comfort scale and an acceptability scale.

Analyses

We examined whether appraisals have an effect upon emotions, acceptability, comfort and sensation. The model used compares the likelihood of a particular evaluation, dependent upon the score on an appraisal dimension. The most appropriate statistical model for this is a logistic regression model. This allows prediction of the presence or absence of a given factor (a set of emotions or acceptance) dependent upon an ordered factor (the appraisal dimension). An extension to this model is the ordinal logistic model, which predicts the likelihood of achieving a given level of comfort or sensation depending on an appraisal dimension.

Equation 1 shows the logistic regression model. The model comprises a linear function and a link function. In the same way as standard linear models, the coefficients are derived so as to maximise the fit of the model. The link function $m()$ transforms the linear model to a probability of success, π_i bounded between one and zero. There are several functions that fit this criteria, the most commonly used are the “logit", "probit", "cauchit", "log", and the "complementary log log”(McCullagh & Nelder, 1989). In this study we compare all possible link functions and selected the best fitting model.

$$\pi_i = \mathrm{m}(\beta_0 + \beta_1 x_i + \beta_2 x_i + \ldots) \qquad \textbf{Equation 10-1}$$

To compare logistic models, we used a chi square test of the deviance accounted for by the regression model. For both the logistic and ordinal logistic model we also characterised the model by the likelihood that the regression coefficients (β_i) are non-zero.

8.3 Results

8.3.1 The experiences reported

Sensation, comfort and acceptability

Participant were asked to report their thermal experience during the period that they recalled. Generally, they recalled periods of time when they were experiencing extreme thermal sensations, either too hot or too cold (Table 8-5). Most participants found this to be *uncomfortable* rather than *very uncomfortable* (Table 8-6). These conditions were found to be unacceptable by the majority of participants (Table 8-7)

Table 8-5: Thermal sensation counts.

Thermal sensation	Count
Cold	30
Cool	6
Slightly cool	1
Neutral	8
Slightly warm	6
Warm	30
Hot	84
Undisclosed	1

Table 8-6: Comfort counts.

Comfort rating	Count
Very uncomfortable	42
Uncomfortable	84
Slightly uncomfortable	38
Comfortable	1
Undisclosed	1

Table 8-7: Acceptability counts.

Acceptability rating	Count
Not acceptable	129
Acceptable	33
Undisclosed	4

Emotions recalled

Participants were asked to choose one of several emotions that best matched their feelings from a closed list. No one reported a positive emotion or an emotion associated with personal responsibility, i.e. regret (Table 8-8). Mostly, participants reported feeling frustrated, resigned or a dislike of the situation. A smaller number of participants felt indifferent, angry or anxious. There were also sixteen participants who felt that none of the ten emotions fitted well with how they felt. Across buildings, the trend was generally the same, except Building A and B where people were more likely to feel dislike and building F where people they were more likely to feel angry (Figure 8-3).

Table 8-8: The emotions reported across all buildings.

Emotion	Count
Frustrated	74
Resigned	30
Dislike	20
None of these	16
Indifferent	10
Angry	8
Anxious	8
Liking	0
Joyful	0
Regretful	0
Proud	0

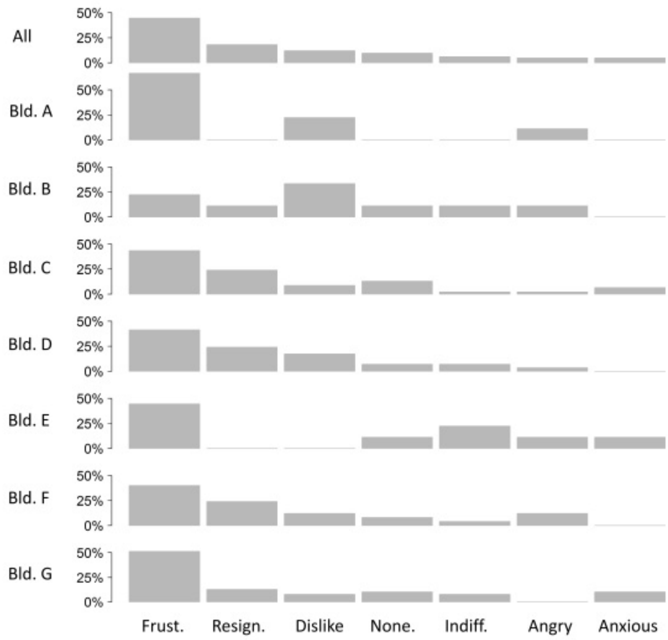


Figure 8-3: The emotions reported across all buildings.

8.3.2 The appraisals

Generally, participants reported that the event was unpleasant and worsened their ability to work. We also asked who they thought was responsible for the events leading up to their emotional experience (Figure 8-4). They rarely thought they themselves were responsible. We asked the participants who they thought was generally in control of the temperature in their office (Figure 8-5).

Occupants of building F felt they had little control. Occupants of buildings C and D thought no person was in control. Across most buildings circumstances were thought to control conditions. Overall, there was a mixture of whether people thought the event they reported could have been expected. However, there is a lot of difference between buildings (Figure 8-6). Occupants from buildings E and F tended to report events that were unexpected. Elsewhere events reported had been expected.

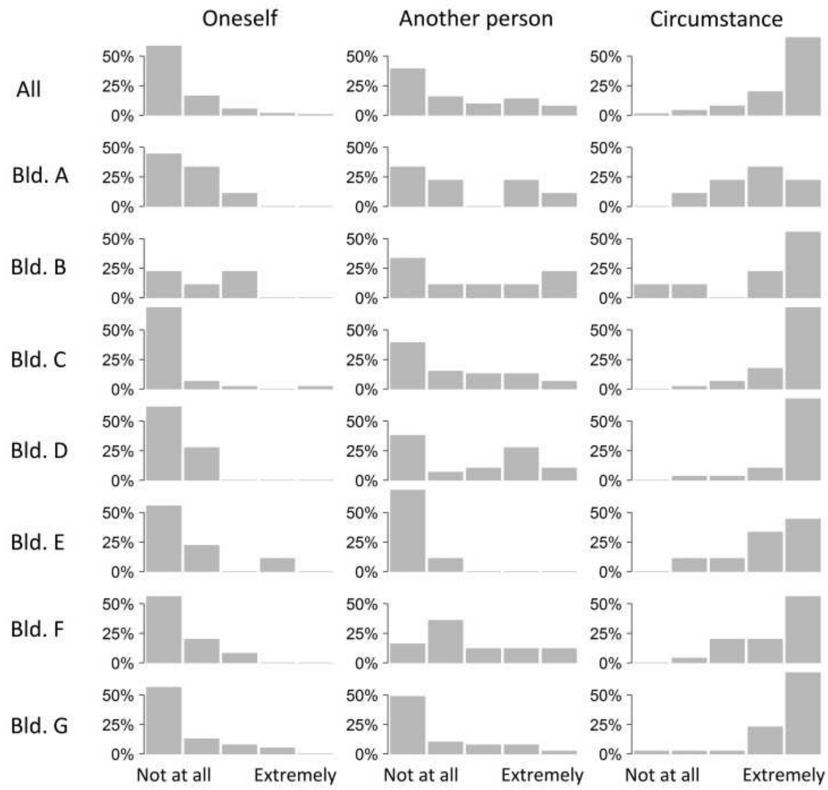


Figure 8-4: Who is appraised as responsible for the event, across the different buildings.

