Evaluation of Environmental Design Strategies for University Buildings

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Abstract

This paper examines the performance of environmental strategies in seven recently constructed or refurbished university buildings in the UK. These buildings contain a range of administrative spaces, classrooms, libraries and studios, reflecting their often complex, multi-use, heterogeneous nature. The key features of each environmental strategy are described (including passive, mixed-mode or active systems), in the context of the occupants and spaces they serve and the level of interaction that they afford. Energy performance and occupant thermal comfort (assessed by user surveys) are analysed and compared with studies of other non-domestic buildings, which have typically focused on more predictable single administrative uses (e.g. government offices), and unusually effective operation scenarios (e.g. continuous monitoring by expert building managers). The paper concludes by examining two of the case studies that reflect an increasingly common model of 'flexible' environmental design in more detail, identifying key features of the strategies for each building that have had a significant impact on their performance. The design assumptions leading to these features will be explored, and key lessons identified, contributing towards the development of a more robust evidential basis for choosing appropriate environmental strategies for university and other non-domestic buildings in the UK.

Keywords: post-occupancy evaluation (PoE), energy performance, thermal comfort, architectural design, university buildings, environmental strategy

Introduction

The Higher Education building stock

The 2016 Higher Education Carbon Challenge report described progress towards the Higher Education Funding Council for England (HEFCE) target to reduce carbon emissions in Higher Education (HE) institutions in the UK by 43% in 2020 against a 2005 baseline of 2.06m tonnes, in line with the 2008 Climate Change Act. According to the report a 9% reduction had been achieved in scope 1 and 2 emissions in a survey of 120 institutions by 2015, meaning that four times these savings would need to be achieved by 2020 if the target were to be met (Carbon Credentials and The Environmental Association for Universities and Colleges 2016). In the same time-frame, energy costs to the sector have more than doubled from around £170m in 2005 to £400m in 2015 (Association of University Directors of Estates 2016).

The carbon savings that have currently been achieved have largely come from supply-side improvements, particularly in the development of Combined Heat and Power (CHP) systems, which now account for 16% of energy use in the sector (Higher Education Statistics Agency 2016). It is likely that the remaining savings will need to come largely from demand-side interventions. Some effort has been undertaken to improve the energy performance of existing buildings, particularly in improving the fabric of mid-twentieth century buildings. However it remains difficult to quantify or track improvements, due to a lack of reliable disaggregated data on carbon emissions (AUDE 2009). Energy savings may be counteracted by a perceived requirement for improved comfort and the installation of new environmental control systems (AUDE and HEFCE 2008).

Similarly, there is no agreed strategy for the Post-Occupancy Evaluation (POE) of HE buildings, as the most up-to-date guidance available from HEFCE, dating from 2006, ‘purposefully avoid[s] adopting any particular definition, preferring instead to embrace the concept that as Estates Professionals the whole life of a building or development is our responsibility' (HEFCE, AUDE, and University of Westminster 2006). This guidance may have been appropriate at the time, but a lack of follow-on agreement on the nature and scope of POE in the sector has meant that very few studies have been published explicitly examining the energy performance of HE buildings, representing a significant knowledge gap. There is therefore an urgent need to understand why HE buildings use more energy, as well as an opportunity to utilise better performing HE buildings to educate users about the impacts of their activities and the need for carbon emission reductions.

This paper builds on previous research contrasting environmental strategies in two HE buildings with five additional case studies, expanding the currently very limited availability of data about the energy performance and thermal comfort of identified Higher Education buildings in the UK. The design concept and environmental strategies of the seven buildings are first outlined. This is followed by the results of thermal comfort surveys conducted in each building, and analysis of their energy performance. Finally the environmental strategies and disaggregated energy data for two of the case studies – reflecting a recent trend to meet a perceived need for flexibility in multifunctional spaces – are examined in further detail.

This approach is employed to examine how environmental design strategy may be related both to energy performance and indoor thermal comfort conditions. Lessons are identified with relevance to the wider non-domestic building sector. The research complements evidence from POE studies that have either suffered from verification bias through the selection of 'model' examples of buildings with highly specialised environmental strategies for predictable and specific use patterns (e.g. schools, hospitals), or studies that have been too large to disaggregate data to explore causal relationships between specific design strategies and performance.

Background

The Performance Gap in non-domestic buildings

While predicted operational energy use in new non-domestic buildings continues to fall, analysis of Display Energy Certificate data has revealed that the standard approaches for estimating operational energy use are often systematically flawed, underestimating regulated energy due to errors in modelling deterministic phenomena, and failing to account for increased unregulated energy due to the stochastic behaviour of building occupants. According to a study of 528 public offices, recent changes in building regulations have reduced thermal energy use by almost 40% in buildings built after 2000. However this has been counteracted by a 75% increase in use of electrical energy in buildings constructed after 2000 (where electrical energy is almost double thermal energy use) relative to those built pre-1959, often due to the installation of heating, ventilation and air conditioning (HVAC) systems, resulting in higher overall CO_2 emissions (Armitage et al. 2015). A study by the Carbon Trust indicated actual energy use was up to five times higher than specified in refurbished offices (Carbon Trust 2008), while K. Gram-Hansen estimates actual energy use up to three times higher in the residential sector (Gram-Hansen 2011). The scale of the performance gap in HE buildings is currently unknown but likely to be comparable. HESA data suggests that mean carbon emissions across 9,833 non-domestic HE buildings are 86.3 $kgCO_2e/m^2$/annum, approximately 25% higher than the average office building in the UK (comparison of data from Higher Education Statistics Agency 2016; Armitage et al. 2015). Of 31 HE buildings for which data is available on CarbonBuzz (the RIBA/CIBSE reporting database), mean actual carbon emissions are 77.8 kg CO_2/m^2/yr, more than double mean design estimates of 36.3kg CO_2/m^2/yr (CarbonBuzz, RIBA and CIBSE, n.d.).

Post-Occupancy Evaluation

Post-Occupancy Evaluation (POE) describes the systematic evaluation of occupied buildings with the aim of providing feedback to inform remedial action and the design of future projects (Nicol and Roaf 2005). POE has been demonstrated to have a positive impact: reducing carbon emissions, running costs, and improving comfort and productivity from one project to the next. However, there remain many challenges to implementing POE in practice, including a lack of recognition of the value of the case study method, difficulty in engaging stakeholders, and concerns about liability following discovery of faults (Stevenson 2009). Findings from POE are often applied only to buildings of a similar scale and function with similar occupancy patterns, and dissemination is often restricted by commercial confidentiality.

Notable post-occupancy studies include the 23 PROBE case study buildings examined between 1995 and 2002 (Bordass et al. 2001), and specialist projects such as the EPSRC-funded 'Design and Delivery of Robust Hospital Environments in a Changing Climate' (DeDeRHECC) project (examining the impact of climate change on 9 hospital buildings) (Lomas and Giridharan 2012), which have revealed that the current and future energy performance of many buildings still falls significantly below expectations. A 2009 study by Newsham et al. of 100 LEED-certified buildings found that there was no statistically significant relationship between LEED-certification level and energy use (Newsham, Mancini, and Birt 2009).

