Bridging the gap between energy and comfort: Post-occupancy evaluation of two higher-education buildings in Sheffield

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Key words

Energy performance, Thermal comfort, Occupancy patterns, Post-occupancy evaluation, Environmental control, Active versus passive design, University buildings

Highlights

- Passive and active energy strategies are compared in two university buildings
- The relationship between energy and comfort is analysed in flexible study spaces
- Occupant survey outlines the impact of user control on perceptions of comfort
- Design for changing occupancy patterns can reduce operational energy consumption

Abstract

Recent technical guidance has suggested that comfort and energy efficiency should not be seen as mutually exclusive [CIBSE, “TM54: Evaluating operational energy performance of buildings at the design stage”, 2013]. Currently, however, there is a lack of comprehensive understanding of energy use during building operation and how it influences user comfort. Through comparison of the complex relationships between energy, thermal comfort, and environmental strategy in two flexible higher-education buildings in Sheffield, this paper demonstrates how designers can utilise aspects of active and passive design to deliver more comfortable, lower-energy workspaces. Analysis of the authors' post-occupancy evaluation of each case study examines what lessons might be learnt and applied to other institutional buildings in order to save energy without compromising occupant comfort.

The findings illustrate how perceptions of comfort can be improved by increasing the degree of environmental control occupants have without necessarily increasing energy consumption. The paper highlights the significance of occupancy patterns to a complete understanding of energy efficiency and comfort, and speculates that the prediction and assessment of energy per occupant may have an important future role to play in bridging the gap between energy performance and comfort.

1. Introduction

In order to limit global temperature rise to as little as possible above 2°C, the 2008 Climate Change Act established a target for the UK to reduce its CO2 emissions by at least 80% from 1990 levels by 2050. The Act established five-yearly carbon budgets to serve as stepping stones to ensure that regular progress is made towards this long term target.[1]

It is estimated that the construction industry has a direct or indirect impact on 47% of all carbon emissions in the UK,[2] and non-domestic buildings account for approximately 18% of the UK's carbon emissions.[3] Architects and other industry professionals therefore have a responsibility to reduce emissions from institutional facilities such as university buildings. Building regulations such as Part L are becoming stricter, and standards such as BREEAM, CIBSE, and Passivhaus have been introduced in order to facilitate low energy design. However, most of these standards only measure regulated energy loads. They do not consider the 'whole life cost', resulting in buildings regularly falling short of design ambitions; commonly referred to as the performance gap.

Therefore, researchers and policy-makers are now focussing on occupant behaviour. One ambition is to encourage occupants of institutional buildings to consume energy in a more responsible way and to transfer this behaviour into their everyday lives, creating an 'environmentally friendly' society.

However, developments in the fields of building physics and environmental psychology have often occurred independently from each other, and there has been little comparative analysis of large-scale surveys into energy consumption and environmental performance in recent years.[4] As such, there is still a lack of comprehensive understanding of energy use during operation[5] and how it influences user comfort. As social expectations and the consumption patterns of occupants can defeat the most careful of designs, designers need to focus on how buildings will be used in order to reduce energy consumption in real terms.

Contrary to domestic buildings, where energy consumption has reduced over the past few decades,[6] medium to large-scale public and commercial buildings have seen an increase in energy use. This is partly due to the utilisation of 'active' environmental control strategies, often associated with improved environmental quality and comfort. However, these strategies can lead to higher electricity consumption,[7] and can also result in increased discomfort by creating unrealistic expectations that they can satisfy all occupants all of the time. Recent research has indicated that from a comfort and satisfaction standpoint passive strategies are often the best solution to building in the UK climate, as they give individuals more control of their thermal environment.[8]

1.1. Background: the performance gap

According to research conducted by Armitage et al. recent changes in building regulations have had a noticeable impact on thermal energy consumption in public offices, with reductions of almost 40% in buildings built after 2000. However this has been counteracted by higher electrical consumption, with an almost 75% increase between buildings constructed pre-1959 and those built since 2000, resulting in higher overall CO_2 emissions.[9]

Much emphasis is placed on achieving energy savings in early design stages. However, with advances in computing power and building simulation software, the accuracy of predictions is increasingly reliant on initial assumptions about occupant behaviour. Therefore, to improve our ability to accurately predict energy consumption, the focus needs to be on understanding the complex relationship between a building and its occupants.[10] Two major steps to reducing energy consumption are understanding where energy is used and the consideration of people and their expectations.[11]

1.2. Thermal comfort

Thermal comfort has been defined as ‘that condition of mind which expresses satisfaction with the thermal environment’.[12] It results from a dynamic equilibrium; the interaction between people and buildings in a particular social and climatic context.[13] 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.

Research has shown that occupants have a certain level of ‘forgiveness’ for buildings where indoor conditions are naturally variable and under their control,[14] as well as where the environmental design intent is legible.[15] It is clear that the provision of adaptive opportunities in a building are crucial, as they allow occupants to adapt both themselves to the environment and the environment to their own requirements.[16] However, providing personal control in open plan spaces is usually costly and impractical; temperature and lighting are therefore usually based on average standards and are automatically controlled.[17]

1.3. Post Occupancy Evaluation (POE)

For a particular strategy to be successful, both designers and occupiers of a low energy building must accept responsibility for how a building will be used. Designers need to understand adaptive mechanisms and engage with the occupants in the design stage in order to acknowledge the richness of human/environment interactions.[18] In order to improve low energy design, feedback measures such as POE are becoming more popular as they encourage a dialogue between designers and occupants, building an evidence-base for future design assumptions.

POE evaluates the functional performance of a building by providing an analysis of energy use, as well as how user needs are supported through satisfaction surveys.[19] POE can reduce the longer-term financial impact and energy consumption of mismanaged and poorly understood buildings, and offers an opportunity to increase occupant wellbeing through continuous development.[20]

The Building User Survey (BUS) methodology is often employed during occupant surveys in the UK. The BUS quantifies individual satisfaction, revealing features of value or concern in the building. The feedback can then be used to ‘close the gap’ between design and performance.[21] However, results can be selectively reported in the form of average mean scores across a wide range of interviewees who may be exposed to a range of different conditions in one building.

2. Methodology

The Arts Tower and Information Commons are two University of Sheffield buildings with different energy strategies where no POE has been previously conducted. Both buildings use the Schneider Electric Sigma System as a Building Management System (BMS), with a set point of 21°C and a 2°C dead band either side. The BMS increases heating or cooling on a proportional basis the further away the temperature moves from the dead band figure.

A field survey of each building was conducted, including collection of subjective data on activity, clothing, comfort vote, and thermal sensation and preference (see Appendix A). In order to obtain as complete a set of data as possible, both staff, students, part-time and full-time users were surveyed. As indicated in CIBSE TM52, occupant evaluation of the indoor thermal environment is largely context dependent and varies over time.[22] Therefore, special attention was paid during the occupant survey to recording when and where the individual was interviewed, as well as activity and clothing levels and the concurrent environmental conditions. The survey recorded occupants' thermal sensation vote (AMV) and thermal preference vote, as well as background environmental parameters for the calculation of the Predicted Mean Vote (PMV). Where mean values are quoted, the number of respondents (N) and standard deviation (SD) are indicated, alongside t-test results (t) where the difference is statistically relevant.

Environmental measurements were conducted using an anemometer, radiant globe thermometer, air thermometer, and RH probe connected to a handheld Testo 435 multifunction meter. Measurements were taken at a height of 1.1m in the centre of the analysed spaces, away from radiators and other heat sources. Energy consumption data for each building was collected via both the Energy Remote Monitoring (ERM) and the Power Monitoring Energy (PME)[1] system. Energy data was examined at the scale of the whole 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). It is also compared to benchmarks for University Campus buildings from CIBSE TM46. Finally, the data is compared with theoretically derived energy per occupant benchmarks. [2]

3. The Arts Tower

The Arts Tower (fig. 1), part of the University of Sheffield and the UK's tallest educational building, opened in 1966 and was listed grade II* in 1993. In 2009, the University of Sheffield started a refurbishment of the building in order to extend its viability. It aimed to provide a comfortable working environment, improving research facilities to meet modern standards, while preserving its heritage interest. Although the Arts Tower received an exemption from Approved Document L2B due to its historic importance, every effort was made to comply wherever it was possible to do so. Analysis showed that the allowable intervention with the greatest impact on thermal comfort would be the reduction in solar gain through the introduction of low G-Value glass to the facade.[23]

The top ten floors of the building are allocated to students and teaching staff, while the lower floors are occupied by staff offices. Any one floor can accommodate up to 220 persons provided that the overall population above ground level does not exceed 1,748.[24] The building is mainly used between 9am and 5pm, though students are granted out of hours access.

Energy for both heating and hot water is supplied through two heat exchangers from the Veolia Sheffield Heat and Power system.[3] One heats a domestic hot water (DHW) tank for the café, showers and toilets on the lower ground floor (DHW on other floors is provided by standalone electric point of

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[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.

[2] Although the data represented in TM46 is more up to date, it does not differentiate naturally ventilated buildings from air-conditioned ones as Part F does. Therefore both Part F and TM46 are used.

