Available online at www.sciencedirect.com
ScienceDirect
Energy and Buildings 39 (2007) 837–846
ENERGY and BUILDINGS
www.elsevier.com/locate/enbuild

Occupant comfort in UK offices—How adaptive comfort theories might influence future low energy office refurbishment strategies

Stuart Barlow [a,*], Dusan Fiala [b,c]

[a] De Montfort University, Leicester & Reid Architecture, West End House, 11 Hills Place, LondonW1F 7SE, United Kingdom
[b] IESD, De Montfort University, Leicester, United kingdom
[c] FBTA, University of Karlsruhe, Germany

Abstract

With the UK commercial sector replacing buildings at 1–1.5% per year adaptations to existing buildings are needed to maintain comfort levels, while reducing energy use and carbon emissions.

In this study, occupants of a refurbished office recorded their thermal sensations, assessment of lighting and air movement, perceptions of comfort and their reactions to adaptive opportunities. The observed mean thermal sensation votes and the overall comfort votes correlated best with mean diurnal internal and external temperatures, respectively. The results appear to indicate heat balance models not fully explaining surveyed responses as occupants reported higher discomfort levels than predicted by the PMV model using on-site temperature and air velocity measurements.

In the study opening windows was voted to be the most favourite adaptive opportunity followed by controlling solar glare, turning lights off locally and controlling solar gain. Occupants also expressed desires to intervene with heating and ventilation currently operated centrally. An interesting result of the survey was that the occupants generally did not change their clothing during the day. The study concluded that both passive and active adaptive opportunities are important in future low energy office refurbishment strategies.

Keywords: Field survey; Thermal comfort; Low energy adaptive opportunities; UK offices

1. Introduction

Non-domestic buildings account for 20% of the United Kingdom's (UK's) carbon dioxide (CO_2) emissions. With 75% of the UK's existing building stock constructed prior to 1980 [1], and with it only being replaced at a rate of 1–1.5% per annum, occupants of existing offices will need to respond to rising temperatures resulting from climate change [2]. Internal temperatures could exceed comfort levels for over a fifth of the working day by 2050 [3]. Forty-one percent of CO_2 emissions from commercial and public buildings, within the United Kingdom (UK), comes from heating, lighting accounts for 23% while cooling only 5% [1]. Yet where cooling is installed into existing offices it typically accounts for 31% of CO_2 emissions [4]. The conventional response of installing air conditioning into existing offices to maintain comfort conditions results in increasing levels of energy, CO_2 emissions and pollution.

Integrating low energy adaptive strategies into the refurbishment cycles of offices could increase their resilience to the effects of climate change [5], while helping to prevent an increase in energy use associated with installing air-conditioning systems. If building occupants were allowed to adapt to a building's environment by adjusting their clothing, location or interacting with it (e.g. by opening windows) they could tolerate environmental conditions considered outside those recommended by the 'steady state' thermal comfort theories [6,7] without, necessarily, increasing energy consumption.

The building studied was refurbished to provide office accommodation for just under 100 people, who had previously been located in separate, and older, premises. The environmental performance of the refurbishment building was subject to a separate investigation, which considered the actual energy consumption of the building [8], undertaken as part of a study of feedback techniques for completed buildings [9]. The main subject of this study is to evaluate the comfort implications of the refurbished building, which included the investigation of occupant perceptions of comfort, their understanding of, and response to, low energy adaptive opportunities which could be

* Corresponding author. Tel.: +44 20 7297 5600.
E-mail address: stuart.barlow@ra-lond.com (S. Barlow).

0378-7788/$ – see front matter
doi:10.1016/j.enbuild.2007.02.002

implemented in a more sustainable approach to office refurbishments.

Conclusions are drawn on which low energy adaptations of buildings and occupant intervention strategies should be adopted for refurbishment strategies of existing UK offices in the future which would contribute to preventing increase energy use and CO_2 emissions while maintaining comfort conditions in offices.

2. Background

Comfort predictive methodologies such as ISO7730 [7] relate physical parameters (activity, clothing, environmental parameters, etc.) with an average person's thermal sensation. They view occupants as passive recipients of thermal stimuli and assume the effects of a thermal environment are mediated exclusively by the physics of heat and mass exchanges between the body and the environment, being mainly related to the thermal balance of the body.