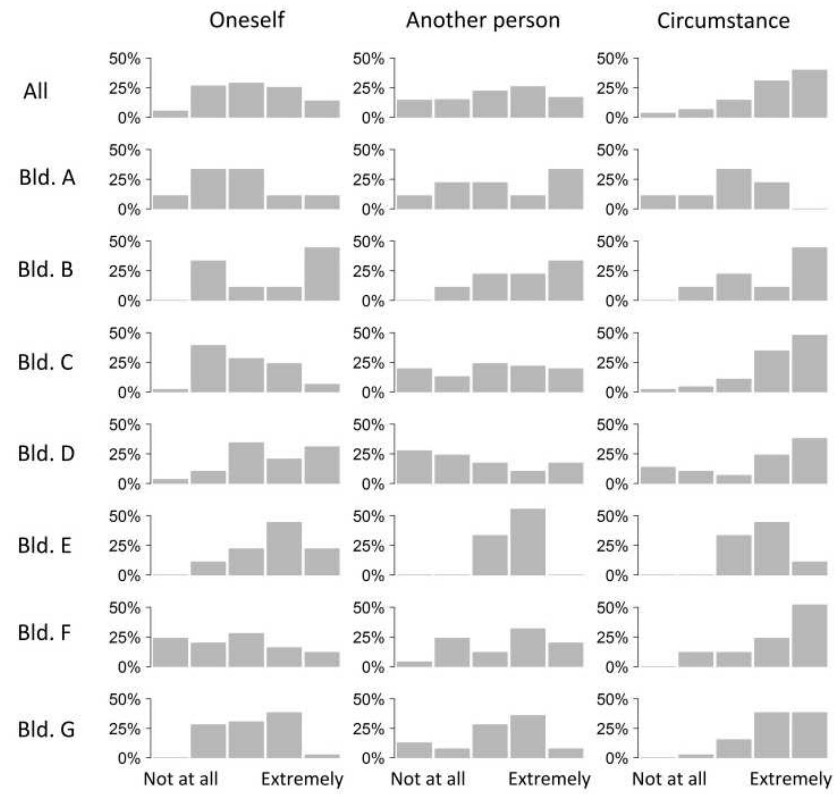


Figure 8-5: Who is appraised as in control in general, across the different buildings.

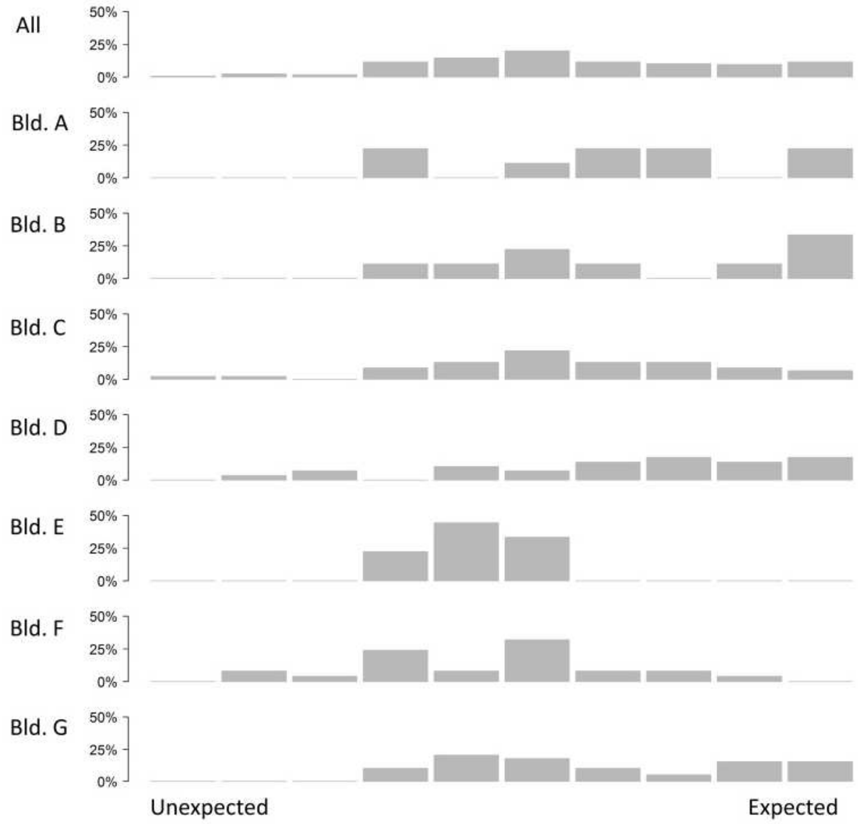


Figure 8-6: Appraisal of expectedness of the event, across different buildings.

8.3.3 Using appraisals to predict emotions

The absence of positive emotions and the absence of positive appraisals of conduciveness is in accordance with appraisal theory. However, the lack of positive emotions also means it is difficult to build a comprehensive statistical model for validation. For the remaining three appraisals, the emotions reported were partitioned into two groups according to the relevant hypothesis, i.e. for Causality, one group was aligned with the appraisal of caused by another (dislike and angry) and the other with appraisal of caused by circumstance (frustrated, resigned, indifferent, anxious). Figure 8-7 shows how the likelihood of feeling one set of emotions rather than another varies with participants' appraisal.