[3] Household waste is burnt at the Bernard Road incinerator. The energy produced is used to heat high pressured water to around 112°C. This is then pumped around the city to provided heat energy to a variety of buildings.

use systems). The other heat exchanger is used to heat a constant temperature circuit to provide heat to radiators and the heating coils in the 10 Air Handling Units (AHU). The AHUs are located in each lecture theatre and the lower ground toilets. The heating on each floor is provided by radiators positioned around the outer perimeter. Each floor is divided into four control zones, except the Ground Floor, which is divided into two. Each zone has its own independent heating circuit and two temperature sensors. Manual opening windows are installed to provide natural ventilation.[25]

Fig. 1. The Arts Tower exterior and internal study space.

3.1. Occupant Survey Analysis

In order to understand people's habits and comfort expectations in the Arts Tower, 50 occupants were surveyed over several days, concentrating on floors 14 to 18 (see table 1). These floors were chosen as there is a diverse range of occupants and working environments, from private offices for staff, to open plan space for students. Surveys were conducted in June 2015, outside of the heating season. In order to produce data as representative as possible, participants were surveyed during usual working hours – 10am to 5pm.

Table 1
Statistics of survey participants in the Arts Tower

Age range		*Gender*		*Role*		*Regularity*		*Workstation*	
20-35	86%	M	52%	Student	76%	Full Time	62%	Open Plan	80%
>35	14%	F	48%	Admin	24%	Part Time	38%	Shared Office	20%

Due to the Arts Tower's shape, glazed façade, and passive nature, surveys were conducted in north and south facing spaces to examine whether orientation had a significant impact on internal conditions and occupant comfort. Table 2 illustrates the internal conditions measured at the time of the survey.

The difference in average humidity and lighting between north and south facing rooms is minimal; whist it might have been due to the different occupancy levels, no specific reason was found for the 16% difference in maximum humidity levels. The 1°C difference in average temperature between north facing rooms and south facing rooms was most likely influenced by orientation as opposed to occupation patterns.

Table 2
Internal conditions measured in the Arts Tower

		Radiative Temperature (°C)	*Air Temperature (°C)*	*Operative Temperature (°C)*	*Humidity (%)*	*Light (Lux)*
North	Minimum	19.9	21	20.9	38.1	100
	Average	21.2	23.2	22.2	41.7	450
	Maximum	23.8	25.6	24.3	47.7	1370
South	Minimum	20.4	22.2	21.7	38.5	85
	Average	22.3	23.9	23.1	42.3	450
	Maximum	25.2	24.9	24.7	63.0	1000

Fig. 2. Arts Tower AMV and PMV compared.

Fig. 2 shows the AMV on the ASHRAE Thermal Sensation Scale in relation to the PMV[26] with the specific room conditions at the time of the survey. Only 58% of the calculated PMV scores are within the ASHRAE thermal neutrality boundary conditions of -0.5 and 0.5. This can be explained by the passive nature of the building – being primarily controlled by the occupants, the internal conditions vary more than in a mechanically controlled environment. With a PMV mean average of -0.48 (N=50, SD=0.55) and an AMV mean average of 0.9 (N=50, SD=1.49), it is clear that the predictions do not reflect reality. Although the PMV suggests that 92% of occupants would feel between neutral and slightly cool, according to AMV scores 77% of occupants were slightly warm, warm or hot. This difference between prediction and observation can be explained by several factors. The PMV model is based on the premise that a person is a passive recipient of thermal stimuli and the effects of a certain thermal environment are mediated solely by the physics of heat transfer.[27] It has been demonstrated to work under controlled test conditions in a climate chamber; however, it does not take into account local contextual and psychological variables. This illustrates the difficulties and problems in predicting occupant behaviour and comfort at the design stage.

From the lack of neutral AMV scores (AMV=0), it is clear that occupants often feel warmer or cooler than neutral. However, as fig. 3 shows, 52% were comfortable and did not want any change, the remaining occupants being almost evenly divided between preferring slightly cooler or slightly warmer temperatures.

Fig. 4 illustrates the seasonal temperature preference vote. Results suggest that occupants are more comfortable in summer, with 26% desiring no change compared with 12% in winter. 42% of votes of 2 and above were also found in winter, as opposed to 24% voting -2 or below in summer.

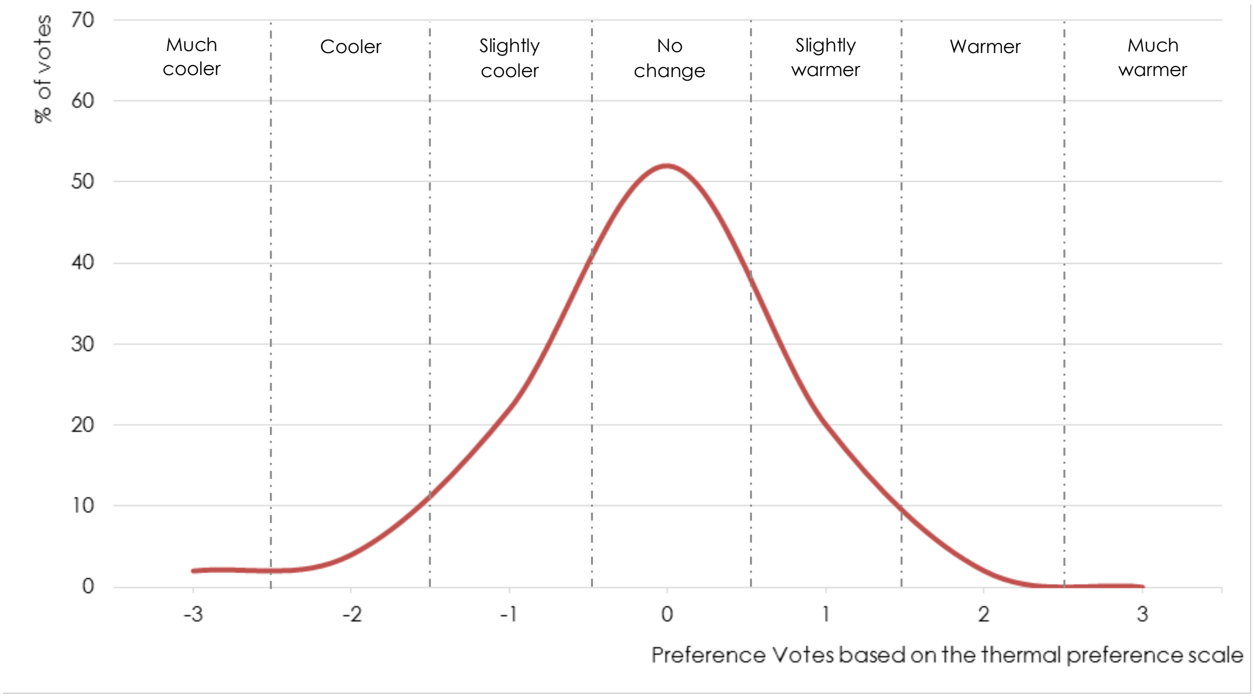
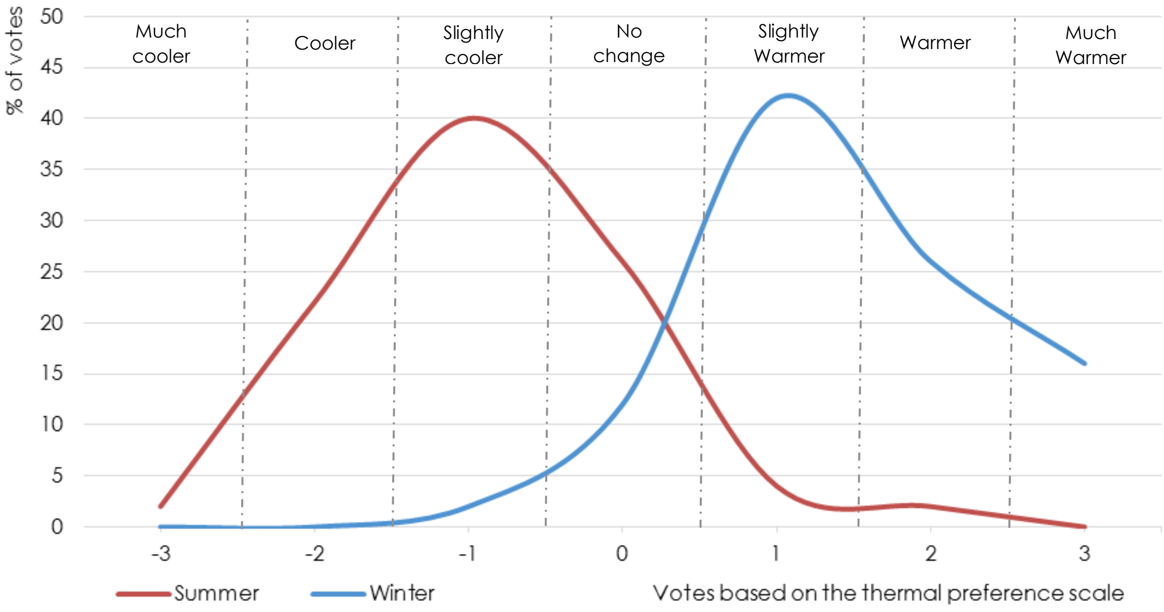


Fig. 3. Arts Tower Thermal Preference Vote.



Fig, 4. Arts Tower Seasonal Preference Vote.

Fig. 5. Left: occupant opening a window to adapt the environment to his needs. Right: overcrowding may lead to excessive heat gain in summer.