The use of heat balance models as predictive design tools have been increasingly questioned when compared to occupants' recorded thermal perceptions [10]. It was suggested that differences between predicted mean vote (PMV) predictions and occupant comfort temperatures observed in naturally ventilated buildings were due to perceived control and greater diversity of thermal experiences. Discomfort was not just an outcome but also the starting point for initiating an adaptive response [11]. Good adaptive opportunities seem to be essential in achieving thermal satisfaction when ambient temperatures fluctuate beyond a predicted neutral zone. Dissatisfaction would occur when the stimulus exceeds the adaptive opportunity or when insufficient adaptive opportunities do not or are perceived not to exist [12].

Humphreys and Nicol [13] formulated guidance relating UK office 'set temperatures' to the preceding week's exponentially weighted running mean external temperature. While external temperatures appear to be a principle factor in determining acceptable comfort temperatures, other influences such as the extent of change, the rate of change that is possible and the ability of occupants to take actions to either change their conditions or directly influence what is an acceptable comfort temperature also effect perceptions of thermal sensations [14].

3. Adaptive strategies suitable for office building refurbishments

To improve existing buildings' capacities to maintain comfort levels, low energy adaptations are required which allow occupants to create their own thermal preferences by interacting with their environment, modifying their behaviour, or gradually adapting their expectations to match ambient thermal conditions [10]. When refurbishing office buildings both classes of adaptive opportunities can be considered, i.e. *active* (where building occupants intervene to change their thermal environment) and *passive* (where a building's environment or fabric is adapted without active occupant intervention).

Possible active adaptive opportunities include:

- Temporal and spatial control—building occupants alter the timing of their work patterns or move to other areas of a building to avoid uncomfortable working conditions.
- Clothing—removed or added when occupants are too hot or too cold.
- Adding occupant controlled solar shading—to reduce solar gains.
- Localized switching to turn off lighting—reduces energy consumption and heat gains.
- Localized control of replacement heating systems—such as thermostatic radiator valves (TRVs).
- Occupant controlled natural ventilation—opening windows providing cross or single sided ventilation to provide fresh air and free cooling.
- Occupant controlled localized assistance to air movement—to offset air stratification, increase local air speed and thus occupant convective/evaporative heat loss.

In addition passive adaptive opportunities can include:

- Adding insulation to walls, roofs and floors, and replacing existing windows—nearly two-thirds of UK offices were constructed prior to requirements for minimum fabric *U*-values.
- Reducing air leakage around existing building element junctions.
- Adding fixed or automatically controlled solar shading—reduces solar gains.
- Centrally controlled replacement heating systems.
- Reducing occupant densities—reduces occupant heat gains.
- Hardware or software solutions to turning equipment off automatically—reduces heat gains.
- Time-off switching, photocell or occupancy sensors to turn of lighting—reduces heat gains.
- Centrally controlled low energy cooling systems—can be required to maintain comfort levels.
- Natural ventilation through centrally controlled grilles—removes internal heat and increases air speeds in spaces.
- Mechanical ventilation—can be required due to proximity of external pollution or noise sources.
- Automatic night time ventilation—cools a building's thermal mass.
- Centrally controlled assistance to air movement—automatically controlled ceiling mounted fans to reduce air stratification and increase air speeds within spaces.

4. The surveyed building

The building surveyed was a Central London architects' office (Reid Architecture), a 1950s building refurbished in 2001/2002. The open plan offices are located on three floors (first, second and third) each with approximately 32 workstations (in a similar arrangement) at an occupant density of 1 person per 7.7 m^2 (Fig. 1) which is higher than recommended by the British Council of Offices Guide (2005).

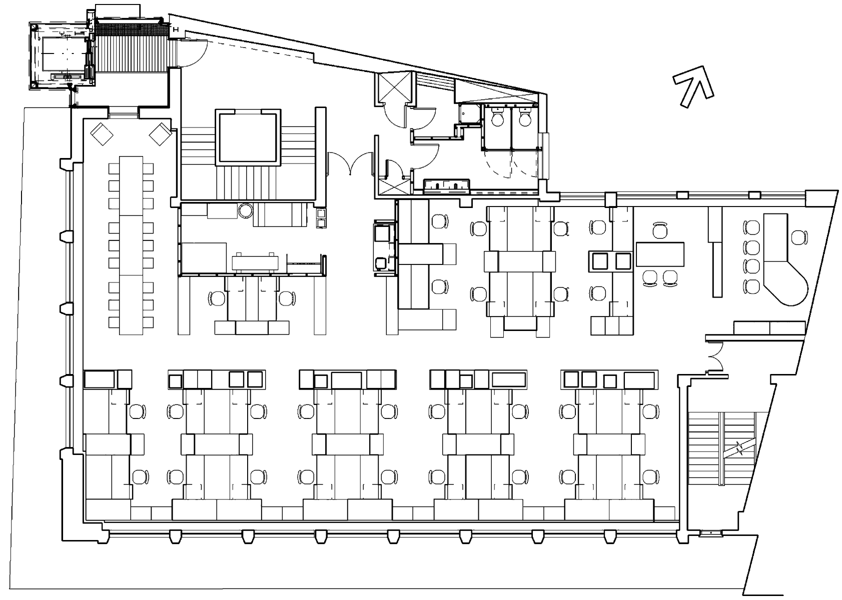

Fig. 1. Typical office floor plan of the surveyed building.