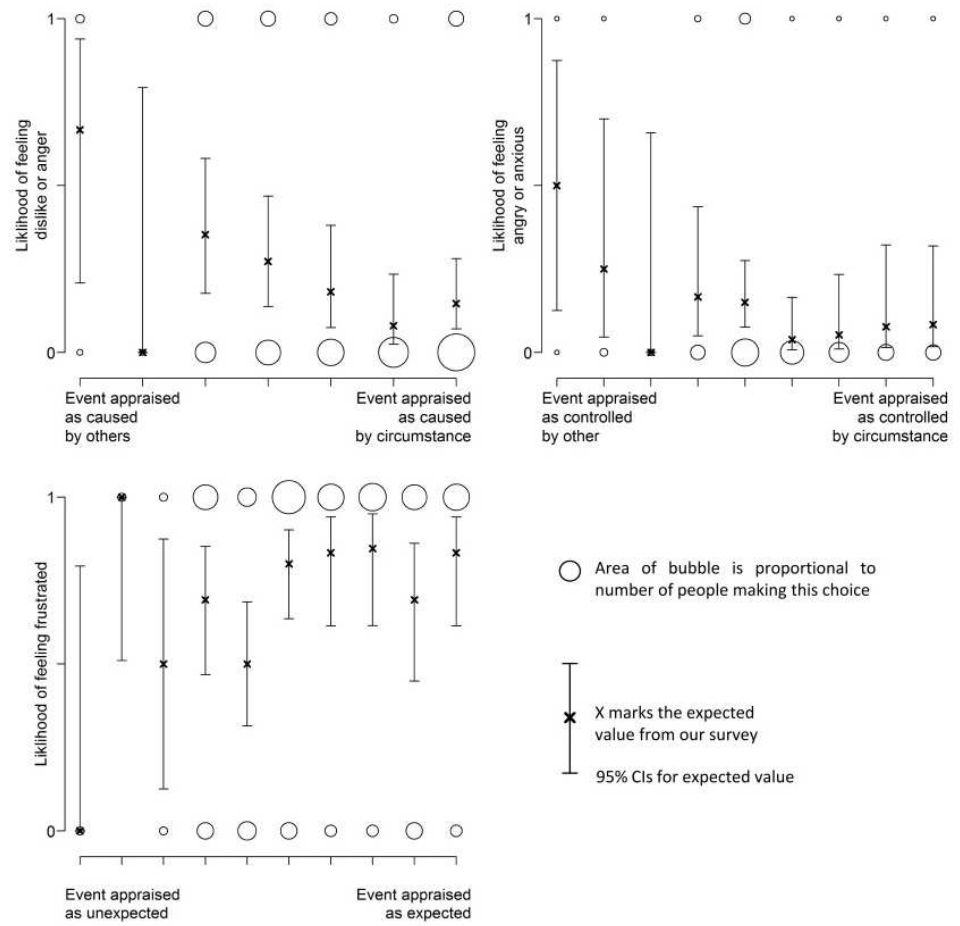


Figure 8-7: Appraisals of responsibility and control have an effect on the emotion reported.

We tested several link functions to model these data, and report statistical tests of the best model in Table 8-9. These suggest that there is a tendency to feel angry or dislike when another person is deemed responsible for the thermal experience, in support of predictions from appraisal theory. The results also show a tendency to feel angry or anxious when another person is appraised as being in control of the thermal experience, again supporting appraisal theory. For the appraisal of Expectations, there is not such an obvious pattern as for the other appraisals.

Table 8-9: Characteristics for emotions models.

Appraisal	Best link function	χ^2 goodness of fit		Model coefficients	
		χ^2	Single tailed	β_0	β_1
Responsibility	Poisson	7.1 (df=1)	***P***=0.01	-1.1 (***p***<0.001)	-0.28 (***p***=0.003)
Control	Cauchit	3.8 (df=1)	***P***=0.05	-2.7 (***p***<0.001)	-0.65 (***p***=0.03)
Expectation	Cauchit	2.70 (df=1)	***P***=0.10	-0.15 (***p***=0.81)	0.21 (***p***=0.11)

8.3.4 Using appraisals to predict comfort and acceptability

Figure 8-8 shows how the likelihood of finding a thermal experience acceptable varies with participants' appraisal. Again, we tested several link functions to model the data, statistical tests of the best models are reported in Table 8-10. These suggest that the appraisals have little effect on the acceptability of the experience. There is a weak link that suggests that, the more a situation is expected, the less acceptable it is.

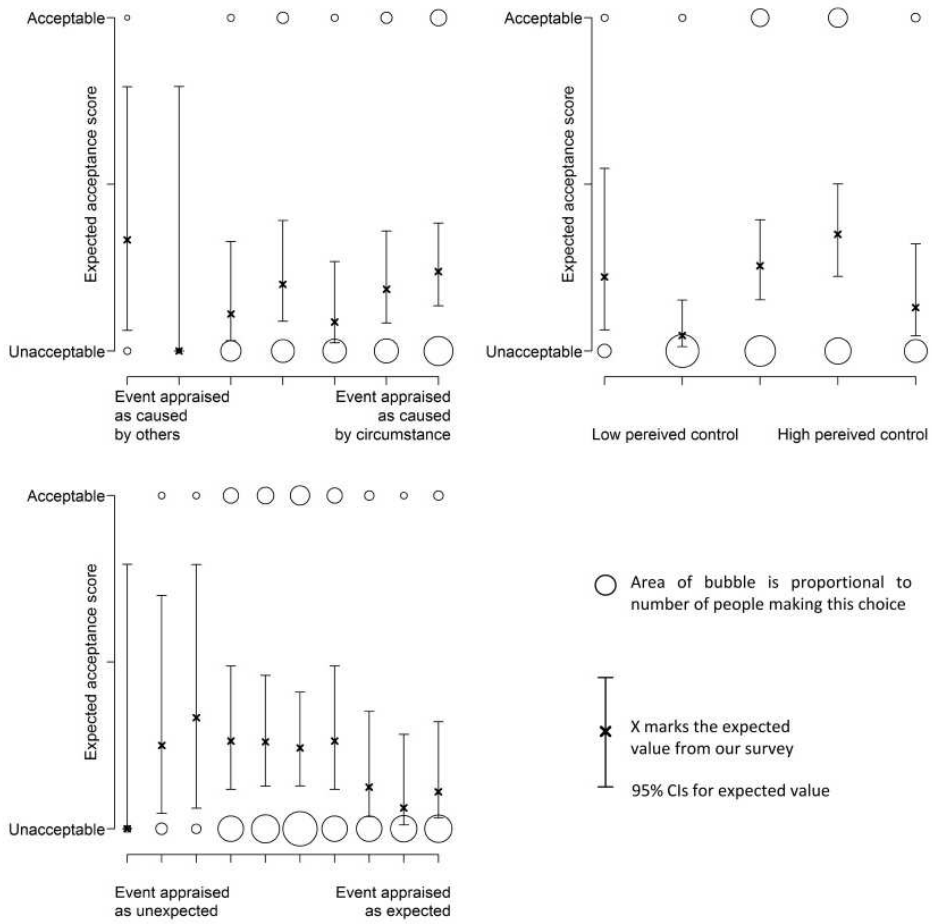


Figure 8-8: The appraisal of expectation has a small effect on acceptability.

Table 8-10: Characteristics of acceptability models.