3.2. Technical Data Analysis

The overall energy consumption for the Arts Tower in 2014 was 116 kWh/m². This is 28% below the CIBSE-Part F standards for Good Practice (a figure of 161 kWh/m² for a naturally ventilated library). Analysing the breakdown of the energy consumption, the heating load of 49 kWh/m²/year is less than half of the CIBSE Part F standard for Good Practice, whereas the electricity load of 67 kWh/m²/year is slightly higher than the typical standard practice of 64 kWh/m²/year (fig. 6). The lower than expected heating load may be the result of the recent improvements to the thermal envelope. The slightly higher than expected electricity load might be explained by the increased usage of IT. However, it is notable that the Arts Tower as an older renovated building has a lower electricity consumption than the newer Information Commons, concurring with other research comparing consumption of buildings of different ages (Armitage et al.).[28]

Fig. 7 compares carbon emissions stated in the standards with the Arts Tower carbon emissions in 2014. It is clear that in terms of carbon the Arts Tower is not performing as well, as it is now only 2% below the CIBSE Part F Good Practice benchmark. The difference between the Arts Tower's performance in energy and carbon terms highlights the importance of understanding the carbon conversion factors of electricity and fossil fuels in the development of an energy strategy.

In addition to the kWh/m² figure, energy use per occupant can provide more information about the efficiency of energy expended to achieve occupant comfort, as well as unregulated energy use by the occupants themselves. The average occupancy of the Arts Tower is estimated to be 800, about 50% of the maximum occupancy.[4] Table 3 illustrates the energy per occupant in the Arts Tower in 2014, compared with an estimated UK benchmark for non-domestic buildings (derived from the UK Government Digest of Energy Statistics 2012).[29] Although the Arts Tower uses slightly more electricity in kWh/m² terms than CIBSE benchmarks, it is only using 64% of the kWhpp benchmark.

When the monthly energy data is analysed (fig. 8), a heating cycle reflecting annual weather patterns is revealed. Contrary to the heating, electricity consumption is generally stable throughout the year and does not seem to be affected by term time occupancy. This could be explained by the fact that the lower floors of the Arts Tower house permanent staff offices. As the Arts Tower is naturally ventilated, the majority of this electricity consumption will be due to unregulated usage.

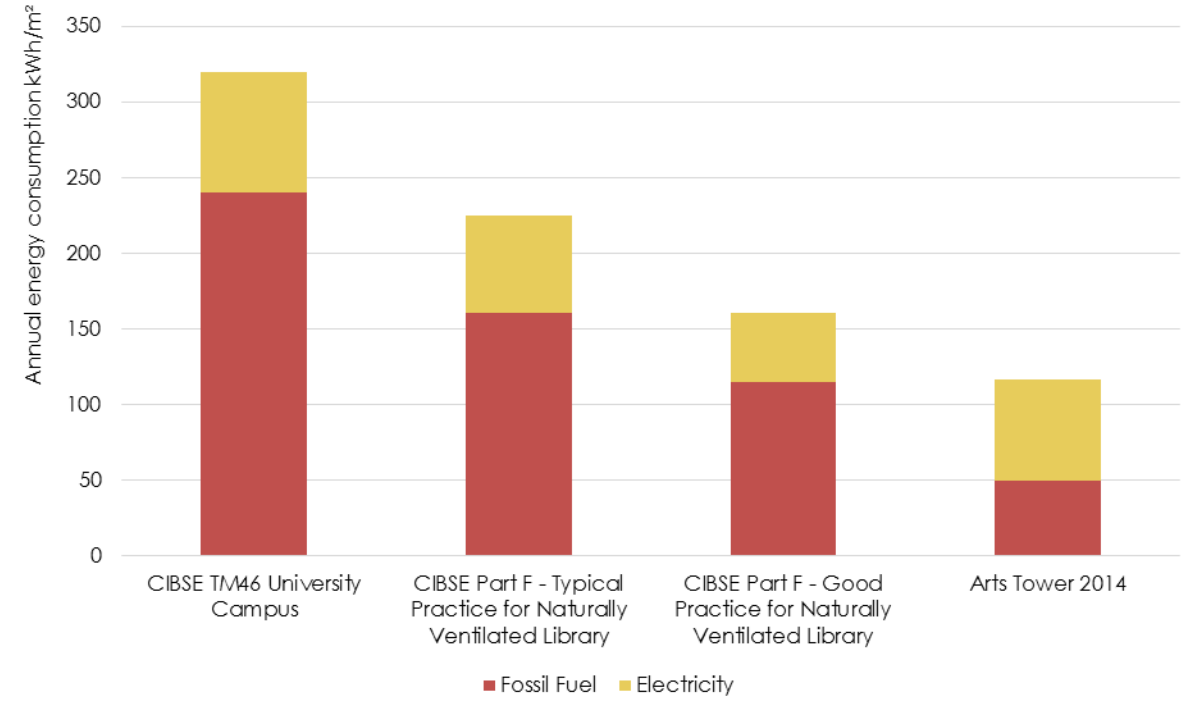


Fig. 6. Arts Tower 2014 energy consumption and CIBSE energy benchmarks.

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[4] This number was derived from working out the usual occupancy of each floor, with an average of 35 people on office floors and 60 on studio floors.

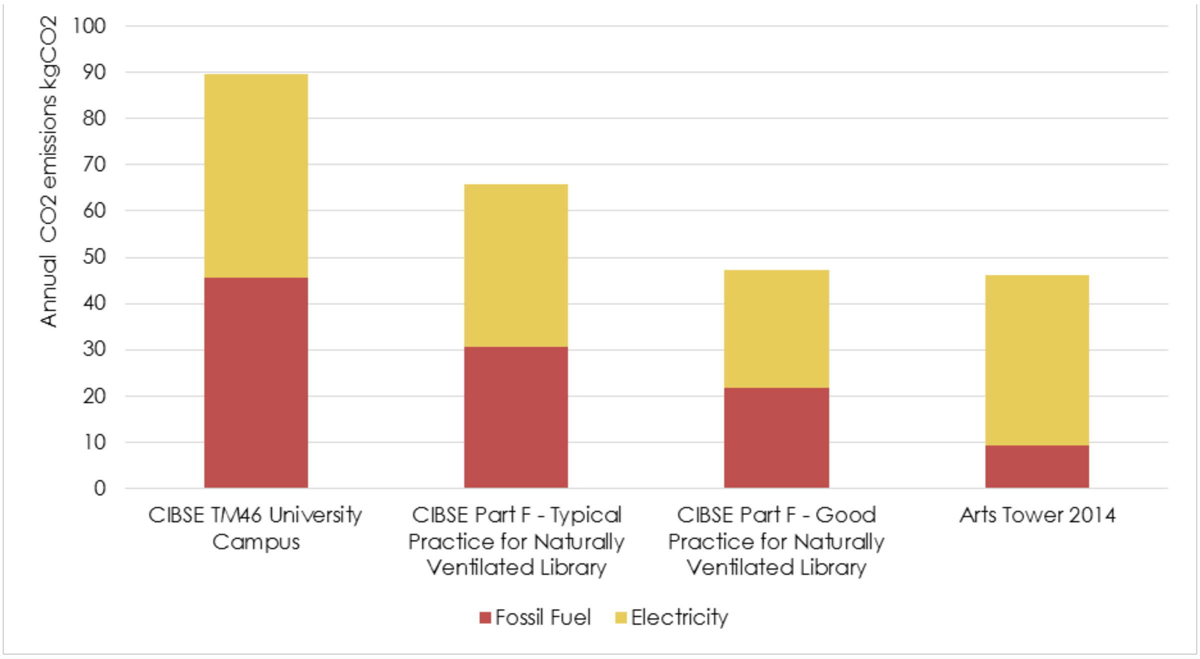

Fig. 7. Arts Tower 2014 CO2 emissions and benchmarks derived using CIBSE TM46 kgCO2/kWh emission factors (electricity: 0.55, fossil fuels: 0.19).

Table 3
Arts Tower energy consumption per person and derived benchmarks.

	Electricity - kWh/person/year	*Gas - kWh/person/year*	*Total - kWh/person/year*
Arts Tower	1342	990	2332
Typical Office Building in the UK	2100	1200	3300