More recently, 56 non-domestic buildings studied as part of the Technology Strategy Board’s Building Performance Evaluation (BPE) programme (Building Performance Evaluation Group, n.d.) revealed actual carbon emissions 3.8 times those predicted at the design stage (Palmer, Terry, and Armitage 2016). Reports from individual TSB BPE projects are being disseminated to industry via the Building Data Exchange web portal launched in February 2016, however the project executive report identifies unexpected and unexplained findings such as:

1. No correlation between airtightness and carbon emissions.

2. Problems with the application of BREEAM assessment as a predictor of energy performance ('Excellent' projects used more energy than 'Very good' projects).

3. A lack of data about the impact of control systems, e.g. Building Management Systems (BMSs).

4. A lack of understanding of the impact of unregulated loads/energy use 'out of hours' (Palmer, Terry, and Armitage 2016).

In order to address a lack of shared information and to identify underlying trends in performance across a wider range of buildings, other research has targeted understanding 'the performance gap' from a macro-scale analysis of larger building stock samples (Steadman and Hong 2013; Armitage et al. 2015). However, while these macro-scale studies reveal that performance data from individual POE studies is broadly representative, it is still not currently possible to identify design decisions in individual buildings that have led to higher than predicted energy use. The TSB BPE programme survey only included four HE buildings, three of which are atypical outliers (Table 1). As a consequence, there is an urgent need to examine the performance of a representative sample of Higher Education buildings in more detail.

Table 1. HE buildings included in TSB BPE programme.

Building	**Location**	**Date**	**Area m^2**	**Description**	**Energy use (kWh/m2/ annum)**
Jarman School of Arts	Canterbury	2009	2,500	A small specialist arts building	252.7
Sus. Con. Academy	Dartford	2014	3,907	An underused building designed as an exemplar	126.4
Thomas Paine Study Centre	Norwich	2010	4,300	Similar design to Elizabeth Fry building (PROBE case study)	212.0
University of West of Scotland	Ayr	2011	7,758	The largest/only typical HE building included in the survey	398.0

Thermal comfort

Thermal comfort has been defined as 'that condition of mind which expresses satisfaction with the thermal environment' (ASHRAE 2004). It results from a dynamic equilibrium; the interaction between people and buildings in a particular social and climatic context. (Nicol and Roaf 2005). As individuals have different comfort thresholds, they will react in different ways at different times, making unanimous perceptions of comfort satisfaction in spaces of multiple occupancy very difficult to achieve.

As different people have different standards for evaluating environments, a variety of environments (environmental diversity) can meet different people's needs, allowing them to choose a particular space to satisfy their own requirements. Thermal adaptation is described by de Dear et al. as consisting of three components: behavioural adjustment (e.g. clothing, controls), psychological adaptation (e.g. habituation, expectation), and physiological adaptation (e.g. acclimatisation) (R. de Dear and Brager 1998).

Even though the adaptive actions of occupants are complex and unpredictable, research has shown that if people can control or choose their environment, their satisfaction with the environment will rise significantly (Leaman and Bordass 1999). Environmental design should therefore aim to provide environmental diversity, as well as opportunities for people to control and adapt to their own environment (Leaman and Bordass 2007).

However, providing personal control in the open plan spaces typical of HE buildings is often considered to be too costly and impractical; temperature and lighting are therefore often designed to meet generic standards, automatically controlled by Building Management Systems (Myerson and Bichard 2010).

Field studies

Due to the complexity of the human sensory system, it is impossible to simulate the thermal comfort of an individual in a particular space in a constantly changing environment through a theoretical model (Nicol, Humphreys, and Roaf 2012). In order to assess the thermal comfort of a space it is therefore necessary to conduct a field survey. Satisfaction is measured by interviewing subjects for a 'vote' on a descriptive scale such as the ASHRAE scale. The AHSRAE scale has been thoroughly tested through continuous use over many years (Nicol, Humphreys, and Roaf 2012). A neutral feeling is recorded as '0', while the two extreme points, cold and hot, are defined as '-3' and '3' respectively. The other scores describe 'slightly warm' (1), 'warm' (2), 'slightly cool' (-1) and 'cool' (-2). These scores can be combined to ascertain the Actual Mean Vote (AMV).

In contrast, the Predicted Mean Vote (PMV) heat exchange model was developed from the principle that a subject is a passive recipient of thermal stimulation, and the effects of a thermal environment are mediated by the physics of heat transfer alone (R. de Dear and Brager 1998). The PMV model was developed from the results of thousands of experiments conducted in controlled conditions in a climate chamber. However, it does not consider contextual and psychological variables. As a result the PMV model is more accurate the more unfamiliar participants are with the space they occupy and the less ability they have to control their conditions (Michael Humphreys, Nicol, and Roaf 2015). Discrepancy between AMV and PMV may be an indication of more adaptive behaviour by occupants seeking to achieve thermal comfort individually. This behaviour is encouraged by adaptive opportunities, more of which are likely to be present in passive, free-running buildings.

Description of case studies

HE buildings are often characterised by more heterogeneous use patterns than other non-domestic buildings, due to a greater diversity of spatial requirements and daily as well as seasonal changes in occupancy, leading to more variation in use. The seven case studies examined here represent buildings of different ages with different environmental design strategies (Figure 1). They include a range of design strategies and use patterns, focussing on more complex situations that have been largely overlooked in existing POE, which has tended to focus on successful examples of buildings fine-tuned with more specialised environmental strategies for more predictable use patterns (Table 2).


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Figure 1. Clockwise from top right: Arts Tower; Western Bank Library; Reid Building; Benzie Building; Information Commons; The Diamond; Potterrow.

Table 2. Case study buildings.

Building	Location	Date (refurbish)	Area m^2	Architect (refurbishment)	Design brief
Arts Tower	Sheffield	1965 (2011)	7,200	Gollins, Melvin, Ward & Partners (HLM Architects)	Refurbishment of offices and studio spaces – occupancy and use well-established
Western Bank Library	Sheffield	1959 (2009)	11,160	Gollins, Melvin, Ward & Partners (Avanti Architects)	Refurbishment of library – occupancy and use well-established
Reid Building	Glasgow	2014	11,250	Steven Holl Architects (with JM Architects)	New art school – occupancy patterns similar to existing school
Benzie Building	Manchester	2012	17,320	Feilden Clegg Bradley Studios	Extension to art school – new flexible space, occupancy and use uncertain
Information Commons	Sheffield	2007	11,500	RMJM	New study centre – occupancy patterns uncertain
The Diamond	Sheffield	2015	19,500	Twelve Architects	New multi-functional faculty building – occupancy and use uncertain
Potterrow	Edinburgh	2008	16,000	Bennetts Associates	Designed as flexible office space to BCO specifications – occupancy and use uncertain

The Arts Tower and Western Bank Library are the oldest buildings included in the survey, dating from the mid 20th century. They neighbour each other and were designed concurrently, connected by a bridge at mezzanine level. The library was completed first in 1959. Its large reading room, characterised by curtain glazing offering views north across Weston Park, sits atop a square plan of book stacks, which rely on artificial lighting and ventilation. Construction of the Arts Tower began in 1961, three years after Mies can der Rohe's Seagram building in New York, to which the Arts Tower, although half the height, clearly owes an aesthetic debt (Everett 2013).