Each floor has windows along almost the whole length of two sides (facing south-east and south-west) onto narrow streets with buildings extending up to a similar height and along 30% of a wall facing north-east into a large light well.

The refurbishment was based around a mixed mode strategy for managing the internal environment using natural ventilation (NV) through grilles set under new windows and night time ventilation, to reduce energy and CO_2 emissions, but without improvements to either wall or roof insulation (due to development cost constraints). Air enters the office spaces at low level through a plenum within a perimeter casing under the window sills (Fig. 2). Controlled by a Building Energy Management System (BEMS), the NV grilles open increasingly while free cooling is available with stack pressure differentials generating air movement across the offices allowing air to be extracted at high level into two vertical stacks (a new glazed entrance tower and existing escape staircase at either end of the floors). Outside normal working hours the NV grilles open when there is a cooling demand and external temperatures are lower than internal temperatures.

The original single glazed steel framed windows were replaced with aluminium double glazed windows with opening lights providing cross and single-sided ventilation. Furthermore, some desk top fans and electric heaters are available to assist in maintaining comfort levels. New external fabric awnings are provided to control solar gains on the south-east and south-west elevations linked to solar sensors controlled automatically by the BEMS. Active occupant intervention is also possible as both elevations of awnings can be manually opened or closed separately on each floor by using manual override switches. No internal blinds had been provided for controlling solar glare at the time of the surveys.

Reid Architecture's working day operates between 09:00 and 17:30 h (although people often work longer). All occupants have a computer at their workstation and a photocopier, printers, drinks station and network hubs are located on each floor. Lighting is provided by fittings

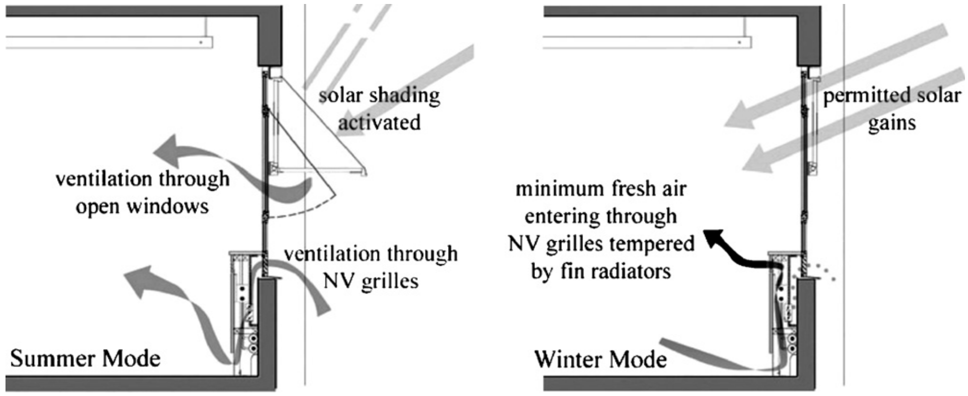

Fig. 2. Typical window section in the surveyed building showing ventilation strategy.

containing high efficiency T5 tubes, controlled by centralised switching on each floor.

The replacement heating system is a low nitrogen-oxide, gas-fired condensing boiler feeding low pressure hot water fin radiators (located in the perimeter casings) which tempers the air entering the building through the NV grilles (Fig. 2). Controlled by the BEMS, the system operates until the set point temperature is exceeded, but is disabled if external temperatures exceed 18 °C.

The building's orientation, level of glazing, occupancy levels and equipment loads meant a chilled beam cooling system was installed which could operate with open windows. The chilled beams are controlled by the BEMS and no active occupant intervention is possible. When the chilled beams are activated the NV grilles close down.