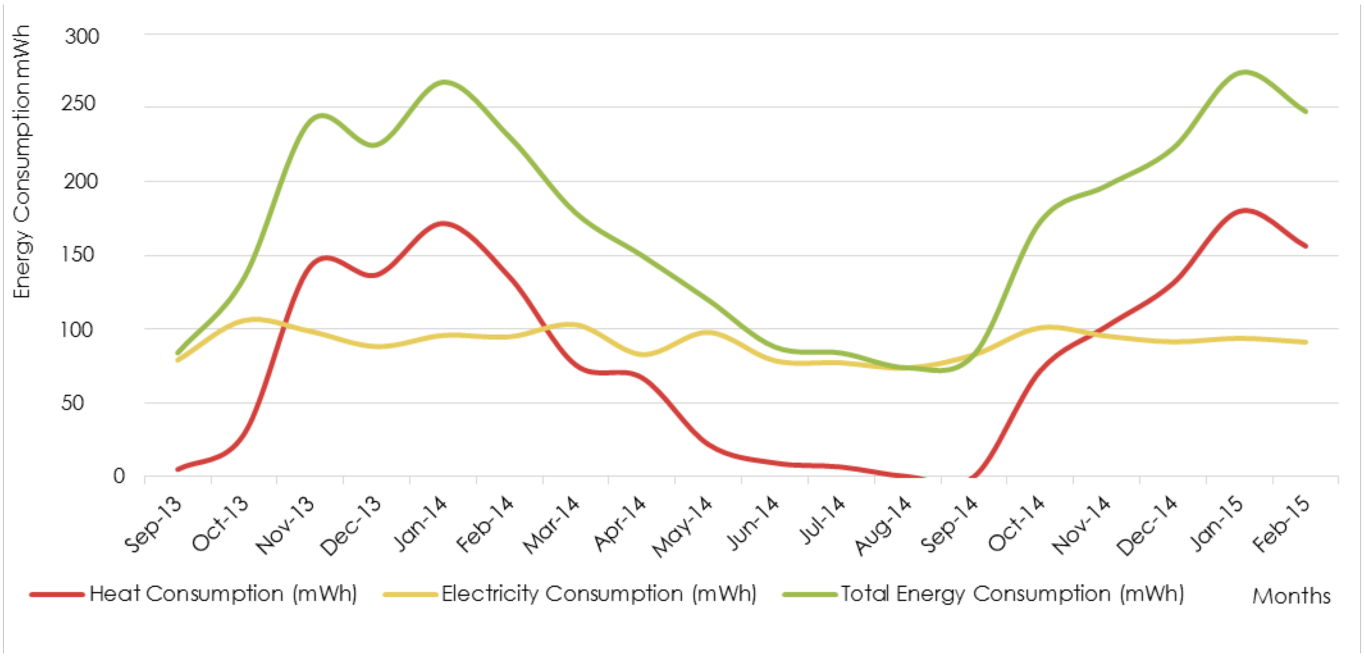

Fig. 8. Arts Tower Energy Data.

4. Information Commons

The Information Commons (IC), opened in 2007. With a maximum capacity of 1,350 occupants[30] and 1,300 workstations spread over seven storeys, it is Sheffield's largest library. It provides a range of spaces, which are available 24 hours every day of the year, to suit a large variety of student working styles.

Fig. 9. External view of the Information Commons.

The IC is one of the most complex buildings in the University of Sheffield in terms of controls and plant. It runs predominantly on electricity, supplemented by heat from the Veolia district heating system. The main background air supply for the building is taken from two large AHUs on the roof. The supply air is heated or cooled with the aid of a thermal wheel that recovers waste heat. Chilled water for all areas of the building is provided by a blast air cooler and two chillers. The BMS utilises the air blast cooler predominately as this is much less energy intensive than the main chillers.

Each floor has between three and six control zones, apart from floors 5 and 6 which are both single zones. Each zone has two space temperature sensors and is served by a single air handling unit, supplying air to the zone through numerous floor grills which control the amount of air needed in the space. Each zone also has a PIR occupancy detector. If no movement is registered for a certain amount of time, the system switches off. As the building is open 24/7 this is a potentially useful energy saving control, as long as no sensors are accidentally triggered.

4.1. Occupant Survey Analysis

51 occupants were surveyed over several days in all parts of the building (see table 4). Contrary to the Arts Tower, a small majority of occupants in the Information Commons are part-time users and therefore occupancy is more variable.

Table 4
Statistics of survey participants in the Information Commons

Age range		*Gender*		*Role*		*Regularity*		*Workstation*	
20-35	82%	M	47%	Student	86%	Full Time	45%	Open Plan	86%
>35	18%	F	53%	Admin	14%	Part Time	55%	Shared Office	14%

Due to the internal organisation and the size of the space, as well as the active nature of the building, it was found that orientation had little influence on the internal conditions or occupant comfort. Table 5 illustrates the internal conditions measured at the time of the survey.

Table 5
Internal conditions measured in the Information Commons

	Radiative Temperature (°C)	*Air Temperature (°C)*	*Operative Temperature (°C)*	*Humidity (%)*	*Light (Lux)*
Minimum	20.4	22.7	21.6	39.5	55
Average	22.2	24.1	23.2	49.0	340
Maximum	24.9	25.2	24.7	62.0	1125

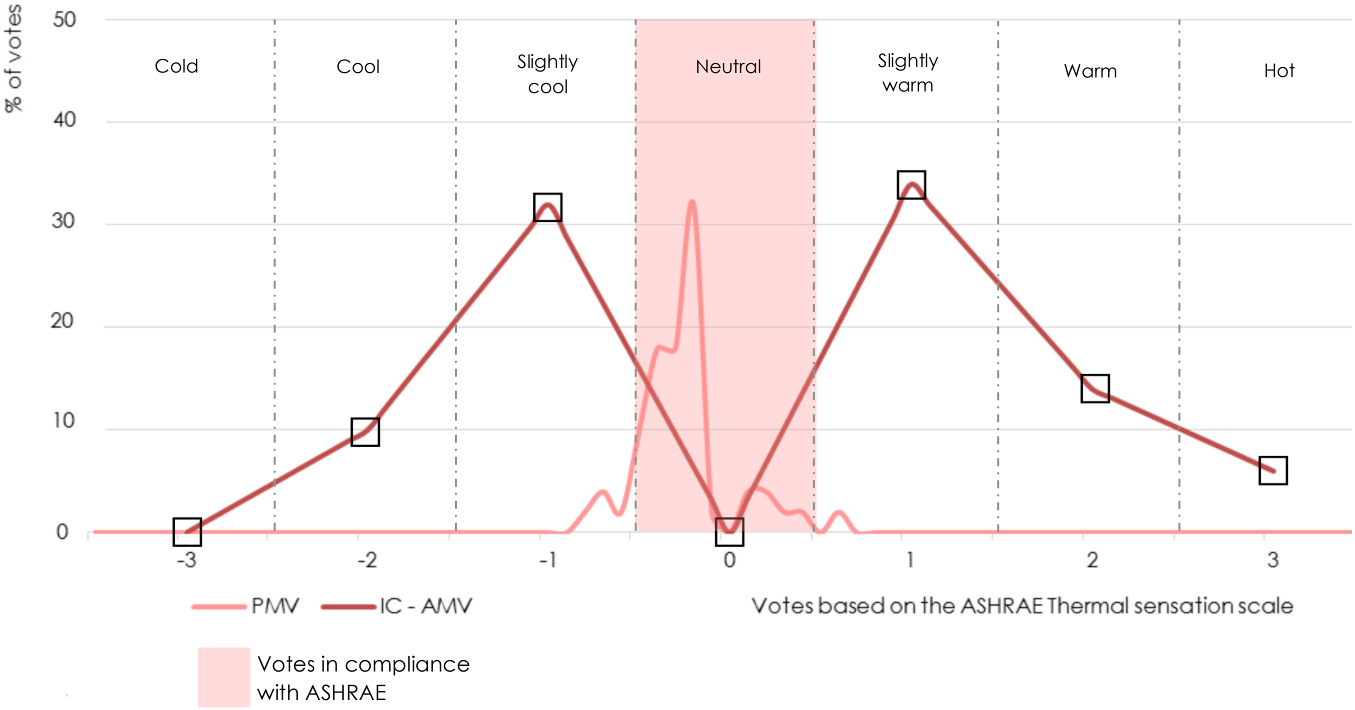

Fig. 10. Information Commons AMV and PMV.

Fig. 10 shows a PMV mean average of -0.26 (N=51, SD=0.37), with 90% of occupants within the ASHRAE thermal neutrality boundary conditions of -0.5 and 0.5. As the internal conditions of the building are more controlled than in the Arts Tower, it is to be expected that the PMV range will be narrower. The average mean of AMV scores was 0.3 (N=51, SD=1.48), however, similar to the Arts Tower, there were no neutral AMV scores (AMV=0). There is an almost even split between occupants feeling slightly too cool and slightly too warm. It seems that in this mechanically controlled environment the neutral conditions derived from a standardised comfort model do not suit all occupants.

These results highlight the importance of being able to relate environmental conditions in the local environment to subjective responses. Contrary to the naturally ventilated Arts Tower, air temperatures measured as high as 25.2°C (more than 2°C above the BMS dead band) would normally be considered too high. However, some occupants complained of feeling cool despite such high temperatures. This may be partially explained by the air diffusers located in the floor close to areas of seating, resulting in uncomfortable draughts (fig. 11).

Fig. 11. Silent study space in the Information Commons illustrating the floor grills near desks.

Fig. 12 shows that 60% of occupants surveyed were comfortable and did not want any change; the remaining 40% had a slight bias towards being slightly cooler. Fig. 13 illustrates the seasonal temperature preference vote. Results suggest that occupants are more comfortable in summer, with 48% desiring no change compared with 38% in winter.