Appraisal	Best fitting link function	χ^2 goodness of fit		Model coefficients	
		χ^2	Single tailed	β_0	β_1
Responsibility	Cauchit	0.82 (df=1)	***P***=0.37	-2.2 (***p***<0.01)	0.24 (***p***=0.36)
Perceived control	Probit	2.46 (df=1)	***P***=0.12	-1.3 (***p***<0.001)	0.16 (***p***=0.11)
Expectation	Probit	3.48 (df=1)	***P***=0.06	-0.27 (***p***=0.39)	-0.10 (***p***=0.06)

Figure 8-9 shows the effect of the same appraisals on comfort rating. As for acceptability, expectation is the only factor that appears to correlate with the resulting set of emotions (Table 8-11).

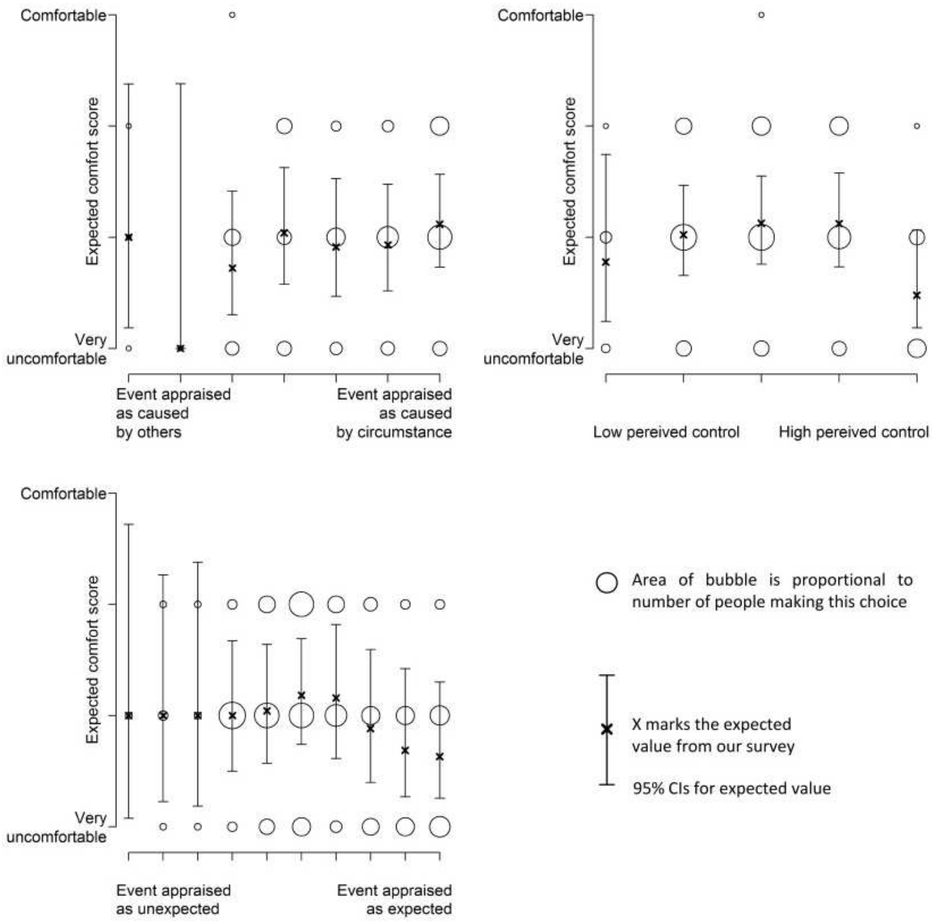


Figure 8-9: The appraisals of control and expectation have a small effect on comfort.

Table 8-11: Characteristics of comfort models.

Appraisal	β_1	SE	t-value	p-value
Responsibility	0.18	0.10	1.76	0.08
Perceived control	-0.20	0.13	-1.55	0.12
Expectation	-0.16	0.07	-2.26	0.02

8.3.5 Using appraisals to predict deviation from neutral sensation

Figure 8-10 shows how the likelihood of reporting a neutral thermal sensation changes with participants' appraisal.

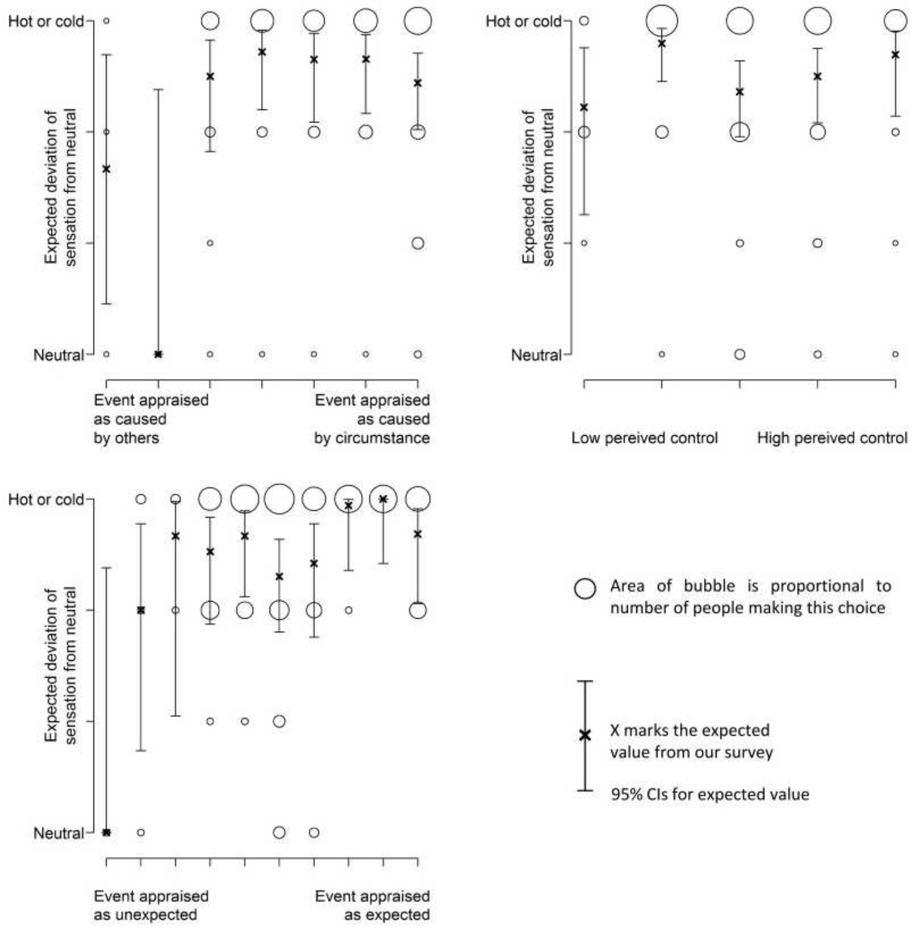


Figure 8-10: The appraisal of expectation has an effect on thermal sensation.