The design, for this refurbished building, had targeted to meet the 'Best Practice' standard for an air-conditioned office indicated in the UK's benchmarking guide 'Energy Consumption Guide 19: Energy Use in Offices' [15]. In the previous study [8] the energy consumption of the completed refurbished building was measured and the heating and electrical loads adjusted (to take account of the number of heating degree days during the year of measurement and occupancy patterns) to allow comparison with standard benchmarks. This study indicated that while the energy consumption for heating was just over 15% better than the 'Typical' ECON19 Standard, the energy consumption for electricity was 16% below the 'Good Practice' ECON19 Standard [15]. When compared to a Taylor-made, mixed-mode building benchmark the energy consumption for heating in the building studied was 10% better than 'Typical', while the electricity consumption was almost the same as 'Good Practice' [8]. The discrepancy in the heating consumption appeared to be due to greater air leakage through the building fabric than anticipated and the decision not to upgrade insulation levels on financial grounds. It was considered that the energy consumption for electricity might have been improved if local switching or photo-sensors had been fitted to dim the lighting in suitable conditions.

5. The surveys

Eight surveys were conducted during March, April and June 2005, covering the end of winter, spring and early summer. Survey forms were issued to the occupants of all three floors and occupants were asked to return them at the end of each survey day. Overall 154 people participated in the eight surveys, with between 15 and 25 people responding on each survey day (out of a potential office population of 87 people over the three floors). On average surveys were returned evenly from each floor. Seventy-eight percent of returned surveys were from occupants in areas adjacent to the south-east and south-west facing windows and a greater number came from occupants sitting right next to open-able windows.

In addition to providing demographic, personal (clothing) and locational information occupants were asked to describe their subjective response (for both mornings and afternoons) to a range of thermal conditions that may have influenced their perceptions of comfort. This produced nearly 1500 data responses describing their perceptions of:

- Thermal sensation (measured on the seven point ASHRAE scale; *hot* +3, *warm* +2, *slightly warm* +1, *neutral/comfortable* 0, *slightly cool* −1, *cool* −2, *cold* −3).
- Preferred changes to the perceived thermal conditions (five point scale; *much warmer* +2, *warmer* +1, *no change* 0, *cooler* −1, *much cooler* −2).
- Perceptions of air movement (seven point scale; *very stuffy* +3, *stuffy* +2, *slightly stuffy* +1, *no draughts felt* 0, *slightly draughty* −1, *draughty* −2, *very draughty* −3).
- Occupants' perceptions of whether air movement was comfortable within the offices (four point scale: *comfortable* 0.0; *slightly uncomfortable* 1.0; *uncomfortable* 2.0; *very uncomfortable* 3.0).
- Occupants' perceptions of the combined thermal and visual comfort (four point scale: *comfortable* 0.0; *slightly uncomfortable* 1.0; *uncomfortable* 2.0; *very uncomfortable* 3.0).

Occupants were also asked to vote on their perceptions of cold or hot radiating from surfaces within the spaces (floors, ceilings, walls, windows) and estimate internal temperatures. Additional questions were asked about visual perceptions, to see if perceptions of thermal conditions were the only criteria influencing comfort [6]. Over 700 data responses were recorded describing occupants' perceptions of lighting levels (seven point scale; *very bright* +3, *bright* +2, *slightly bright* +1, *satisfactory/neither bright or dim* 0, *slightly dim* −1, *dim* −2, *very dim* −3), preferred changes to perceived lighting levels (five point scale; *much dimmer* +2, *a bit dimmer* +1, *no change* 0, *a bit brighter* −1, *much brighter* −2) and whether occupants suffered from solar glare.

In the surveys occupants recorded their interventions in relation to the limited range of available active adaptive opportunities, which included opening windows, manual opening or closing of the external awnings and use of localized heaters or fans. Occupants were also asked which adaptive opportunities they would support if available. These ranged from opening windows, controlling solar glare, turning lights off locally, increasing levels of ventilation, ability to alter room temperatures, controlling solar gain, increasing levels of cooling, turning lights off automatically and using localized heaters and fans.

On each survey day objective measurements were taken. Manual readings of internal and external temperatures, external solar radiation levels, heating, natural ventilation and cooling systems status were taken from the BEMS. Further measurements of air and operative temperatures, air movement and relative humidity were recorded using Dantec Dynamics A/S Vivo Operative Temperature, Vivo Humidity and the Vivo Draught/Low Air Velocity measuring units in similar locations on one floor on each survey day (rotated to ensure all floors were covered). Data was recorded over a 7-h period, at approximately 1-min intervals, and then downloaded onto a computer for analysis, using the Dantec Dynamics A/S Vivo Controller PC (version 1.2) software to calculate

PMV/predicted percentage of disatisfaction (PPD) values, with upper and lower limits for PMV votes calculated from their standard deviation (S.D.). These calculations were based on measured parameters of the thermal environment, estimated mean Clo values (from occupants' descriptions of their clothing contained in the surveys) and an assumed activity level of 1.2Met, i.e. office sedentary activity according to Table A1, ISO 7730 [7].