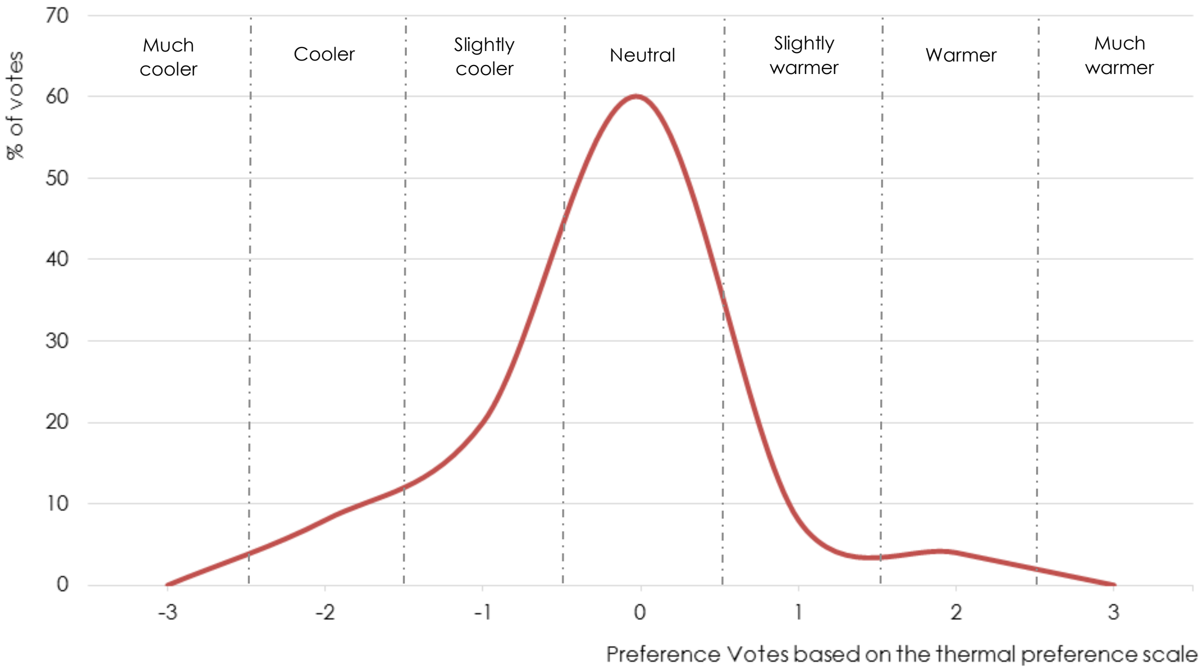

Fig. 12. Information Commons Actual Thermal Preference Vote.

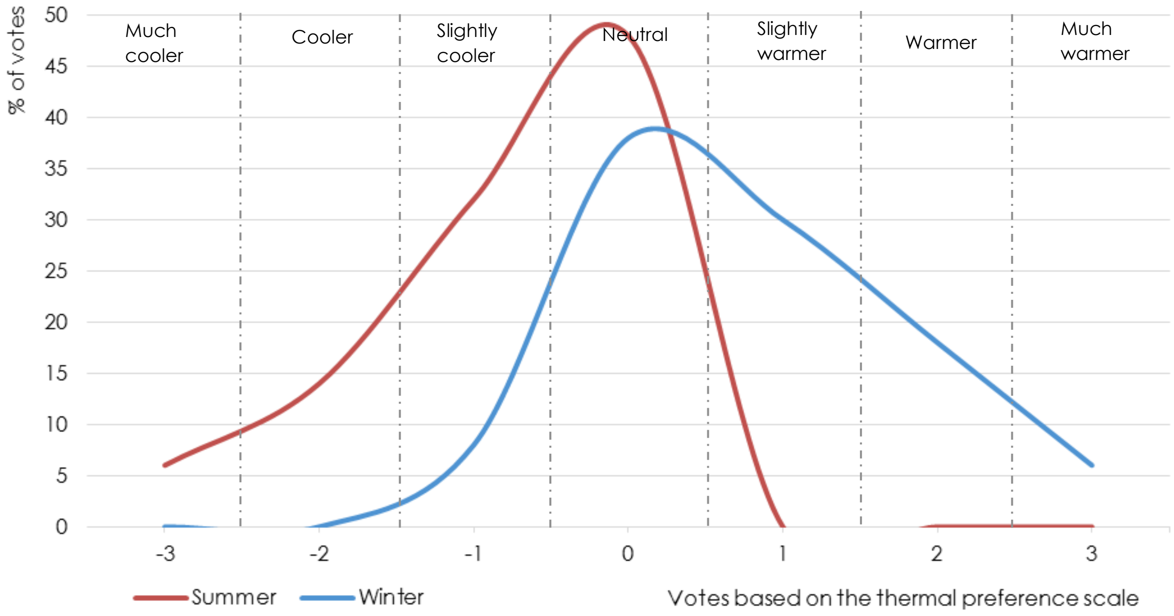

Fig. 13. Information Commons Seasonal Preference Vote.

4.2. Technical Data Analysis

The overall energy consumption for the Information Commons in 2014 was 265 kWh/m². This is significantly less than the CIBSE-Part F standards for Good Practice. Analysing the breakdown of the energy consumption, the heating load of 32 kWh/m²/year is less than a fifth of the CIBSE PART F Good Practice benchmark, and the electricity load, 233 kWh/m²/year, is also less than the Good Practice benchmark of 292 kWh/m²/year (fig. 14).

Fig. 15 compares carbon emissions stated in the standards with the Information Commons carbon emissions in 2014. While the energy consumption of the Information Commons equates to 57% of the CIBSE Part F of Good Practice benchmark, 82% of this energy is electricity consumption, resulting in higher carbon emissions.

In his research, Alex Buckman found that the Information Commons had a ‘sub-optimal’ occupancy of 71% for 2014, with an average occupancy of 218 people.[31] It is assumed that during the remaining 29% of the time, the building will be close to full capacity (around the exam period). Table 6 illustrates the energy per occupant in the Information Commons in 2014, compared with the estimated UK benchmark for non-domestic buildings.

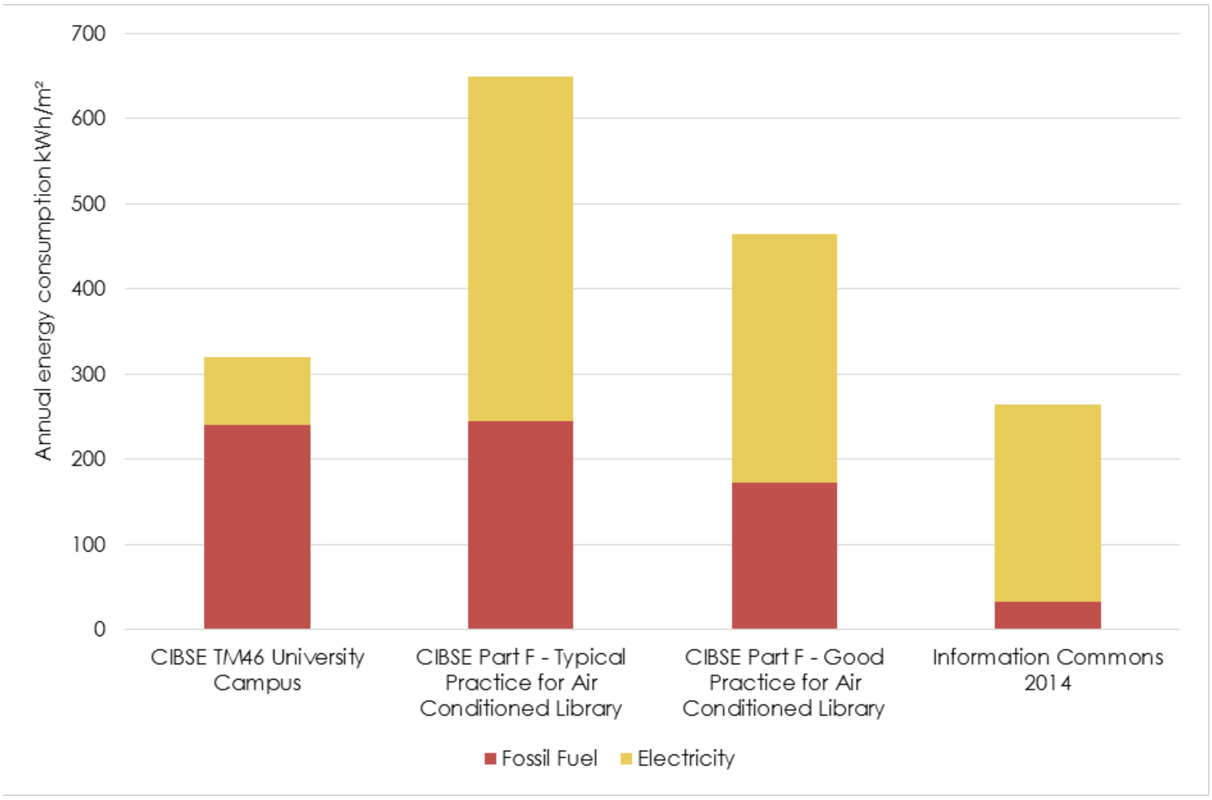

Fig. 14. Information Commons 2014 energy consumption and CIBSE energy benchmarks.