Table 8-12 shows the different model characteristics. These results suggest that the expectation appraisal influences bodily symptoms (thermal sensation) but the other appraisals do not.

Table 8-12: Characteristics of sensation models.

Appraisal	β_1	SE	t-value	p-value
Responsibility	0.04	0.12	0.30	0.76
Perceived control	0.07	0.15	0.51	0.61
Expectation	0.24	0.87	2.75	0.006

8.4 Discussion

Taken together, our results show that appraisal processes are important for shaping evaluation of the thermal environment. The appraisals of causality and control were less useful for predicting the traditional thermal comfort evaluations of acceptability and comfort. This contradicts the extensive literature on perceived control and thermal comfort (Brager & de Dear, 1998; Hellwig, 2015). This unexpected result could be a side effect of the recall method. The recall method provides access to thermal events that are of high saliency, thereby biasing the distribution of events under investigation. It is possible that perceived control does not affect the severity of the most extreme bad events, or rather, that the skewed distribution of events reported did not allow for our models to explore the full range of responses.

The appraisal of Expectations was successful in predicting comfort evaluation. However, the correlation was opposite to that expected. The more an event was predictable or expected the more uncomfortable it was. Thermal comfort theory would predict that occupants acclimatise to events over time (Brager & de Dear, 1998). Our results suggest that events that are novel and fleeting may cause less discomfort than recurring and predictable problems.

When we asked about expectations, participants may have focused on recurrent salient situations, whereas the classic expectation of thermal comfort refers to repeated and continuous exposure to a ubiquitous climatic experience. Given this observation, it appears that our results draw attention to a different type of expectation effect. Namely that when problematic conditions are recurrent, they become less and less acceptable.

This suggests that occupants will forgive events that they perceive as one-off or rare. This could have important implications for the usage of thermal comfort standards in heat waves. It suggests that using comfort models based on environments where there is one set of expectations (i.e. usual operating conditions in offices) is inappropriate for assessment of environments where there is another set of expectations (i.e. homes during heatwaves). However, this is currently what occurs when *CIBSE TM52 The Limits of Thermal Comfort: Avoiding Overheating in European Buildings (CIBSE, 2013)* is used to test overheating in UK homes.

The work on psychological adaption and embodied cognition hints at two different mechanisms through which psychological factors could affect thermal experience. The first mechanism suggests that psychological factors change the mapping between thermal sensation and thermal evaluation. These theories suggest that the benefit of personal control is that it reduces stress from mildly unfavourable conditions and effective control provides pleasure (Hellwig, 2015). In contrast, embodied cognition suggest that the psychological factor would change thermal sensation itself. Interestingly, a study carried out in a climate chamber by Zhou *et al.* (2014) suggests that perceived control actually changes both bodily sensation as well as reducing stress.

Our results support theories of embodiment because where appraisals have an effect on comfort, they also have an effect on reported sensation. However, this can only be taken as weak support for embodiment because our field study did not assess specific thermal environments. The inclusion of synchronous temperature measurements would provide conclusive evidence that the appraisal caused a sensation change, as opposed to thermal sensations causing both comfort and appraisal.

The lack of positive emotions supports work that suggests that temperature is a hygiene or basic factor responsible only for dissatisfaction (Herzberg, 1964; Kim & de Dear, 2012). However, it may be that people chose to focus on negative events from their past—although they were not specifically asked to do so. Future investigations could be contrived to test this by asking participants to describe two experiences and stipulate that one had to be positive. This approach would provide a greater range of experiences and hopefully contribute positive emotions to improve our analyses.

The results here supports the notion that thermal experience is rich and complex, and requires understanding of how people conceptualise their thermal environment (Heschong, 1979). It is possible that appraisals, especially conduciveness, could be driven by the thermo-physiological state of the participant, though there is no need for this to be the case. What appraisals provide is a short hand for understanding a person's thinking process. This could be used in a sensor system by incorporating questions about appraisals into surveys and user feedback (e.g. through experience sampling). It shows that an essential part of a sensor system is understanding people's subjective experience, not just in terms of satisfaction, but through key elements of their (subconscious) thought process.

To improve the method and repeatability, the survey could also be made easier to analyse. We focused here on the comparison of sets of theories and assessment of the best explanatory models. Further studies may choose to simplify the design by focusing on particular aspects. First, appraisal dimension could be specified to ease coding. The current system of combining many ordinal responses is convoluted and builds in uncertainty, which was reflected in our analyses. Second, continuous response for variables could be used. This would mean that analysis could be done with genuine ratio scale numbers rather than an ordinal scale that was transformed into a ratio scale.

8.5 Conclusions

Our analysis suggests a new aspect to how expectation affects psychological adaption. We observe that recurrent problems (those that happened often and were predictable) resulted in greatest discomfort. People did not appear to adapt to them. This suggests an alternative way to conceptualise expectation and that recurrent problems may be much worse than unexpected and one-off problems. This could have important ramifications for the use of thermal comfort standards to predict how people react to one-off heatwaves.

Appraisal theory provides a simplified way to encapsulate people's thoughts about their thermal experience. These thoughts cover not only a person's core temperature and peripheral thermal stimulus but also their past experiences and future desires. The theory does not try to predict why people make certain appraisals but it identifies which appraisals are key. Overall, our results show that it is the combination of these appraisals that shapes a thermal experience. Any system of measurements that incorporate elements of user feedback should incorporate appraisals if they wish to understand peoples thought process.

A survey tool that incorporates these appraisals could then be used as a diagnostic tool where discomfort and dissatisfaction are caused because of psychological factors (as opposed to poor thermal conditions). From this it may be possible to design a programme of measures that tackle those psychological causes. This would be in contrast to current industry approaches that focus on costly technical fixes and chase ever more control over the physical environment.

We chose to test appraisals on thermal comfort because, as previously noted, it is one IEQ factor that is particularly suited to approaches that are deterministic, physiological and dose-response based. Yet this study has shown the importance of the thinking process, in particular appraisals, for understanding thermal experience. This leads us to suspect that this method could be used to understand emotions and their appraisals during multisensory experiences of buildings, beyond just thermal comfort.

Part 3

Discussion and conclusions

Chapter 9

Discussion

This chapter

Sensor systems are only as good as the performance metrics that they are set up to measure. Bottom up approaches are biased towards a data driven, deterministic viewpoint of the world. Characterising IEQ using occupant outcomes allow a less deterministic approach to be taken. It also provides a framework within which to utilise sensors to evaluate user experience.