For further analysis, data from occupants' descriptive votes was logged into an Excel spreadsheet and using the Excel 'data analysis tools' a series of mean, median and mode values were calculated as were the upper and lower error limits of estimated mean values indicated by the standard error margins (S.E.M.). The mean votes were evaluated in relation to the likely distribution of votes recommended in ISO 7730 [7] for spaces for human occupancy where the PPD achieved is lower than 10% (corresponding to $-0.5 < \mathrm{PMV} < +0.5$).

An additional objective analysis of the survey data was undertaken to see whether there were any underlying trends between occupants' votes (ordinal data) and measured environmental data. Spearman non-parametric rank correlation tests were used to investigate relationships between dependant and independent variables, establishing the correlation values 'r_s' to test the hypothesis whether there were any monotronic relationships between paired values [16].

6. Results

As a dress code was not operated in the building surveyed, occupants were asked to record their clothing for both the morning and afternoon. Using thermal insulation values from ISO7730 [7] for the recorded clothing combinations mean Clo values were estimated to calculate the PMV index using the Dantec Dynamics A/S Vivo software. The mean Clo values decreased from 0.8Clo to 0.66Clo over all the surveys as working day mean external temperatures increased from 6.7 °C to 27.3 °C (Fig. 3). While people changed their clothing to reflect external temperatures, as seen in the reducing mean Clo value (Fig. 3), less than 4% of respondents, however, indicated a change of clothing during a survey day (despite environmental conditions within the offices varying between mornings and afternoons).

Fig. 4. Occupants' mean thermal sensation vote and calculated PMV values.

A comparison of occupants mean thermal sensation votes for the 8 survey days and calculated PMV values is given in Fig. 4. While all the calculated PMV values fell within the $-0.5 < \mathrm{PMV} < +0.5$ limits for 10% PPD, occupants' mean thermal sensation votes fell outside this on three occasions (16 March 2005; 22 April 2005; 17 June 2005). When S.E.M. values were considered for these three occupants' votes, there was a 68% probability in one instance (22 April 2005) that the lower S.E.M. value might fall within $-0.5 < \mathrm{PMV} < +0.5$. Generally occupants' votes were evenly distributed around 'neutral/comfortable' (0.0), with the most frequent observed vote 'neutral/comfortable' (0.0) (mode: 0.0). On the three occasions when the observed mean vote fell outside the $-0.5 < \mathrm{PMV} < +0.5$ range median values moved towards 'slightly warm' (+1.0). In all instances calculated PMV values were closer to 'neutral/comfortable' (0.0) than the survey votes.

The standard deviations for the calculated PMV indicated the values within which 68% of occupants would probably vote. The distribution of the actual votes only approached the spread of calculated S.D. values on 2 days (66.6% on 1 March 2005 and 9 June 2005). On 4 other days between 62% and 54% of actual votes fell within the calculated S.D. range and on 2 survey days (17 June 2005 and 29 June 2005) this number fell to

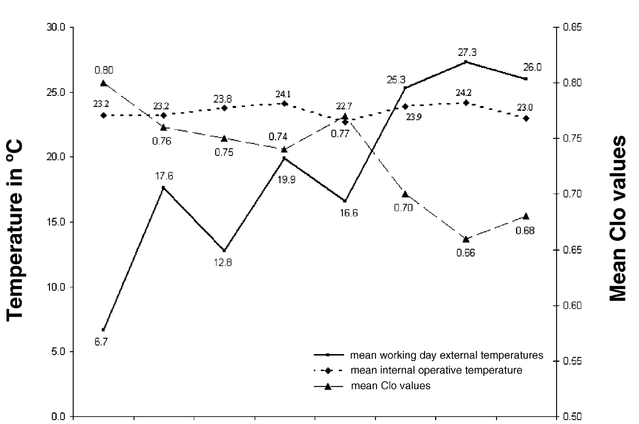

Fig. 3. Mean working day external, internal operative temperature and the corresponding mean Clo values.