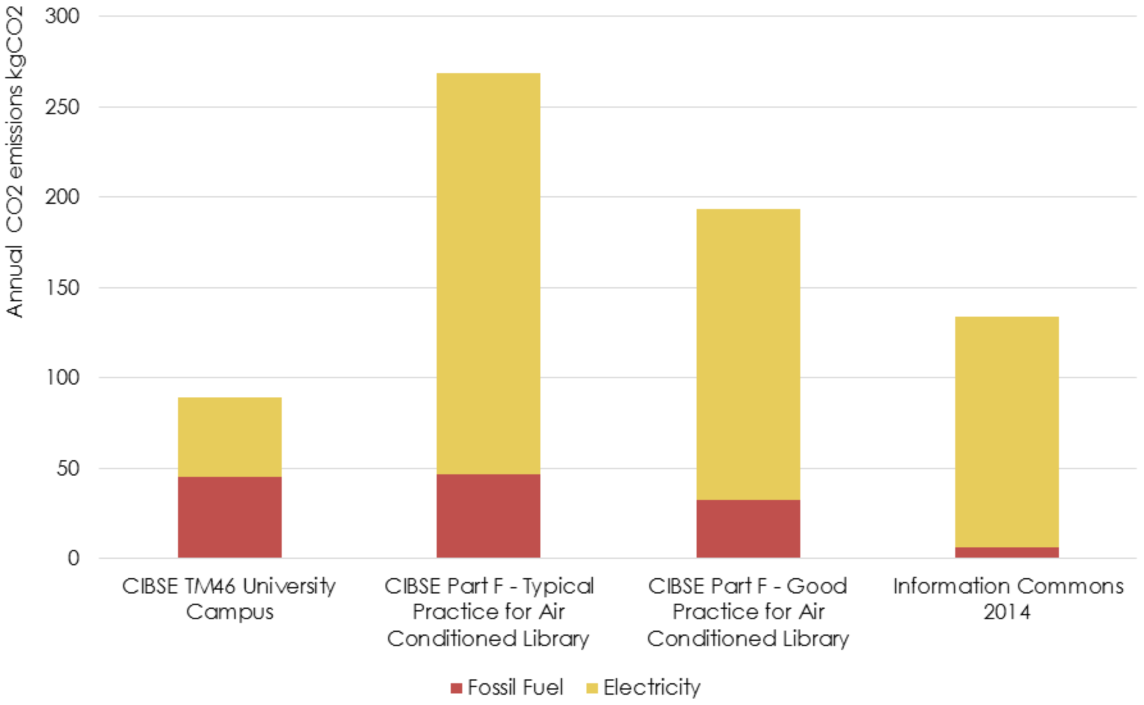

Fig. 15. Information Commons 2014 CO2 emissions and benchmarks derived using CIBSE TM46 kgCO2/kWh emission factors (electricity: 0.55, fossil fuels: 0.19).

Although the Information Commons annual energy consumption is below the CIBSE benchmark in kWh/m² terms, it is using 84% more energy per occupant than the kWhpp benchmark, largely due to high electricity usage. This can be attributed to the variable occupancy, resulting in the building operating at ‘sub-optimal’ occupancy for a large part of the year (table 6). Alex Buckman found that when the building is at optimal capacity (approximately 600 occupants), the average energy consumption per occupant-hour is 0.72kWhpp/hour. In contrast, the average for ‘sub-optimal’ energy usage is 3.34kWhpp/hour, a factor of almost five times higher.[32]

Table 6
Table of the Information Commons energy consumption per person and derived benchmarks

	Electricity - kWh/person/year	*Gas - kWh/person/year*	*Total - kWh/person/year*
Information Commons at low occupancy 218 occupants for 71% of the year	10898	1503	12401
Information Commons at high occupancy 1000 occupants for 29% of the year	2376	328	2703
Information Commons average occupancy 445 occupants on average all year	5339	736	6075
Typical Office Building in the UK	2100	1200	3300

When the monthly energy data is analysed (fig. 16), a heating cycle reflecting annual weather patterns is revealed. The electricity consumption fluctuates throughout the year, peaking in summer. This may be explained by an active summer cooling requirement, as well as higher unregulated energy usage from computers over the exam period (April-May).

Fig. 17 illustrates the breakdown of the Information Commons energy consumption. It is noticeable that unregulated electricity consumption represents the largest share of energy end-use. Given the continuous occupancy and nature of the activity, there are high incidental gains from both occupants and IT related equipment, which could explain the requirement for cooling most of the year and the fact that small electric heaters have been permanently disabled. With its heavyweight construction, the Information Commons has the ability to buffer large daily temperature variations. However, without effective night purging – difficult given 24/7 occupancy – excess heat may also be trapped for longer.

Electricity consumption in the Informatics Commons represents 82% of the building’s overall energy consumption. Reducing it will therefore have a much greater impact in carbon terms than reducing heating. Some efforts have been made to reduce electricity use, such as automated computer shut down after 20 minutes of inactivity and the use of PIR sensors to turn the lights off after 30 minutes of inactivity. However frequent tours of the building by cleaners and security staff has reduced the effectiveness of these measures.

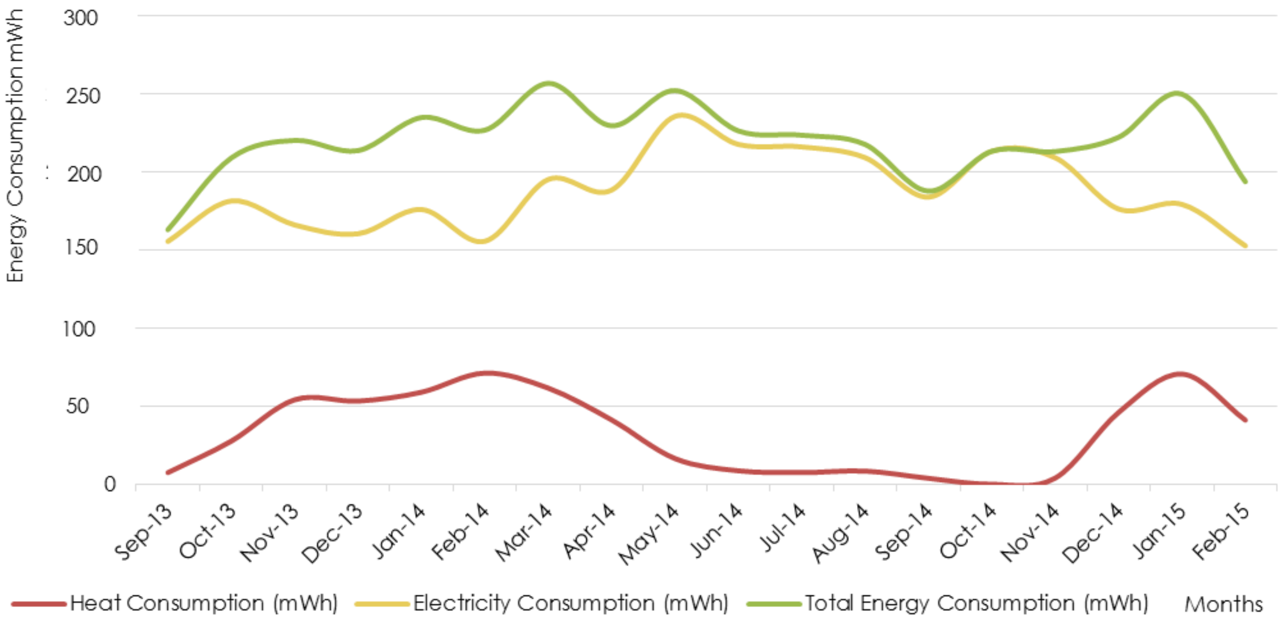

Fig. 16. Information Commons Energy Data.

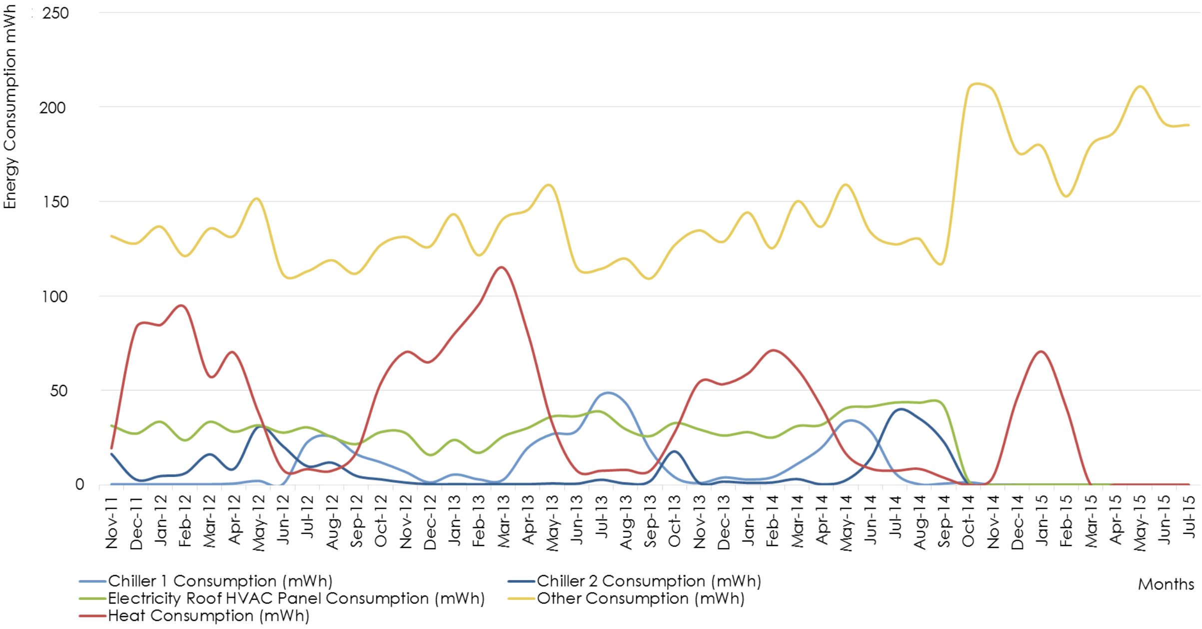

Fig. 17. Information Commons Detailed Energy Consumption Breakdown.