A fuller description of IEQ requires categorisation of environments. Categorisation is one method of overcoming the problem of complex characterisations. It requires some degree of subjectivity to identify the important elements of the environment that define a type. It is a challenge for sensors to do this work of categorisation. It is important to work out the best ways to incorporate subjective experience from users into sensor systems.

Variability within limits and with sufficient control can improve user experience. Current standards encourage provision of *optimal conditions*; an alternative approach is to encourage provision of *optimum control*. Sensor systems can improve control by being designed to augment (rather than replace) current methods of decision making.

9.1 Emergent outcomes not physical components

In drawing conclusions, we accept the inevitable limitations of our approach. The buildings were each visited for a week, in summer; many of the questions asked were specifically about that week. Our aim is to not generalise from this investigation to all buildings everywhere. Instead, this discussion allows us to fully explore the contextual factors and underlying mechanisms that can explain how these buildings operate. From this we put forward an alternative perspective on IEQ, one that avoids creating prescriptive rules for specification of IEQ parameters.

The bottom up approach understands IEQ in terms of a set of performance criteria. A high quality indoor environment will be within a certain temperature band, below a given noise level, above a given light level and have below threshold levels of specific air pollutants. These provide a fundamentally positivist definition of IEQ. It is positivist because it believes that people's experience can be comprehended by measuring and combining empirical data.

In Chapter 5 we tried to access the values and identity of a building. This approach acknowledged that there was something about the building that could have a nuanced and emergent effect on occupants. It was nuanced because it was not simply hot or cold, satisfactory or unsatisfactory, good or bad. It was instead a multidimensional way of defining the quality of a building's identity. It was emergent because it could not easily be tied back to physical parameters or features of the space. We cannot imagine a bottom up method to define practicality as a value and we are not sure there would be much benefit in doing such a thing. The values and identity were found to be important for building performance. This suggests that IEQ is as much about emergent factors, such as the identity of the building, as it is about component factors, such as thermal and visual comfort.

These emergent factors are similar to the top down factors discussed by Bluyssen (2008), the Gestallt approaches of Vischer (2008a) and the human needs of Lehman (2011). All of these focus the narrative of building performance on the emergent needs of people not component IEQ factors. Privacy is another emergent outcome. It is possible to tie it back to physical factors such as sight line, noise levels and spatial features but it also relies on contextual factors such as worker mobility. The importance of physical factors for privacy depends partially on which of the three distinct types of privacy is important. These complexities mean it may never be possible to pin privacy down to a universal bottom up approach. Instead it would be wiser to look towards critical realism, to find the correct epistemological approach, because it specifies much looser ties between causal elements and greater flexibility concerning which components are important in a given context (Table 9-1). Because relationships between components are not fixed, mathematical rules (however complicated) cannot be used to predict outcomes(Clark *et al.*, 2012). However, the lack of maths does not prevent an understanding of the system.

Table 9-1: Components of interventions in healthcare and privacy (columns 1, 2 and 3 from Clark *et al.* (2012)).

Facet of complexity	Definition	Healthcare examples	Privacy examples
Main components	The main parts of the intervention	Important components of a disease management programme, including: personnel, setting, content and theoretical basis	Typology of space, requirement for privacy, spatial features, worker mobility.
Sub-components	The parts of the main components	The values, skills and practices of the healthcare professionals providing the intervention	Why the worker is mobile, what their role is in the company, how they interact with people.
Generative effects	Outcomes are generated by components in combination	Smoking cessation occurs only when patients feel the healthcare provider has listened to their past difficulties, has incorporated these difficulties into intervention content, and instigates telephone follow up.	Different typologies of space, encourage different modes of working. This changes how people experience privacy. This in turn changes their needs for their office space.

Defining the environment with a critical realist approach using occupant outcomes recognises much more of the complexity of user–building interactions. It allows for components to have powers that are unexercised in different contexts (Sayer, 2000) and encourages the exploration of generative effects (Clark *et al.*, 2012). In Chapter 7 agile workspace is found to affect occupant experience of privacy. This is not just because it affects a person's immediate environment but because it affects how a person behaves. This means that, to solve a person's problem with visual privacy, it may be better to change their behaviour rather than their immediate environmental experience (e.g. create an alternative place for them to go to, rather than change their sightlines). This suggests that designing for occupant outcomes requires an appreciation of interlocking components. Possible design solutions can be generated through understanding how components fit together so that problems can be transformed in a way that improves all outcomes (Craig, 2008). Conversely a bottom up approach tends to keep the problem fixed and optimise trade-offs between outcomes. Taking a critical realist view of complexity enables designers to understand underlying mechanisms enough to be able to redefine problem situations and change the system for the better.

Privacy and building identity are just two of many emergent outcomes that can be used to define occupant experience. Some of these outcomes will be universally desirable but some will be unique to specific organisations and groups of people. Defining these occupant outcomes (Table 2-8) provides a menu of what IEQ can achieve. Having the menu will make IEQ more comprehendible.

The bottom up approach is particularly suited to sensor systems because of its deterministic viewpoint and reliance on physical measurements. The use of outcomes as a unit of study provides a level of repeatability to measurements and sensor methods. This allows approximately the same set of measurements to be carried out repeatedly for a given outcome. However, the measurements required to track outcomes will not be simple or straightforward. It will be necessary to consider what outcomes are important and how those outcomes should be measured in a specific situation. Occupant outcomes combine the benefit of predefined targets, as per the bottom up approach, with the user focus and flexibility of top down approaches.

9.2 Quantifying complex characterisations

Some criteria of environmental quality are relatively easy to reduce to a single number, such as thermal comfort, others such as soundscape are harder. In section 6.4 (Between-subject) we defined the physical environment in terms of background levels. This bottom up characterisation was useful for temperature and lighting but not for sound levels. In section 6.5 we took the same data and used the short term physiological response to identify salient noise levels. This suggests that short term changes in physiology can be used to track peak experiences, a similar finding as made by Tröndle *et al.* (2014). This could be used to overcome the problem of complex characterisation. Physiological data would make it possible to identify soundscapes that are salient. This categorisation of soundscape would have overcome the problem of complex characterisation.

In Chapter 7 we tried to overcome the problem of complex characterisations by defining the physical environment using typologies and features. We also analysed people not by their age or sex, but using a construct wholly based upon a person’s relationship to their environment (their mobility). This suggests that any sensor system for monitoring privacy would have to recognise different categories of space (such as open plan or cellular office). For example, a sensor system would have to be able to detect when a partition was added to an open plan office, and evaluate whether that office had then become cellular or remained open plan. Such a sensor system would need to be able to interpret the environment and make some level of subjective evaluation to summarise and encapsulate the complexity of the situation. This would have to account for changes in occupant experience as well as spatial arrangement because the identification of the transition point (from open plan to cellular) is as much dependent upon people's experience of it as the spatial configuration itself.