The buildings were amongst the first of a new generation of post-war university buildings constructed in the UK, representing the arrival of the International Style as the architectural language that best symbolised the ambition of what Harold Wilson described as the 'white heat of the technological revolution', including the promise of unlimited energy from nuclear fusion (Calder Hall, the world's first nuclear power station, opened in 1956). For the first time Mies's vision of curtain-walled towers seemed practical, aided by advances in air conditioning and fluorescent lighting, although, intriguingly, the former was considered to be unaffordable in the Arts Tower, which was instead fitted with opening metal sash framed windows (Schneider 2007). This compromise, together with the relatively poor thermal characteristics of the facades (which are identical regardless of orientation), led to regular overheating in the south side of the tower in summer. Both buildings have recently been refurbished, however intervention to the fabric has been limited by their Grade II* listing (Everett 2013). The library is still in use largely as designed, while the Arts Tower is divided between university administration on the lower levels and academic departments (Landscape and Architecture) above.

Mies's legacy – divorcing the envelope of the building from open plan spaces inside, which are largely mechanically serviced regardless of orientation – is still apparent today, as can be seen in several of the later case studies included in this survey, the designs of which have often been driven by a perceived need for more 'flexible' space planning.

The Reid Building was completed in 2014. It sits directly opposite Mackintosh's Glasgow School of Art of 1910, and accommodates a range of new studio spaces for that institution at different scales. Despite being designed over a century apart the plans of the two buildings are in fact broadly similar, with high ceilinged and brightly day lit teaching spaces to the north, and a range of ancillary spaces to the south. The circulation of the Reid building is arranged around three 'driven voids', admitting daylight into the centre of the plan and permitting natural stack ventilation ('Art Academy in Glasgow' 2014).

The Benzie building, completed in 2012, is the latest extension of Manchester School of Art, joined to a three storey 1960's building with a nine storey tower to the east. The new building is composed of a six storey ‘living room’ (café and social space) behind a highly glazed north façade, and a four storey ‘factory’ (composed of classrooms and open plan working space) to the south. The ‘factory’ is organised around an atrium with two lanterns to the roof, however the admission of daylight is carefully restricted. Fresh air is supplied through floor diffusers and extracted at high level through a heat exchanger on the roof (Mara 2013).

The Information Commons opened in 2007. With 1,300 workstations over seven levels, it is Sheffield’s largest library, open 24/7 (Salter 2015). Located at the junction of two major trunk roads, it is orientated around a central atrium with restricted views to the exterior. It is mechanically ventilated and air conditioned, and largely closed off from the outside world.

The Diamond, housing teaching and research space for the Faculty of Engineering, represents the largest ever capital investment for the University of Sheffield. Costing £81m, the building was opened in 2015. The Diamond is also a 24/7 facility, with six levels housing a range of lecture theatres, seminar rooms, open plan study spaces, library, IT services, spaces for informal study and a café. The top four levels of the building include an atrium designed to provide an open and light atmosphere. The building operates in a mixed mode, with mechanical ventilation in closed spaces and stack ventilation in the atrium (Cousins 2016).

Potterrow is a multi-departmental building organised around a central atrium for the University of Edinburgh. The first phase was completed in 2008, housing the School of Informatics and the School of Philosophy, Psychology and Language Sciences. To facilitate a requirement for ‘simple flexible space to accommodate constantly changing academic requirements’, the building was designed with moveable partitions providing cellular accommodation (MacGregor 2004).

Corridors provide access to offices on the outside of the building or looking into the central atrium, with breakout spaces at a range of scales. The servicing strategy is a complex hybrid, with air supplied from sub-floor plenums or opening windows to the outside, and extracted via a heat exchanger at the top of the atrium.

The environmental strategies and the thermal characteristics of the fabric of the seven case studies are summarised below (Table 3).

Table 3. Environmental strategies and thermal characteristics.

Building	Mode	Fabric	Environmental strategies	U-value (fabric)	U-value (glazing)	Glazing ratio %
Arts Tower	Naturally ventilated	Concrete frame, glass spandrel panel facade	Operable windows, high-performance glazing	1.10	2.2	55
Western Bank Library	Mechanical ventilation/ AC	Concrete frame, Portland stone cladding on brick base	Air conditioning, perimeter heating around glazed facades	0.70	1.6	55
Reid Building	Naturally ventilated	In-situ concrete structure clad over in glass	Stack ventilation through circulation spaces with radiant heating and exposed thermal mass	0.24	1.6	40
Benzie Building	Mechanical ventilation/ AC	Concrete frame, glass aluminium curtain walling system	Variable air volume system and lighting controls to adapt to different occupancies	0.17	1.1	60 (N), 20 (S)
Information Commons	Mechanical ventilation/ AC	Concrete frame, cladding (glazing, copper, terracotta tile) supported by steel frame	Conditional air module (CAM) climate control with underfloor plenums	0.25	1.6	20
The Diamond	Mixed-mode	Steel frame, anodised aluminium and glass spandrel panel facade	Air conditioning in closed spaces and stack ventilation in atrium	0.22	0.8	40
Potterrow	Mixed-mode	Concrete frame, cast stone panel facade	Exposed concrete slabs and sub-floor plenums, heat recovery system in atrium	0.25	1.9	40

Methodology

Field surveys

As indicated in CIBSE TM52, occupant evaluation of the indoor thermal environment is largely context dependent and varies over time (CIBSE 2013). A transverse occupant field survey of each building was therefore conducted. Participants were interviewed in situ with date, time and location recorded. The questionnaire was designed to be completed as quickly as practically possible (under 5 minutes) while meeting the requirements of what has been defined as a 'level 3' survey, including 'all factors needed to calculate the heat exchange between a person and the environment, together with subjective responses' (Nicol, Humphreys, and Roaf 2012).

A seven-point ASHRAE scale was used to measure subject's thermal sensation and thermal satisfaction votes as recommended by Humphreys and Hancock (M. Humphreys and Hancock 2007) (see Appendix A). In total 403 thermal sensation votes (Actual Mean Vote) and 405 winter thermal preference votes were recorded across six buildings, and 505 summer thermal preference votes were recorded across seven buildings. Data was simultaneously collected on subject activity and clothing (clo value) (Table 4).

Table 4. Survey details.

Building	Survey date	Sample size	Mean operative temp. (°C)	Mean clo value	Mean neutral temp. (°C)	Thermal sensa-tion	Thermal pref. (summer)	Thermal pref. (winter)
Arts Tower	June 2015	50	23.5	0.82	21.7	X	X	X
Western Bank Library	July/Aug 2017	30	23.0	0.87	22.5	X	X	X
Reid Building	October 2016	72	18.3	1.28	16.8	X	X	X
Benzie Building	July 2018	100	24.7	0.59	23.8	X	X	-
Information Commons	June 2015	51	24.1	0.85	23.5	X	X	X
The Diamond	June/July 2017	100	23.0	0.53	22.6	X	X	X
Potterrow	October 2013	102	21.0	0.96	-	-	X	X

Environmental measurements were collected concurrently to the administration of the occupant survey using a handheld Testo 435 multifunction meter with Testo radiant globe thermometer, air thermometer, Relative Humidity (RH) and hot-wire anemometer probes.

This equipment offers an operating temperature range of -50° to 150°C with a resolution of 0.1°C, 0 to 20m/s for air velocity with a resolution of 0.1m/s, and 0 to 100% for RH with a resolution of 0.1%. Accuracy for temperature is ± 0.2°C from -25°C to 75°C, ±0.03 m/s +5% for air velocity, and ± 2% from 2 to 98% for RH. Measurements were taken at a height of 1.1m at the location of each interviewed subject, away from radiators and other heat sources. The Predicted Mean Vote (PMV) was then calculated for comparison with Actual Mean Vote (AMV), using the CBE Thermal Comfort Tool, according to ASHRAE Standard 55 (University of California Berkeley n.d.).