5. Comparison of case studies

Comparison of PMV and AMV would suggest that the Information Commons appears to be a more comfortable building (table 7). However, despite the difference in the disparity between the mean PMV and AMV in each building, the mean thermal preference score for each building was remarkably similar; AT: -0.11 (N=50, SD=0.88), IC: -0.14 (N=51, SD=0.87).

This would suggest that there is a higher level of ‘forgiveness’ in the Arts Tower, possibly due to the level of control occupants have over their environment and consequentially their ability to adapt.

Table 7
Disparity between mean PMV and mean AMV in the Arts Tower and Information Commons

Building	*Sample*	*PMV*	*AMV*	*AMV-PMV*	*t-test*
Arts Tower	50	-0.48	0.9	1.38	t (98) – 6.12, $p < 0.001$
Information Commons	51	-0.26	0.3	0.56	t (100) – 2.60, $p < 0.01$

5.1. Comfort and control

In order to further test this hypothesis, survey participants were questioned about other aspects that might affect their comfort, and asked to score their preference. Scores are based on the thermal preference scale and adapted to suit different aspects such as light levels (see Appendix A). Scores of -1, 0, and 1 (no change and slight change) were discounted, in order to clearly identify the causes of most discomfort.

As fig. 18 shows, the main reported causes of discomfort in the Arts Tower were winter temperature, followed by control of temperature and the level of fresh air. Occupants cannot control temperature settings in the Arts Tower, and opening windows is not always possible due to external conditions such as rain or heavy wind. Although participants were generally satisfied with light levels (probably due to the large areas of glazing), some mentioned a preference for dimmable lights and some for directional lights.

As fig. 19 shows, the main reported causes of discomfort in the Information Commons were control of temperature, followed by preferred light and winter light. A number of people mentioned desiring the possibility to open windows. 46% of the participants found light levels to be too low at the time of the survey. Light levels seem to be more of a problem in winter, when 42% of participants would prefer more light, as opposed to only 8% in summer. This suggests that the artificial lighting does not sufficiently compensate for a lack of daylight in winter.

While the mean seasonal thermal preference vote in both buildings was similar in summer; AT: -0.83 (N=50, SD=0.99), IC: -0.73 (N=51, SD=0.95), in winter, occupants in the Arts Tower expressed a greater desire to feel warmer; AT: 1.44 (N=50, SD=0.96), IC: 0.80 (N=51, SD=1.01), t (99) – 4.60, $p < 0.001$. However, when questioned further about control of temperature, 52% of occupants in the Information Commons stated that they desired more, or much more, control (M=1.49, N=51, SD=1.39) compared with only 40% in the Arts Tower (M=1.28, N=50, SD=1.09). (Q: How much control would you prefer to have over the temperature? A: -3–much less control, -2–less control, -1–a bit less control, 0–no change, 1–a bit more control, 2–more control, 3–much more control).

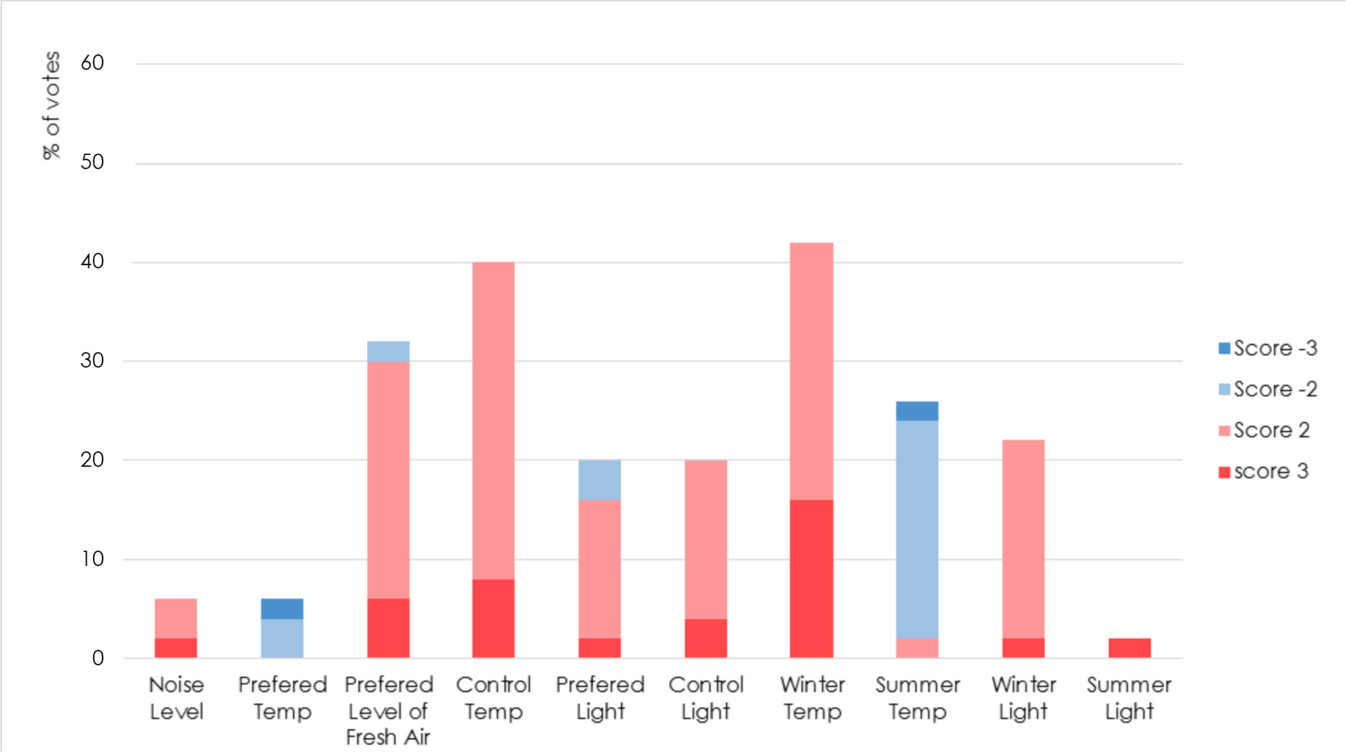

Fig. 18. Causes of Occupant Discomfort in the Arts Tower.

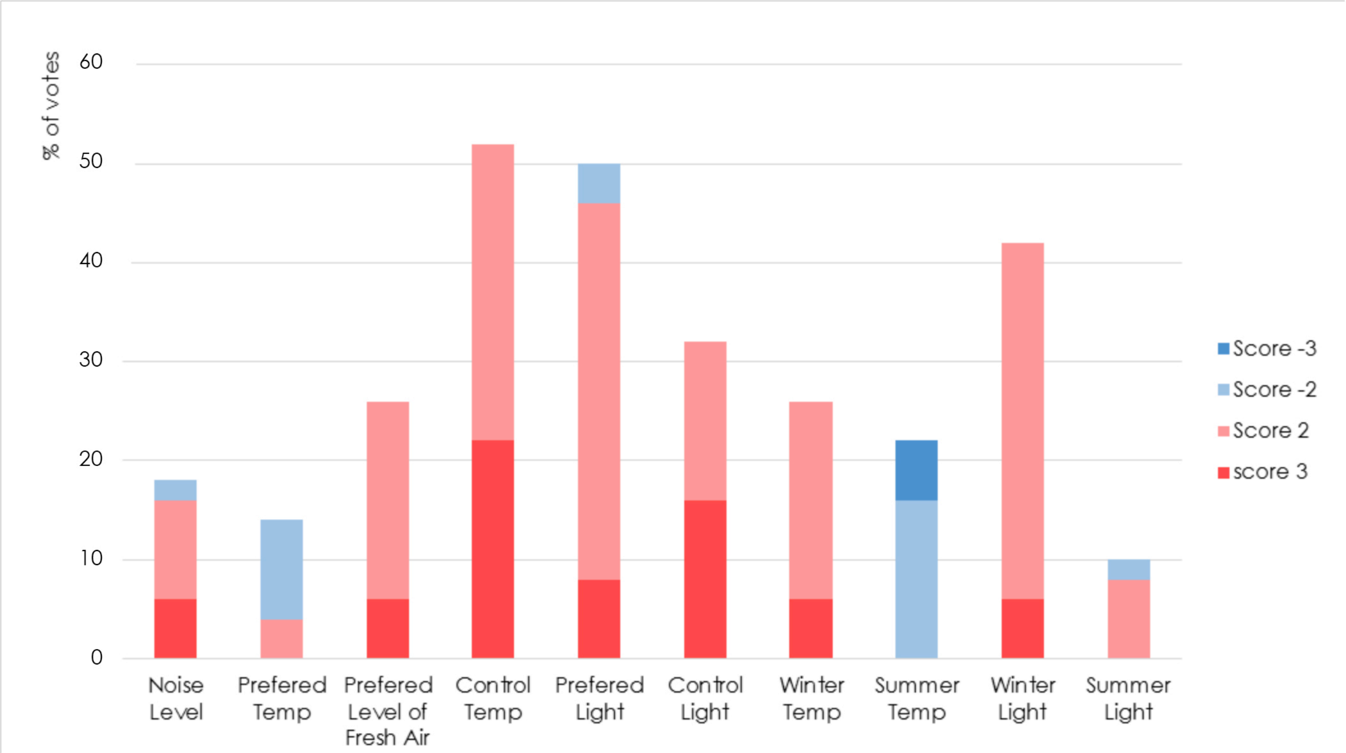

Fig. 19. Causes of Occupant Discomfort in the Information Commons.