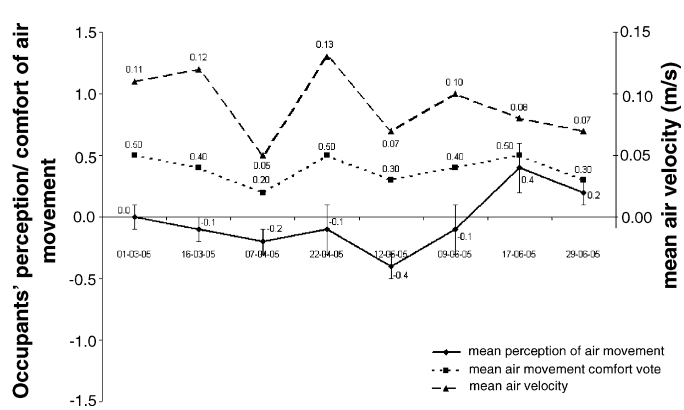

Fig. 5. Occupants' mean perception of air movement, air movement comfort vote and mean air speeds.

33% and 25%. Yet on each survey day between 55% and 66% of occupants preferred no change to the thermal conditions, although significant minorities expressed preferences for conditions to be either 'a bit cooler' (36%, 22 April 2005; 44%, 17 June 2005; 30%, 29 June 2005) or 'a bit warmer' (35%, 7 April 2005). Interestingly when occupants were asked to estimate internal temperatures they consistently underestimated the measured mean internal room temperatures on average by −3.2 °C.

The mean votes for occupants' perceptions of air movement (Fig. 5) were all close to and evenly distributed around 'neutral/no draughts felt' (0.0) (median: 0.0), with the most frequent observation 'neutral/no draughts felt' (0.0) (mode: 0.0). While on 5 days the mean vote was located on the 'slightly draughty' side of 'neutral', occupants' perceptions of whether they found air movement comfortable remained relatively consistent as indicated by the relationship of their mean votes to 'comfortable' (0.0), which did not exceed 0.5 on any survey day and were all well short of 'slightly uncomfortable' (1.0). S.E.M. values for occupants' perceptions of air movement indicated a 68% probability that possible mean vote values would not deviate greatly from the recorded mean values.

Based on measured indoor environment parameters (mean air speed, air temperature and turbulence intensity) taken on survey days Draught Rate (DR) values were calculated using the Dantec Dynamics A/S Vivo Controller PC (version 1.2) software. Compared to the corresponding observed occupants' votes on air movement perceptions, these indicated a greater variability (Fig. 6). On three occasions (1 March 2005, 22 April 2005, and 9 June 2005) the DR exceeded both the 15% DR indicated in ISO 7730 [7] as the threshold for causing local thermal discomfort and the 20% suggested by Olesen [17] for avoiding local thermal discomfort if <10%PPD is to be achieved. Only on one occasion did these higher values coincide with a measured thermal sensation PPD above the 10% PPD (13% PPD on 22 April 2005) suggested by ISO 7730 [7]. Higher calculated DR values were generally recorded when occupants opened windows and the BEMS opened NV grilles to increase ventilation. Lower calculated DR values were recorded on days (17 June 2005, 12 May 2005, and 29 June 2005) when fewer windows were opened.

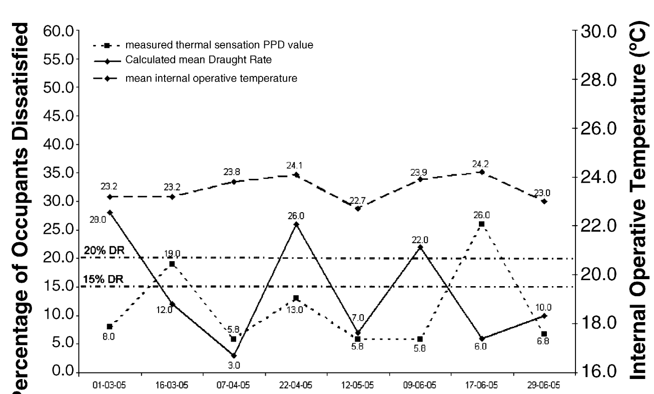

Fig. 6. Draught rate (DR), measured thermal sensation PPD value and internal operative temperature.

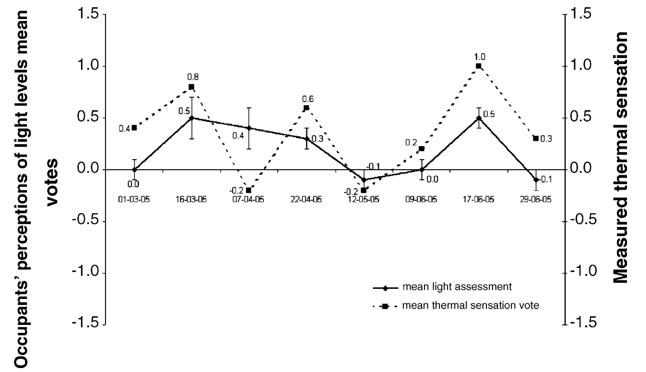

Fig. 7. Occupants' perceptions of lighting levels mean votes and measured thermal sensation.