The methods of Chapter 8 make deep layers of occupant experience accessible. This could be the key to a critical realist use of sensors, where people's experiences and thought processes are put on an equal footing to measurements of the physical world. Enabling sensor to accommodate and respond to the experience of occupants, as suggested by both Clements-Croome (2013b) and Lehman (2013), could help the problem of categorisation.

These results suggest that a sensor system must be able to intelligently select what set of parameters to measure in a given context. If the selection is done incorrectly then occupant outcomes may be wrongly attributed to causes other than IEQ (a false negative). This suggests that IEQ is a wicked problem that cannot be solved by using a predetermined set of parameters (Rittel & Webber, 1973). The Vischer (2008a) top down approach considers first the user, then the experience, then the building. So for each new experience studied it takes a fresh look at how to define IEQ. In contrast the bottom up approach is less flexible. This suggests bottom up models are not compatible with wicked problems and are inappropriate for complex situations. To accommodate this flexibility, sensor systems would have to be able to identify and prioritise different measurements of the building to evaluate changes in optimum outcomes. This definition of sensor systems converges with several aspects of intelligent buildings (Ghaffarianhoseini *et al.*, 2016; Kaya & Kahraman, 2014).

9.3 Using sensors to overcome the inability of pre-defined parameter sets to consistently predict optimal conditions

Chapter 5 explored a situation in which, for lighting, variability was marginally preferable to uniformity, but for temperature, variation was detrimental to satisfaction. The agile workspaces described in Chapter 7 also had variety in the form of different spatial settings. In the cases where variation is satisfactory, people have control of it, as in the case of the agile workspaces described, or it is within certain limits as for the lighting of Building E. This suggests that where possible, variation of environmental variables should be encouraged but it should be within limits and there should be sufficient controls.

Building F had artificial constraints imposed on it. It had been designed to achieve a temperature of 20–24°C all year round. This design goal had turned into a rule about how to operate the building. The building manager was more concerned with keeping the building within these design conditions than improving the comfort of occupants. In this case the knowledge of optimal temperatures had been taken out of context and used inappropriately. It would have been better to say the building is designed to achieve 20–24°C but it should be operated to maximise comfort.

Often the goal of bottom up component approaches is to specify optimal conditions and allowed deviances, e.g. optimal temperatures and allowed temperature drifts (Nicol & Humphreys, 2009) or optimal light levels (Rea, 1986) and minimum uniformity factors (SLL, 2012). These approaches place too much importance on the designer and not enough on the future operatives of the building (both facility managers and occupants). It is these operatives who will decide what the environment is by opening windows, turning plant on and off and altering set points. Rather than provide optimal conditions, an alternative design goal could be to enable the optimal operation of the building. Systems should be designed to achieve a range of internal environmental conditions but these must not be imposed upon the facilities team or occupants. This does not mean that all occupants have to have personal control, only that someone, somewhere, should have control over the operation of the building, and that it is possible to achieve the range of environmental conditions that might be desired. This leans towards control focused design as proposed by Bordass *et al.* (2007).

This alternative design goal has ramifications for how buildings are conceptualised throughout the design process. Currently the internal conditions are specified and, from this, the systems are designed to achieve these conditions. User control and interaction with the system is considered as an afterthought. The proposed alternative would put control and interactions at the centre of design. Models of affordances (Norman, 1998) could be used to understand the indoor environment. A building could be understood in terms of the affordance to deviate internal conditions from external conditions and to deviate local conditions from the average. Then the energy potential of these affordances could be calculated.

In this regime the goal of sensor systems could be to provide the most useful and appropriate information to augment decision making. An example of such a system is window opening signals (Ackerly & Brager, 2013). They consist of temperature, CO_2 and humidity sensors linked to a sign on the wall near windows. The sign either recommends that windows should be opened or closed. It then rests with building occupants to make the final decision. These systems overcome the inability of predefined parameter sets to consistently predict what is best for occupants given real world complexity. Instead they augment existing decision processes with information about weather and predicted energy consumption while still allowing occupants to retain the privileged insight of their own experience.

Chapter 10

Conclusions

This chapter

We identify a number of contributions to knowledge, including:

- Recall survey as a method for accessing occupant's peak experiences and the psychological factors that shape their experience;
- Methods and algorithms for, as well as the limits of, using physiological sensors for monitoring user comfort;
- Two possible approaches to characterising complex environments are put forward. Firstly, according to their salience as measured using physiological response. Secondly, by categorising an environment as a particular typology and developing a repertoire of features that are important for a given environmental experience.
- Group control (as opposed to individual control) is identified as important;

As the number of options for sensors multiply it is important that they are properly integrated into standards for building monitoring.

A key future research area is the integration of multiple data sources. To monitor IEQ it is essential to monitor physical data and also user data. User data could consist of location, photos, preferences, experience sampling and appraisal dimensions. This should take account of high level occupant outcomes, such as privacy, identity and values, as well as component factors, such as temperature and light levels.

10.1 Contributions to knowledge

10.1.1 Methods for research and POE

This thesis has tested the novel application of the recall method and wearable sensors. The recall method has not been used for understanding the built environment before. Wearable sensors have not been used in offices to monitor people's response to sound levels. The recall survey, coupled with appraisal theory, gave us access to an occupant's peak experience and the psychological factors that shaped it. Wearable sensors enable the study of events as they unfold, in real time, without conscious input from the participant; this enabled us to objectively measure the saliency of complex environmental experiences. These tools are useful because they improve the direct investigation of particular office environments and allow detailed understanding of individuals. This means that the running of a building or briefing for design could be much more personalised to the groups of users and the tasks carried out.

Using appraisal theory of emotions is an efficient way to define the psychological factors that affect occupants. No longer is it necessary to assume that people with the same age, gender and personal control have the same evaluation of the environment. Nor is It necessary to understand a person's thermal history in detail. Instead, we see that people's personal appraisals can be used to understand the thinking processes that underpin their experience.

We have provided practical methods for use of wearable sensors as part of building POE. The combination of heart rate and noise measurements can be used to indicate when a particular area of a building is too loud for specific occupants. In addition, we have provided a step by step procedure and details of the algorithms to compile the many different environmental and physiological data streams.

Physiological statistics for the whole session did not help to distinguish between buildings (Figure 6-5) but there was a correlation between environmental variables and physiological response (Figure 6-9 and Figure 6-10). This suggests that the variation of environmental conditions within the buildings, was larger than the variation between the buildings. So although this tool cannot differentiate between buildings it can be used to identify areas of building that are performing poorly.