Mean neutral temperature (T_n) was calculated from the mean operative temperature (T_o) employing the Griffiths method, assuming that a thermal sensation vote (V) of 0 represents comfort. $T_n = T_o - V/G$, where G represent the 'Griffiths constant' (K^{-1}), a standard value for the relationship between sensation vote and operative temperature, assuming no adaptive behaviour occurs (Griffiths 1990). A value of 0.5 has been chosen for the Griffiths constant as recommended by Nicol and Humphreys, based on observations of thermal comfort collated from databases compiled by de Dear (R. de Dear 1998) and the Smart Controls and Thermal Comfort project (McCartney and Nicol 2001). It should be noted that no relationship was found between the Griffiths constant and the mode of building operation (M. A. Humphreys, Nicol, and Raja 2007; Nicol and Humphreys 2010).

Energy data

Energy use data for the Arts Tower, Western Bank Library, the Information Commons and the Diamond was collected via Energy Remote Monitoring (ERM) and Power Monitoring Energy (PME)[1] systems. Energy use data for the Reid and Benzie buildings and Potterrow was obtained from Building Managers. Energy data is examined at the scale of the whole

[1] The ERM system collects ½ hourly electricity consumption data. The PME system monitors consumption at a more detailed level (e.g. by floor). It also allows electricity consumption data to be collected in real time.

building. This data is compared with CIBSE Part F annual energy usage for libraries (the most relevant in terms of occupancy patterns and small power use for study spaces).

Results

The mean thermal sensation, recorded as Actual Mean Vote (AMV), was compared with the Predicted Mean Vote (PMV) for six of the case studies (thermal sensation was not recorded for Potterrow). Thermal preference was also examined, as it should not be assumed that the preferred thermal sensation is neutral (M. Humphreys and Hancock 2007). Thermal preference was recorded for seven case studies in summer, and six of the case studies in winter (winter thermal preference was not recorded for the Benzie Building), reflecting changing preferences over an annual cycle. The results of the field surveys of each case study are presented below (Table 5).

Table 5. Results.

Building	Sample size	PMV	Mean thermal sensation (AMV)	SD	Mean thermal pref. (summer)	SD	Mean thermal pref. (winter)	SD
Arts Tower	50	-0.48	0.90	1.17	-0.82	0.96	1.40	0.99
Western Bank Library	30	-0.28	0.23	0.96	-0.43	0.82	1.13	0.82
Reid Building	72	-0.55	0.76	1.25	-0.75	0.80	0.25	0.80
Benzie Building	100	-0.12	0.45	0.88	-0.38	0.72	-	-
Information Commons	51	-0.26	0.29	1.43	-0.80	0.92	0.78	1.05
The Diamond	100	-0.70	0.22	1.00	-0.99	0.94	0.04	0.85
Potterrow	102	-	-	-	-0.79	0.94	0.24	1.01

One-way ANOVA tests were conducted to compare thermal sensation scores (AMV) (Table 6), thermal preference scores in summer (Table 7), and thermal preference scores in winter (Table 8). There was a significant difference in thermal sensation scores [F(5, 397) =

4.042, p = 0.001], summer thermal preference scores [F(6, 498) = 4.981, p = 0.000], and winter thermal preference scores [F(5, 399) = 20.798, p = 0.000] between the buildings. Post hoc comparisons using the Tukey test were carried out with significant findings reported below.

Table 6. Thermal sensation statistical tests.

ANOVA	Sum of squares	df	Mean square	F	Sig.
Building	25.011	5	5.002	4.042	0.001
Error	491.351	397	1.238		
Total	516.362	402			

Tukey HSD	Mean difference	Std. error	Sig.	90% confidence interval	
				Lower bound	Upper bound
Arts Tower/Diamond	0.68	0.192	0.006	0.179	1.181
Reid Building/Diamond	0.54	0.172	0.021	0.097	0.991
Arts Tower/Information Commons	0.61	0.221	0.070	0.031	1.181

Table 7. Summer thermal preference statistical tests.

ANOVA	Sum of squares	df	Mean square	F	Sig.
Building	22.777	6	3.796	4.981	0.000
Error	379.512	498	0.762		
Total	402.289	504			

Tukey HSD	Mean difference	Std. error	Sig.	90% confidence interval	
				Lower bound	Upper bound
Diamond/Benzie Building	-0.61	0.123	0.000	-0.944	-0.277
Potterrow/Benzie Building	-0.41	0.123	0.014	-0.746	-0.823
Diamond/Western Bank	-0.56	0.182	0.037	-1.048	-0.066
Arts Tower/Benzie Building	-0.44	0.151	0.058	-0.849	-0.032
Information Commons/Benzie Building	-0.42	0.150	0.073	-0.830	-0.018
Reid Building/Benzie Building	-0.37	0.135	0.090	-0.735	-0.006

Table 8. Winter thermal preference statistical tests.

ANOVA	Sum of squares	df	Mean square	F	Sig.
Building	89.077	5	17.815	20.798	0.000
Error	341.787	399	0.857		
Total	430.864	404			

Tukey HSD	Mean difference	Std. error	Sig.	90% confidence interval	
				Lower bound	Upper bound
Arts Tower/Diamond	1.36	0.160	0.000	0.944	1.777
Arts Tower/Potterrow	1.16	0.160	0.000	0.750	1.580
Arts Tower/Reid Building	1.15	0.170	0.000	0.707	1.593
Western Bank/Diamond	1.09	0.193	0.000	0.593	1.594
Western Bank/Potterrow	0.90	0.192	0.000	0.399	1.398
Western Bank/Reid Building	0.88	0.201	0.000	0.361	1.406
Information Commons/Diamond	0.74	0.159	0.000	0.331	1.158
Information Commons/Potterrow	0.55	0.159	0.008	0.137	0.962
Arts Tower/Information Commons	0.62	0.184	0.012	0.137	1.094
Information Commons/Reid Building	0.53	0.169	0.021	0.942	0.975

Thermal sensation

According to the thermal sensation scores (AMV) it appears that the buildings which are naturally ventilated and more passively controlled (the Arts Tower and the Reid Building) are perceived to be warmer than the buildings which are more mechanically conditioned and controlled by active environmental systems such as BMSs (the Diamond and the Information Commons) (Figure 2).