On each of the survey days the mean vote of occupants' perception of lighting levels (Fig. 7) fell between −0.2 and +0.5. The mean votes were close to and the overall votes were evenly distributed around 'satisfactory/neither bright or dim' (0.0) (median: 0.0), with the most frequent observation 'satisfactory/neither bright or dim' (0.0) (mode: 0.0). S.E.M. values for the mean light assessment vote indicated a 68% probability that on three occasions (16 March 2005; 7 April 2005; 17 June 2005) the upper end mean votes values might lie above +0.5. Although most mean votes were on the 'slightly bright' (+1.0) side of 'satisfactory/neither bright or dim' between 50% and 75% of occupants voted for 'no change' to light levels on five occasions and were 'not at all affected by solar glare', though not always coinciding with preferences for 'no change'. Occupants actively opened and closed the external awnings more in March and April than May and June.

Occupants were asked to vote on their overall thermal and visual perceptions as a combined thermal and visual comfort vote (Fig. 8) to see whether other environmental factors (such as lighting levels) were influencing occupants overall perceptions either in negative or positive ways [6]. The combined thermal and visual comfort mean votes ranging from 'comfortable' (0.0) to 'very uncomfortable' (3.0), appeared to produce a 'flatter' response with mean votes on all but one occasion (mean = 0.6 on 29 June 2005) below 0.5. Even when S.E.M. values were considered only one additional vote (9 June 2005) indicated a 68% probability that its upper end mean value might lie above 0.5. Votes were evenly distributed around 'comfortable' (0.0) (median: 0.0), with the most frequent observation 'comfortable' (0.0) (mode: 0.0).

The majority of occupants voted they had not felt either cold or heat radiating from the floors, solid wall areas, windows or ceilings on any of the survey days. On 6 days this amounted to 60–86% of the occupants. Eight percent or less voted feeling asymmetric radiation from floors or solid wall areas, while 3% or less from the ceilings on the days when the chilled beams were activated. An exception occurred on 1 day (29 June 2005) when 22% voted feeling cold or heat radiating from the ceilings.

When asked which adaptive opportunities they would support occupants voted by a significant majority for opening windows (74%) which remained constant through all the

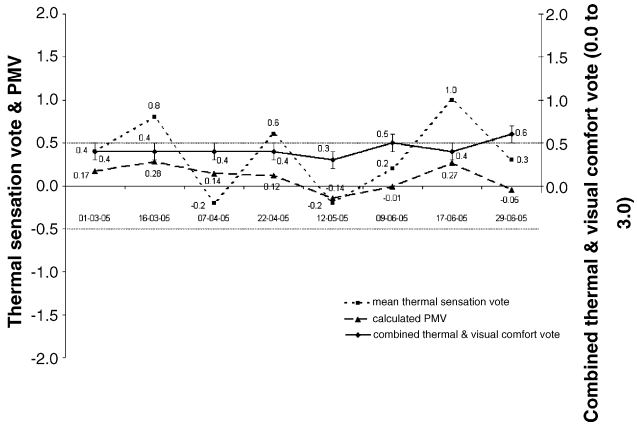

Fig. 8. Combined mean thermal and visual comfort vote, mean thermal sensation vote and calculated PMV.

surveys. Sixty-nine percent voted for controlling solar glare, reflecting anecdotal comments that glare was a problem, even though occupants consistently voted they were ‘not at all’ suffering from solar glare in the surveys. Forty-seven percent voted for adaptive opportunities to control solar gain. A majority voted for turning lights off locally (56%) which might have been in response to the existing central controls on each floor. A similar number (55%) wanted to be able to increase levels of ventilation, and 50% voted for actively intervening to alter room temperatures, both of which were operated by a centralised BEMS. Similar numbers of occupants voted to support and oppose the use of localized heaters (35%; 31%) and fans (35%; 27%).

7. Discussion

The culture of fixed working day periods, fixed workstation layout and set team structure meant neither temporal nor spatial adaptive opportunities were available to the occupants surveyed. It appears, economic pressures on companies from office overheads (rental, staff costs, etc.) are making both temporal and spatial adaptations unlikely within the UK context [18]. Although mean Clo values fell across the period of the surveys only 4% of occupants appeared to adapt to changing environmental conditions by changing their clothing during any particular survey day. This is an interesting observation indicating that cultural influences (fashion trends; wanting to wear the same clothes at different time of the year) might be stronger than the willingness to use this form of adaptation.