When questioned further about overall control, out of 101 participants surveyed, 72% (M=0.8, N=101, SD=1.06) agreed that the more control they have, the more productive they are due to their increased comfort (Q: To what extent do you agree with the following statement: 'the more control I have over my environment, the more comfortable, therefore more productive, I am'? A: -2–strongly disagree, -1–disagree, 0–neither agree nor disagree, 1–agree, 2–strongly agree).

These results suggest that the passive strategy of the Arts Tower, where the occupant is more in control of his or her environment, results in more understanding and adaptable building users.

5.2. Energy and occupancy patterns

In both buildings, the electricity load represented the largest share of energy use, however, both buildings showed little to no variation in electricity usage due to increased occupancy in term time. In the Arts Tower electricity consumption was mostly unregulated usage, however in the Information Commons a significant share of consumption was due to the HVAC system and chillers.

The desire for flexible open-plan spaces in higher-educational facilities (such as the Information Commons) can often lead to 'orthodox' design solutions such as multi-zone HVAC systems to maintain conditions within a close comfort range, regardless of the wide variation in occupancy patterns typical of this kind of building. Arguably this 'flexibility' is only worth the energy investment if the use of the building is likely to change to a more intensive and fixed occupancy pattern in future. If the Information Commons was at an optimal capacity of 800 occupants per day throughout the year, it would consume 3,379 kWhpp/annum, only 2% above the derived benchmark.

On the other hand, the ability of occupants to adapt to the environment of the Arts Tower at different times and seasons demonstrates a more flexible long-term design approach than a solution that is optimised for one peak occupancy scenario.

6. Conclusion

This study has demonstrated that the more passive environmental strategy of the Arts Tower results in a considerably lower energy consumption compared with the Information Commons, with little impact on overall occupant comfort.

Further analysis has also revealed a tendency for occupants in the Information Commons to feel either slightly cool or slightly warm, rather than neutral. This may reflect less tolerance on the part of occupants exposed to mechanically controlled conditions that differ from their own expectations of comfort. In contrast the majority of people in the Arts Tower agree that the internal conditions were slightly warm at the time of the survey (June), suggesting that a slight cooling of internal temperatures in summer would increase occupant comfort. However analysis of thermal preference votes reveals that a thermal sensation other than neutral is tolerated by a majority of occupants in both buildings, with 52% and 60% of occupants expressing a desire for 'no change' to their thermal environment in the Arts Tower and the Information Commons respectively (see figs. 3, 12).

As the Information Commons is broadly open plan, it would be assumed that internal temperatures would equilibrate and only require seasonal heating or cooling; however, the HVAC system often supplies warmed and cooled air to different spaces simultaneously, wasting energy. Further analysis would be required to determine if the Arts Tower could be cooled further through the buildings existing natural ventilation strategy, or if a more energy intensive active cooling strategy would be required.

This capacity to 'fine-tune' environmental conditions in different spaces is arguably necessitated by the reduced potential of occupants to adapt to their immediate thermal environment. A more passive environmental design strategy may have offered energy savings as well as reducing costs, utilising the properties of different materials in combination with thermal buffering, and a more diurnally and seasonally responsive external fabric (permitting the purging of significant internal heat gains). These strategies may result in a requirement for further heating, but the reduction or removal of active cooling, and therefore in carbon-intensive electricity load, would likely reduce the building's overall carbon emissions.

In the Arts Tower, passive natural ventilation in summer could be augmented by more localised user control of comfort heating and task lighting. This would likely improve comfort in winter with little impact on carbon emissions, which may in fact be reduced by savings in unused spaces.

6.1. Active and passive strategies

The analysis of the energy consumption of the case studies has shown the need for designers to consider variation in occupancy patterns when choosing between active and passive environmental strategies or systems. While it is difficult to predict future use accurately, designers should model a range of possible scenarios that design decisions can be tested against, including analysis of energy consumption in kWh/m² terms during peak occupancy as well as in kWhpp terms over a range of different occupancy scenarios. This would provide more evidence at the design stage to guide decisions such as the choice of more passive strategies and the sizing and flexibility of active systems.

Despite evidence to the contrary, there is still a misconception that increased energy consumption usually equates to improved comfort. This study has demonstrated that a less technologically dependent environmental strategy can prove more robust, in terms of both comfort and energy, over a building's lifespan. This finding is supported by other studies, including the PROBE case studies,[33] and is particularly relevant to higher educational buildings.

6.2. The impact of control

This study has also outlined the need for a more detailed understanding of the variability of perceptions of comfort in different spaces, and the impact of environmental control. The Building User Survey (BUS) methodology assesses satisfaction with overall temperature in winter and summer on a preference scale from 'too cold' to 'too hot'.[21] However, a combination of scores at opposite ends of this scale can cancel out to be read as evidence of thermal neutrality. As this study has demonstrated, an average mean AMV score tending towards neutral does not mean that a majority of occupants tend to feel neutral (no neutral AMV scores were recorded in either the Arts Tower or the Information Commons).

Other questions in the BUS methodology ask users to rate 'overall temperature' in winter and summer on a scale from 'uncomfortable' to 'comfortable', and control over heating on a scale from 'no control' to 'full control'. The former question does not permit conclusions to be drawn about the specific cause of discomfort and the latter question does not distinguish between a subject's preference for more or less control. The BUS Comfort Index is intended to give a benchmarked headline overview of user perception of building performance. It combines scores for 'overall temperature' with corresponding scores for comfort, lighting, noise and air quality, but does not take account of control.[34] However, as this study has demonstrated, a lack of control of temperature can be one of the most important causes of discomfort.

Environmental strategies in institutional buildings should be dynamic not only in terms of changing weather and seasons, but also building use; a significant challenge. It is important that opportunities for adaptive behaviour are promoted, including localised control, and there is a need to further understand both individual occupant comfort and behaviour in order to accurately anticipate, respond to, and manage needs and expectations.

Current technologies allow building managers to know how many people are in a building and where they are. This could aid in the development of intelligent control systems that augment predominantly passive design solutions to reduce the overall energy use of a building. However, improvements arguably depend on perceiving occupants as part of the solution, rather than viewing their behaviour as part of the problem.

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Appendix A: Occupant Satisfaction Survey

General Information

a) Gender: ☐ Male ☐ Female

b) Age ☐ < 20 ☐ 20-35 ☐ 35-50 ☐ > 50

c) Role within University ☐ Admin ☐ Lecturer / Tutor ☐ Student

d) Time usually spent in the building: ☐ Full-time ☐ Part-time ☐ 1 day a week

e) Workstation type ☐ Open plan ☐ Shared office ☐ Private office

f) Room conditions when interviewed:
Radiative temperature: Air temperature: Humidity: Light:
Floor: Time: Metabolic rate: ‘Clo’ Value: Time spent there:

Votes

a) How do you feel right now?
☐ 3 Hot ☐ 2 Warm ☐ 1 Slightly warm ☐ 0 No change
☐ -1 Slightly cool ☐ -2 Cool ☐ -3 Cold

b) How would you prefer to feel right now?
☐ 3 Much warmer ☐ 2 Warmer ☐ 1 A bit warmer ☐ 0 No change
☐ -1 A bit cooler ☐ -2 Cooler ☐ -3 Much cooler

c) What level of fresh air would you prefer right now?
☐ 3 Much more ☐ 2 More ☐ 1 A bit more ☐ 0 No change
☐ -1 A bit less ☐ -2 Less ☐ -3 A lot less

d) How much control would you prefer to have over the temperature?
☐ 3 Much more control ☐ 2 More control ☐ 1 A bit more control ☐ 0 No change
☐ -1 A bit less control ☐ -2 Less control ☐ -3 Much less control

e) What lighting would you prefer right now?
☐ 3 Much lighter ☐ 2 Lighter ☐ 1 Slightly lighter ☐ 0 No change
☐ -1 Slightly darker ☐ -2 Darker ☐ -3 Much darker

f) How much control would you prefer to have over the lighting?
☐ 3 Much more control ☐ 2 More control ☐ 1 A bit more control ☐ 0 No change
☐ -1 A bit less control ☐ -2 Less control ☐ -3 Much less control

g) How would you prefer the noise level to be right now?
☐ 3 Much quieter ☐ 2 Quieter ☐ 1 A bit quieter ☐ 0 No change
☐ -1 A bit noisier ☐ -2 Noisier ☐ -3 A lot noisie

h) 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

i) 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

j) In general in winter, how would you prefer the lighting to be?
☐ 3 Much lighter ☐ 2 Lighter ☐ 1 Slightly lighter ☐ 0 No change
☐ -1 Slightly darker ☐ -2 Darker ☐ -3 Much darker

k) In general in summer, how would you prefer the lighting to be?
☐ 3 Much lighter ☐ 2 Lighter ☐ 1 Slightly lighter ☐ 0 No change
☐ -1 Slightly darker ☐ -2 Darker ☐ -3 Much darker

l) To what extent do you agree with the following statement: ‘the more control I have over my environment, the more comfortable, therefore more productive, I am’?
☐ 2 Strongly agree ☐ 1 Agree ☐ 0 Neither agree nor disagree
☐ -1 Disagree ☐ -1 Strongly disagree