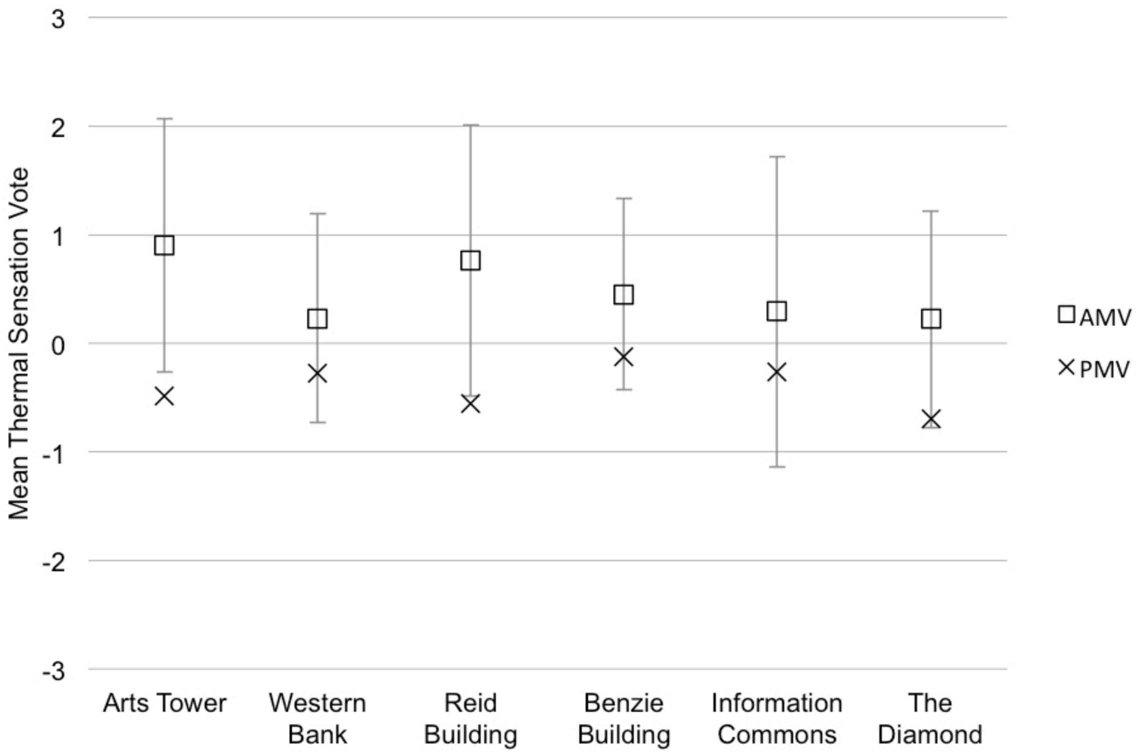

Figure 2. AMV and PMV compared.

Disparities greater than ±1 on the ASHRAE scale were identified between AMV and PMV in the Arts Tower and the Reid Building. This supports the hypothesis that the PMV model is a more accurate predictor of thermal sensation in buildings with more active control of the thermal environment, such as the Benzie Building and Information Commons. In the naturally ventilated Arts Tower and Reid Building, subjects reported feeling ‘quite warm’, while the PMV model suggested they should feel between ‘neutral’ and ‘slightly cool’. This may demonstrate the impact of psychological variables on perceptions of comfort in more dynamic environments. These variables have been identified as naturalness, expectations, experience (short- and long-term), time of exposure, perceived control and environmental stimulation (Nikolopoulou and Steemers 2003).

Thermal preference

According to the thermal preference scores, in summer the Benzie Building and Western Bank Library are perceived to be more comfortable (cooler) than the other five buildings. In winter the Diamond, Potterrow and the Reid Building are perceived to be more comfortable (warmer) than the other three buildings (Figures 3, 4).

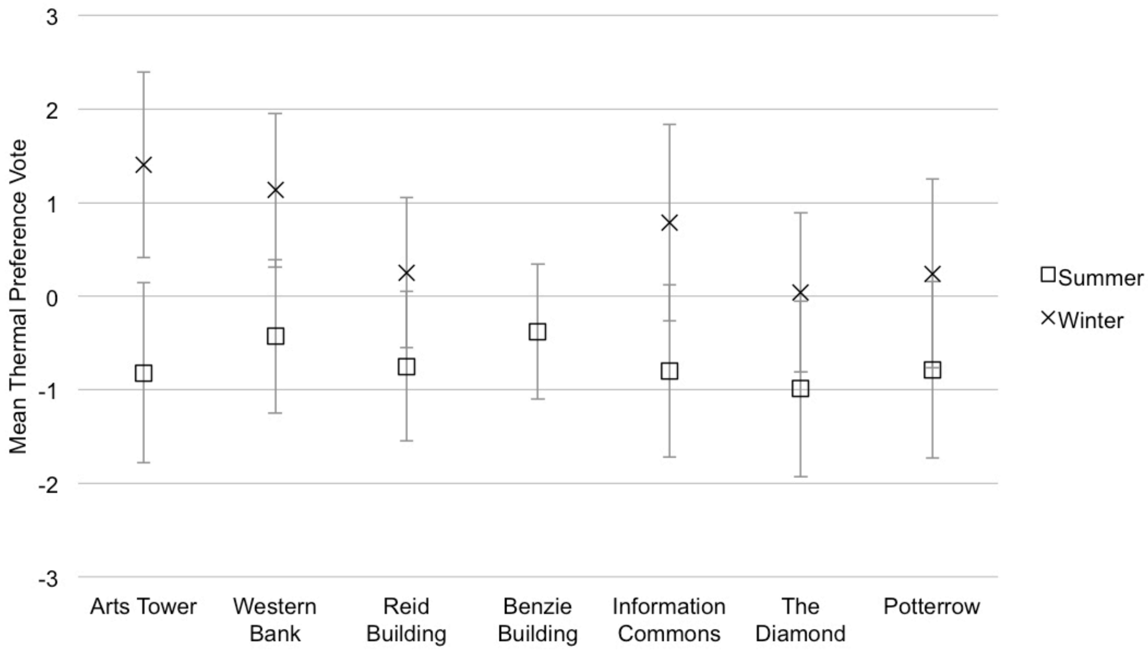

Figure 3. Mean thermal preference in summer and winter.

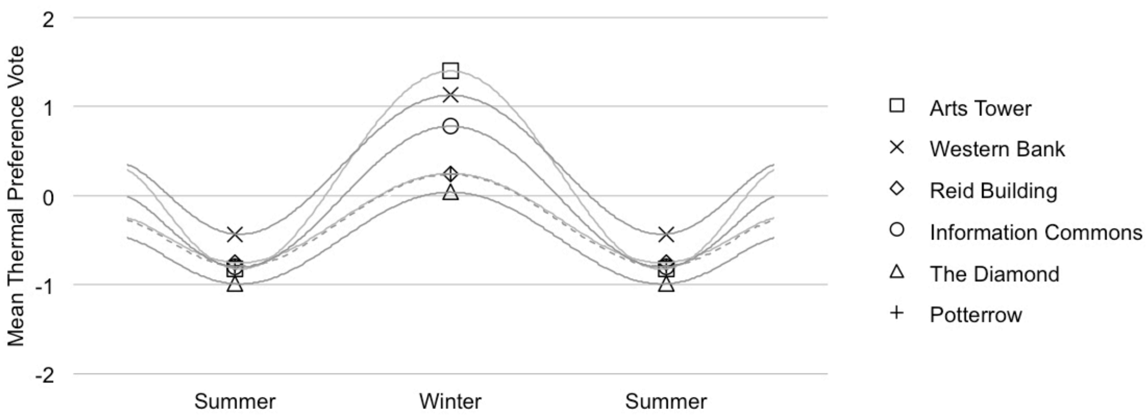

Figure 4. Mean thermal preference showing seasonal variation.

The buildings perceived to be most uncomfortable in summer (The Diamond and Potterrow) both rely on mechanical ventilation and cooling, while the Arts Tower is perceived to be the most uncomfortable naturally ventilated building. In winter it appears that the older buildings with the highest u-values (the Arts Tower and Western Bank Library) are perceived to be less comfortable (cooler) than the newer buildings with improved fabric performance, such as the Diamond, Potterrow and the Reid Building.

Energy performance

The oldest buildings (the Arts Tower and Western Bank) use significantly less energy than the more recently constructed buildings. These two buildings are the only buildings to achieve below the CIBSE-Part F standard for Good Practice for a naturally ventilated library, considered to be a reasonable proxy for student study spaces (a figure of 161 kWh/m2). Of the recently completed buildings, the naturally ventilated Reid building uses the least energy. It has not been possible to disaggregate energy data for the Reid building as heating is provided by a campus wide CHP system (Figure 5).