10.1.2 Theory and practice

This work suggests the importance of emergent outcomes for understanding people's perception of building performance. This is confirmed by our work on building identity and values as well as privacy. It is also backed up by the study on thermal emotions which suggest that it is not the physical environment that is directly responsible for the emotion experienced. This suggests top down approaches are suitable for outcomes that are higher up on a hierarchy of needs (such as belonging and self-esteem) and it goes against the notion that a reliable score for building satisfaction can be built bottom up from models of individual physical components alone.

Just because outcomes higher up on a hierarchy of needs cannot be easily predicted using bottom up approaches it does not mean that they cannot be supported by buildings. It just means that characterising how a building supports them is complex. This thesis offers two routes forward for complex characterisations. Firstly, it may be possible to use physiological sensors to identify salient moments of environmental experience. Environmental data can then be categorised according to physiological response. Secondly and more broadly, it is necessary to be able to categorise building environments and score them against a given category. This can be done by breaking a building into typologies and specific design features that support a given outcome but it will also need to be supported by user's subjective experience of that environment. The development of these methods to characterise environments will enable sensor systems and parametric design to capture complex environmental stimuli, such as soundscapes, visual scene or the experience of privacy.

Both these methods for complex characterisations assume it is possible to predict the effect of the environment without understanding how people think about the environment. As if the processes that underpin how people think weren't important or could be inferred from a physiological measurement. In the thermal emotions study (Chapter 8) we show that underlying thought processes are important. What people think is not just a result of their environment, it shapes the experience of their environment. Psychological appraisals offer a way to efficiently understand the thought processes that shape our emotional experience of thermal comfort.

Occupant outcomes were described in the literature review and explored in detail in Chapter 5 and Chapter 7. We found them useful to characterise indoor environment quality. In particular, they provide the means to conceptualise the environment somewhere between low level physical parameters and high level definitions of health, wellbeing and productivity. It makes it possible to break down performance into a defined set of outcomes. This can then be translated into a specification for the environment. This elevates the conversation about IEQ from physical parameters to specific aspects of occupant experience.

One such outcome is control, normally this is talked about in terms of perceived individual control. However, in our studies we found that group dynamics often govern how buildings are controlled. In one building the building manager controlled the building according to prescribed industry standards, this was sub optimal for occupant comfort. In another building control was exercised by a small number of individuals when internal conditions entered crisis mode. In another of the buildings a single person pre-empted prevailing thermal conditions and opened windows early on in the morning, which later on others would sometimes close. These different modes of control were partly borne from the different systems installed in the buildings and partly from the structures that permeate both those offices and the building profession. This shows that the group dynamics of environmental control should be considered as part of any retrofit or behaviour change programme.

Often when buildings are designed any consideration of controls is an afterthought because IEQ is defined in terms of a singular optimum set of conditions; deviation from this optimum is seen as poor performance. This design mindset pursues and idealises tight control of environmental conditions. However, in our studies we saw that sometimes variations of environmental conditions are not unsatisfactory and there may be some benefit to variation as long as it controllable and within limits. This suggests an alternative way to define IEQ is in terms of a building's potential to be controlled by occupants. Both their potential to make the internal conditions different from the external and their potential to make their local conditions different from the average internal conditions. A building would then be defined in terms of the affordances it provides people rather than its ability to reach and maintain any particular set of conditions. In terms of energy performance there would be an energy penalty associated with provision of such control, a good building would be one that provided plenty of scope for deviation, from external and average conditions, while using minimal energy.

10.2 Future directions

10.2.1 Policy

Guidance on post occupancy evaluation should recognise the large role that wearable sensors can play in understanding the built environment. Most people now carry in their pocket something that is able to monitor IEQ, carry out experience sampling and sometimes measure activity levels and heart rate. Utilising these could provide a huge resource for remote monitoring of buildings. However, there needs to be clear guidelines to help people understand their suitability for characterising IEQ. Firstly, the purpose of the sensors must be clearly established, they are not an elixir to building monitoring and currently can only monitor and evaluate a finite set of IEQ outcomes. The accuracy of the sensors needs to be appropriate for their use. Finally, there is clearly issues around ethics, data privacy and device intrusiveness that need to be managed.

Sensor systems can also enhance building operation. They can provide more complete and up to date information to building users and operators about occupant experience. User feedback through photos and short surveys could also help remote facilities teams better understand the use of space. Experience sampling of appraisals could identify the causes of persistent psychological discomfort. However, it is important to understand the drawbacks of these systems and how they complement rather than replace existing methods for understanding buildings. This thesis has identified a number of issues that need to be overcome by future research before it is possible to fully rely on sensor systems for monitoring and evaluating occupant experience.

10.2.2 Future research

Methods to enable sensors to categorise environments

It is difficult to categorise environments as one type or another (e.g. the difference between open plan offices and agile workspace). Perhaps it is best to understand what people do best, what sensors can add and design systems around these constraints. The aim of the system would be to develop a type of augmented reality, where sensor measurements supplement direct experience and direct experience, in the form of experience sampling and expert evaluation, become a key component of a set of parameters to evaluate IEQ.

The privacy study identified the relationship between typologies and the design features that support those typologies. This provides an outline method of how to categorise spaces according to their privacy potential. This should be added to with some element of user experience because essentially it is the type of user experience that defines what typology a space is. This user feedback doesn’t have to be in the form of a standard survey. A system could be developed that enabled users to take photos of their work settings and pertinent features and provide location and experience sampling data. This would enable a researcher or building operator to understand the privacy experience in more detail and provide a much more user centric appreciation of the supporting features. Such a system could also be useful to building users. In a large complex building, with a number of different work settings, it could be a useful way for users to gain knowledge of their building. It might enable them to identify and share the best places for different types of work.

Wearable sensors

Our technique for measuring physiology suffers from a number of practical problems. One of the key problems is the level of intrusion of the devices. This is caused by their bulk and their novelty. Because of this, users are constantly aware of them. Using heart rate and other physiological data collected by smart phones and ancillary wrist devices would overcome these issues and could lead to more widespread usage.

As these are remedied wearables could be used to improve the control of buildings. For example, windows can close when it is sensed that people are overly distracted by external noise. They can also be used in POE to judge the saliency of contextual information. Further work could also investigate other physiological data such as blood oxygen and EEG.

Measuring wellbeing in situ

A future wellbeing sensor system could be developed that would consist of a number of different components:

- Smart phone apps to record a combination of data both continuously and as part of experience sampling. These data would include:
    - Photos of settings;
    - Local environmental quality;
    - Short survey responses;
    - Physiological data;
    - Location
- External sensor system / internet of things:
    - Location
    - Zone level environmental quality;
    - Behaviour /device usage

This would provide a large array of data. How this was then collated to provide useful analysis would be an essential area of study.

List of appendices

Survey questions used in study (paper)

Review of survey questions (electronic)

Consent forms (electronic)

Photos (electronic)

Building plans (electronic)

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