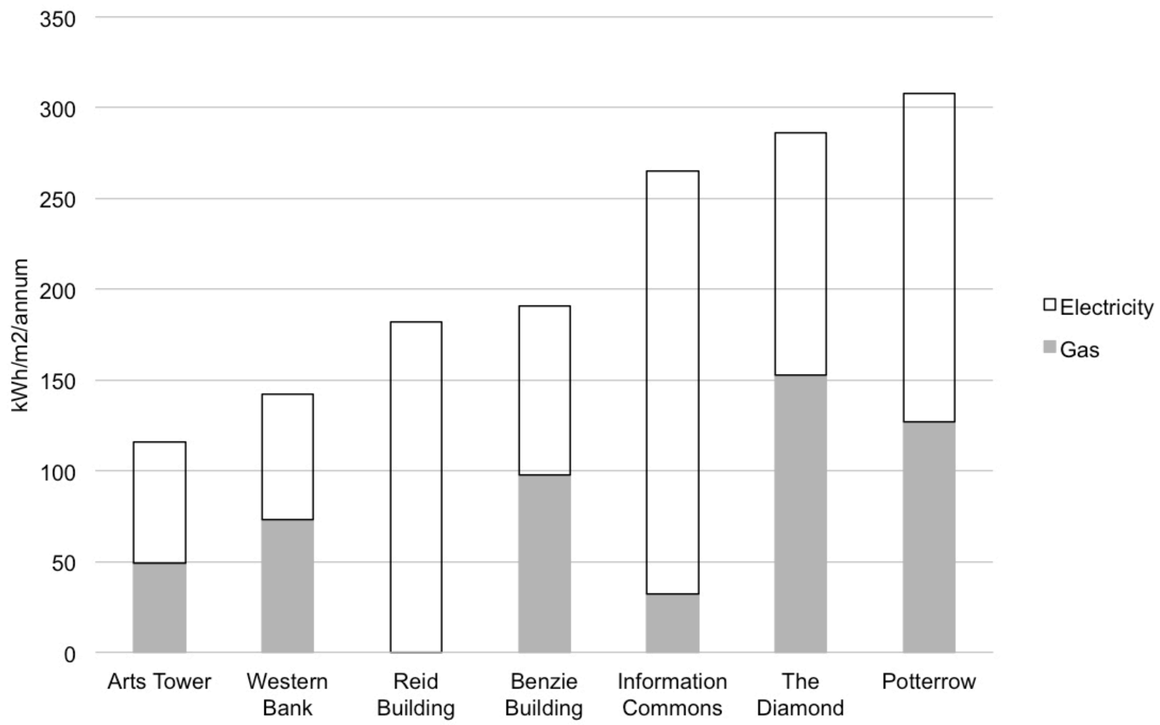

Figure 5. Energy use.

However when carbon emissions are considered, the Benzie building may be responsible for lower emissions than the Reid building, as the carbon content of gas for heating (which is responsible for a larger share of energy use in the Benzie building) is lower than electricity (Figure 6). Similarly, buildings with significantly greater electricity use are responsible for greater carbon emissions (carbon emissions from Potterrow are however reduced through connection to a CHP network). This highlights the significance of understanding carbon conversion factors in the development of the environmental strategy for HE buildings, particularly in achieving the right balance between heating, and ventilation and cooling, which represent significant end uses of electricity.

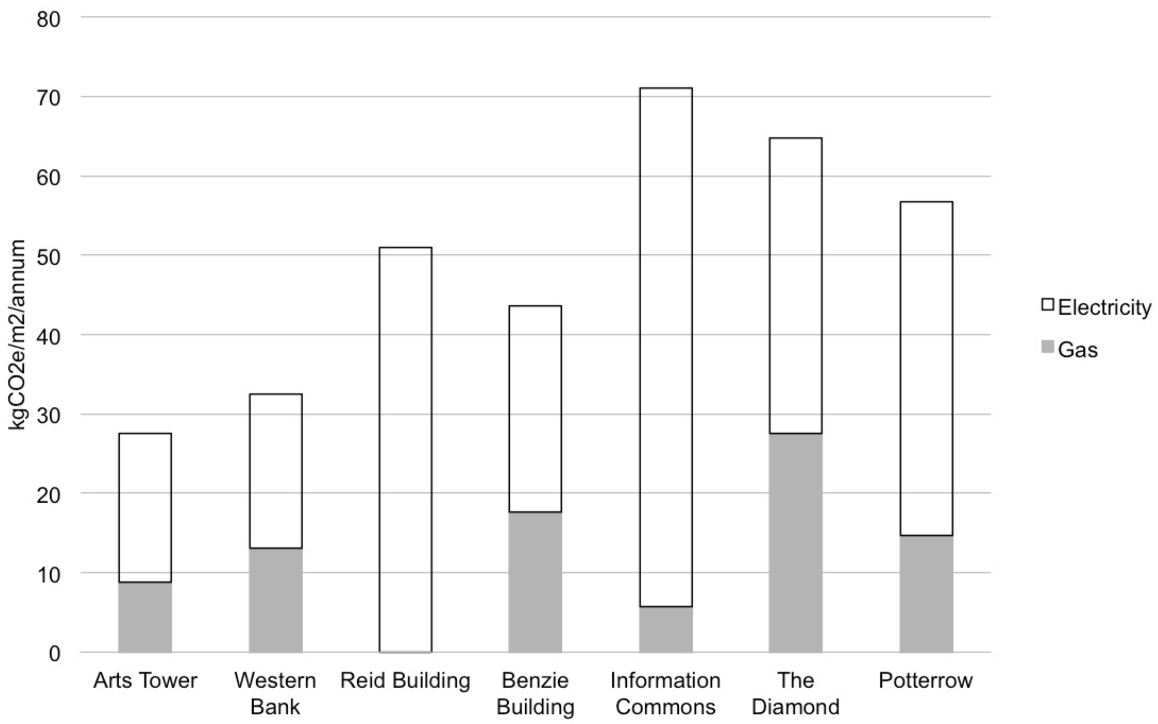

Figure 6. Carbon emissions.

Discussion

The thermal sensation scores suggest that the naturally ventilated buildings tend to be perceived as warmer than the mechanically ventilated or air-conditioned buildings. This may partly be accounted for by the timing of the surveys, the majority of which took place over summer. However, as the thermal preference scores show, this finding does not equate to greater discomfort on the part of the users of these buildings. This supports the findings of previous research (M. Humphreys and Hancock 2007; Roaf et al. 2010).

The thermal preference scores show that, while Western Bank Library and the Arts Tower were refurbished in 2009 and 2011 respectively, in winter users feel the consequences of the relatively poor thermal performance of their fabric, characterised by high u-values and low standards of airtightness compared with the newer buildings. In particular, large areas of curtain glazing on the Arts Tower, and problems with the opening windows, are the cause of noticeable discomfort. This may also reveal a decline in adaptive tolerance in recent years, as expectations of thermal comfort have changed with the development of new buildings that provide more constant conditions all year round (Roaf et al. 2010).

However, in summer it is notable that the Information Commons, the Diamond and Potterrow are perceived to be almost equally too warm. With projected increases in temperature due to climate change in coming decades, there is a danger that these new buildings, which rely on mechanical HVAC systems with spaces largely sealed off from the outside, may cause greater discomfort as users struggle to adapt. Based on this research there is little evidence to support the hypothesis that mixed-mode or hybrid buildings (such as the Diamond and Potterrow) can promote adaptive thermal comfort behaviour more readily than those that employ mechanical HVAC exclusively (such as the Information Commons), though more research is required in this area (Carlucci et al. 2018).

Naturally ventilated buildings are likely to be perceived as more comfortable as winters become warmer, and more resilient to perceived discomfort during summer heatwaves (Lun, Ohba, and Morikami 2012). The variety of spaces in the naturally ventilated Reid Building, for example, together with the careful consideration of orientation (unlike the other naturally ventilated building in the survey, the Arts Tower), afford users more control of their working environment. Students and staff can choose to work in brighter, darker, side or toplit studios, and adjust ventilation and temperature by manually opening and closing windows and blinds.

A similar observation may be made with regard to energy efficiency. With warmer summers and increased incidence of heat waves, the energy performance of buildings that rely on air conditioning to maintain comfort conditions may steadily decline in comparison with buildings that rely on connections to the outside for users to adapt. This supports the findings of previous research examining council offices, which found a significant increase in electricity use in buildings constructed over the last two decades, despite for example a 60% decrease in maximum permissible u-values in UK building regulations over the same period

(Armitage et al. 2015).

In the next section examples of two recently constructed case studies are examined in more detail. In particular, the environmental implications of the design ambition for open plan flexible spaces are considered.

The environmental design of flexible spaces

The Information Commons

The Information Commons is an example of a modern building that has been designed to take control away from occupants and use automated systems to control environmental conditions and mitigate interventions by occupants (Figure 7). Two Air Handling Units located on the roof incorporate supply and extract fans, hot water heating coils, cross-flow heat exchangers, and chilled water provided by a blast air cooler and two chillers (Buckman 2016).

Figure 7. Study space, the Information Commons.

A complex Building Management System is employed to manage the internal environment. Each level is divided into between three and six control zones, except levels 5 and 6 which are treated as single zones. Air supply is mostly from a raised floor void, via swirl outlets. Artificial lighting is restricted to a relatively dull 150 lux in most areas, rising to 300 lux in study spaces. PIR occupancy detectors in each zone turn off the HVAC and lighting systems after 30 minutes of inactivity. However this is often rendered ineffective by cleaning staff and 24/7 security checks by porters (Figure 8). Computers will automatically turn off after 20 minutes of inactivity when logged off.

Figure 8. PIR detectors activating lighting in the Information Commons.

The Diamond

The Diamond also employs a Building Management System to manage the internal environment. This controls the mechanical ventilation system in closed spaces, and automated louvres at clerestory level in the atrium. These open if the outside air temperature is between 17°C and 25°C and the indoor temperature has reached 24°C. Vents in the east and west façades are also automated to provide the building with natural ventilation, and for smoke extraction (Plockova 2016).

The building relies on artificial lighting, particularly at lower levels (Figure 9). Most of the study spaces have a desk lamp overhead, which can be turned on, off, or dimmed by the user. This supplements background lighting. Each of the building zones has a presence detector. If no movement is registered for a specific amount of time, the system will turn off the main lights and in return will turn them back on if movement is detected. Lighting in corridors is controlled manually by building managers. In other places, especially closed bookable rooms, users can control the light by turning it on or off. Projection units located at a higher level project lights toward celling mirrors which provide artificial light in the atrium, which is otherwise poorly daylit by deep circular skylights in the roof (Figure 10).

Figure 9. Lower levels, the Diamond.

Figure 10. The atrium in the Diamond.

Performance issues

The Information Commons and the Diamond are responsible for the highest carbon emissions of the seven buildings included in this study, with artificial lighting operating extensively throughout for 24 hours a day, and narrow temperature set point ranges maintained by mechanical HVAC systems (Figure 11).

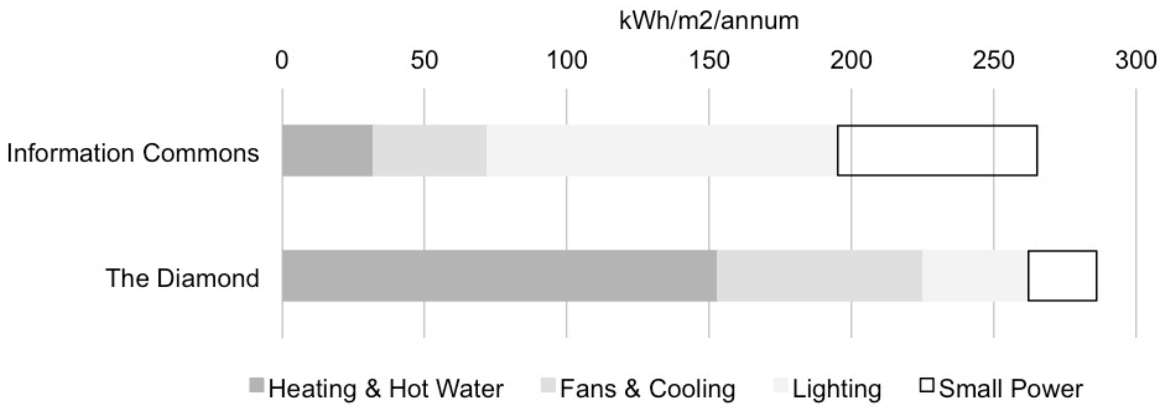

Figure 11. Breakdown of energy use in the Information Commons and the Diamond.

Despite this, they do not appear to offer any significant advantages in terms of how comfortable they are perceived to be by users. Conversely, the use of complex BMS systems to prevent users from 'interfering' with the 'correct' running of each building has led to user complaints about a lack of control over the internal environment. 32% of users of the Information Commons would prefer to have 'more' or 'much more' control over the temperature of their environment (Figure 12), and 51% of users would prefer to have 'more' or 'much more' control over lighting, despite it being the biggest end use of energy in the building (Figure 13).

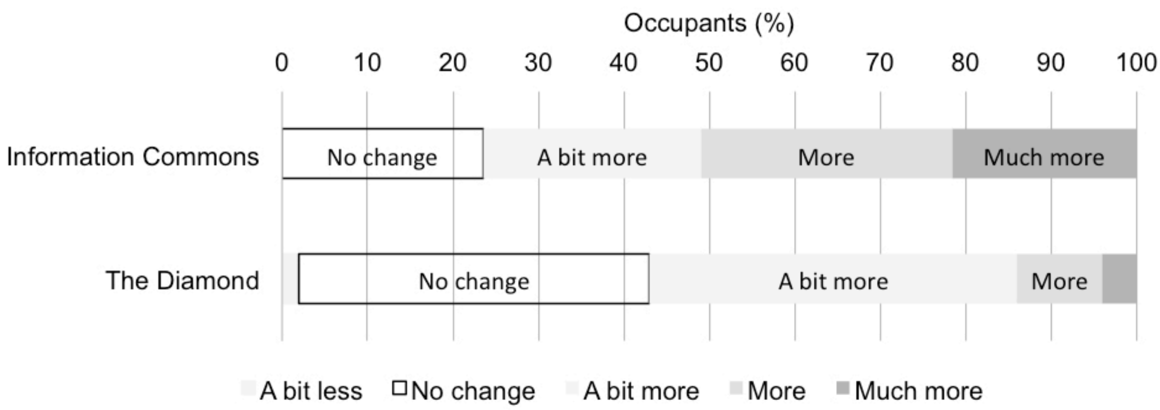

Figure 12. Preferred control of temperature in the Information Commons and the Diamond.

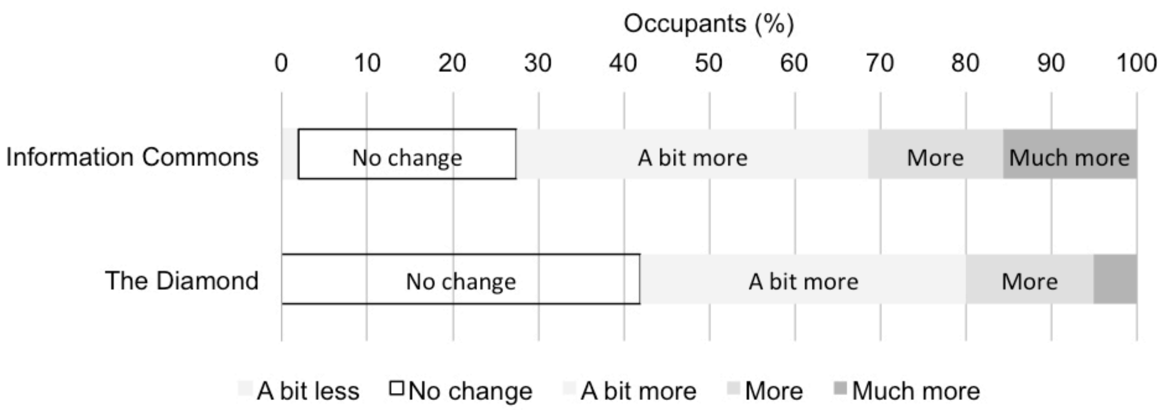

Figure 13. Preferred control of lighting in the Information Commons and the Diamond.

The inflexibility of the environmental strategy and control systems in these buildings contrasts with the ambitions of their designers: to create ‘flexi-spaces’ which are ‘user-configurable’ in the Information Commons (Lewis 2010); and ‘flexible’ and ‘adaptable’ spaces for informal study in the Diamond (Arup n.d.). Arguably the ‘flexible’ occupancy and use patterns desired for both buildings have led to a lack of user interface with the environment, leading to complaints as users struggle to adapt. This supports previous research that shows that occupants show more ‘forgiveness’ for naturally variable indoor conditions which they can control (Leaman and Bordass 1999), and where the environmental design intent is more legible (Leaman and Bordass 2007).

The theoretical justification for the complex automated systems incorporated into these buildings are that they are necessary to easily adjust to the varying demands of heterogeneous patterns of occupancy and use over both diurnal and seasonal cycles, exacerbated by periods of intensive student activity around exams and long transient periods outside of term.

However research has shown that increased automation of environmental systems is only efficient when buildings approach near maximum occupancy, which is often not the case in HE institutions. For example, ‘sub-optimal’ energy use in the Information Commons (when the occupancy of the building is less than 50% capacity) is on average five times higher per person than ‘optimal’ use (when occupancy is over 50% capacity). ‘Optimal’ conditions are only reached for 30% of the year (Buckman 2016).

Conclusion

With Post-Occupancy Evaluation becoming more routine, together with year-on-year growth in investment and the professionalisation of HE estate management, it is often assumed that the performance of new HE buildings is continually improving. However, this research has revealed a far more complex situation, with a fashion for flexibility in the design of HE buildings leading to environmental strategies that are increasingly disconnected from the outside world, with control systems routinely automated. This has not translated either into improved performance in terms of energy use or improved comfort for occupants.

The findings of this paper supports existing research which suggests that there is up to a three times scalar difference in the energy performance of non-domestic buildings. This hypothesis has been tested in seven higher education buildings with similar functional requirements. Intriguingly, of the seven buildings considered in this study, the two refurbished mid-twentieth century buildings use the least energy. This suggests that an energy-first approach to improving performance may be to adopt the passive design strategies of earlier buildings, which together with recent improvements to fabric (u-vales and airtightness), may offer users more opportunities to control and adapt to their environment locally, rather than attempting to design one-size-fits-all universal systems.

The new building which uses the least energy (the Reid building) is closest to this model, while the buildings that use the most energy follow the standard contemporary approach of highly-automated HVAC systems, with deep plans oriented around central atriums rather than connection to the outside environment. These buildings often do not perform as well as expected, partly because of over-optimistic assumptions about occupancy and use patterns made at the design stages, contributing to overly ambitious predictions of energy use (the performance gap). Similarly, it does not appear that increased automation translates into improved comfort, with broadly similar thermal preference scores across the case studies.

Specifically, this research has highlighted the following key issues:

1. The perceived need for ‘flexible’ open-plan spaces in HE buildings has led to increasing reliance on automated control systems, with negative consequences in terms of perceived occupant comfort.

2. The naturally ventilated buildings in this study suggest that alternative passive environmental strategies can be as effective as technological solutions in providing comfort, particularly when these are in tune with the local climate.

3. There is little evidence that improvements to building fabric as a result of recent changes to building regulations have had any impact on energy performance in HE buildings.

4. HE buildings that rely on mechanical HVAC systems perform poorly in energy terms during periods of low occupancy, despite automated control by BMSs.

These findings suggest that it is necessary to reevaluate the assumptions that have led to the highly automated environmental design strategies perceived to be required for the provision and management of more open plan or 'flexible' spaces. An over-emphasis on the need for flexibility (often understood as a need for more open plan spaces, or spaces with reconfigurable divisions) has led to an increasing reliance on mechanical servicing via floor or ceiling voids rather than connection with outdoors. However there is little evidence that HE institutions reconfigure or adapt these spaces more often than in the past. It is possible that the desire for flexibility may simply reflect the complexity of HE client requirements, and the need to placate different, and often competing, groups of users in the design stages.

If HE clients and design teams were able to better define future occupancy and use patterns following completion and over a building's lifetime, it may be possible to develop more robust environmental strategies that reduce the performance gap. Passive design alternatives, such as improved daylighting or accepting a wider range of temperatures in different spaces, may result in better performance. For example, carefully designing a series of environmental transition spaces from outdoors has been shown to increase user tolerance to a broader range of temperatures, permitting HVAC systems to be reduced in size (Vargas, Lawrence, and Stevenson 2017). Similarly occupants will feel more comfortable as they regain control over how they inhabit their immediate environment. Reducing servicing requirements and improving comfort in turn improve flexibility, as obsolescence of equipment and control systems is avoided, and spaces are more adaptable for future occupants and/or change of use.

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Appendix A. Occupant Survey

General Information

a) Date: Time:

b) Gender:

c) Location: Time spent in the building:

d) Activity: Clo value:

e) Conditions:
Radiative temperature: Air temperature: RH:
AV:

Votes

a) How do you feel at this time?
□ 3 Hot □ 2 Warm □ 1 Slightly warm □ 0 No change
□ -1 Slightly cool □ -2 Cool □ -3 Cold

b) In general in summer, how would you prefer to feel?
□ 3 Much warmer □ 2 Warmer □ 1 A bit warmer □ 0 No change
□ -1 A bit cooler □ -2 Cooler □ -3 Much cooler

c) In general in winter, how would you prefer to feel?
□ 3 Much warmer □ 2 Warmer □ 1 A bit warmer □ 0 No change
□ -1 A bit cooler □ -2 Cooler □ -3 Much cooler