While active occupant adaptive opportunities in the building studied were limited, occupants generally took advantage of opening windows, manually opening and closing the external awnings and using the limited number of localized heaters and fans available. Awareness of possible adaptation strategies appeared to be strong as only 9% voted ‘don’t know’ when asked their views on suitable intervention strategies. The surveys indicated significant support (74% of occupants) for the ability to open windows. Generally, the greatest number of windows were opened on days with higher external temperatures, suggesting occupants actively intervening to increase ventilation rates and room air speed to control internal temperatures and reduce occupant heat load via elevated convective and evaporative body heat loss (even if NV grilles were being opened by the BEMS). This appeared to reinforce results from other studies in that opening windows have a positive influence on occupants’ comfort votes [10].

It appeared, occupants wanted to actively intervene in those systems centrally controlled through the BEMS. Support was expressed for intervening to increase levels of ventilation through the NV grilles. The desire to alter room temperatures appeared to be another example of occupants wanting to actively control centralized environmental systems. This might have been influenced by the inaccessibility of localized TRVs in the office studied.

The ability to open or close the external awnings for controlling glare was also considered important by occupants (69% positive votes). Intervention appeared to decline during summer months suggesting low level winter sun might have proved a greater problem than higher summer sun elevations. This suggests occupants intervened more frequently as the result of solar glare from lower sun altitudes experienced during the earlier period of surveys.

The control of solar gain (to reduce cooling demand) is often fixed or controlled through centralized controls. Occupant support for active intervention with the external awnings in the surveys might be a reflection of the positive impact this adaptive opportunity has had on perceptions of comfort in the surveyed building.

While occupant intervention through the use of localized switching was positively supported, 59% voted against turning lights off automatically. Lighting can account for between 13% and 16% of energy and 18% and 25% of CO_2 emissions in a typical office building [4]. So reducing the use of lighting through adaptive opportunities could contribute to reducing both energy and CO_2 emissions. The observed response might be a reflection of occupants’ unease with centrally controlled systems, even where they would reduce energy consumption.

One might have expected the opportunity to use localized methods of adapting the environment (such as the use of heaters and fans) to have received greater support than observed in the survey. There appeared to be a greater desire to actively control centralised heating and ventilation systems rather than using individual items of equipment. Sixty-six percent voted against the ability to increase cooling which might reflect positive experiences of the chilled beams used in the building studied or that passive control of cooling is more acceptable to occupants. This appears to be reflected by the fact that generally very few occupants voted feeling cold or heat radiating from the ceilings when the chilled beams were activated, suggesting they are not perceived as being uncomfortable. Even on the one day when a fifth of occupants voted to record cold or heat radiating from the ceilings occupants voted within acceptable thermal sensation and comfort parameters.

It has been considered the norm, in relation to adaptive comfort theory, that when occupants of a building have adaptive opportunities they would (as a large group) tolerate greater environmental variations than suggested by predictive heat balance models [12], such as ISO7730 [7]. It might thus be expected that the distribution of occupants' mean thermal sensation votes obtained through surveys would result in a mean closer to 'neutral' than would be calculated by the heat balance approach. This did not occur in this study. The opposite occurred and on each survey day the calculated mean PMV values were closer to 'neutral' than the mean thermal sensation votes statistically derived from the occupant surveys. Furthermore, heat balance model predictive calculations produced a narrower distribution of votes than occupants' perceptions of acceptable thermal sensations.

The fact that in this study occupants appeared to be more vulnerable to warm discomfort than predicted by the PMV model (see Fig. 4) seems to be surprising. For instance, internal air temperatures reached 25.0 °C on 16 March 2005 and up to 25.7 °C on 17 June 2005. These temperatures resulted in PMV values (with all the other measured parameters used) of 0.58 (16 March 2005) and 0.7 (17 June 2005). Both were still lower than the observed mean comfort vote from survey returns of 0.8 and 1.0, respectively. Similar observations were made for example by Fishman and Pimbert [19] who observed that occupants of a London office felt warmer in response to indoor temperatures above 25 °C than predicted by the PMV model for the same boundary conditions.

A variation analysis using the PMV model indicated that possible internal temperature and air velocity variations across the occupied spaces, standard deviations of clothing insulation levels, etc., would not fully explain the discrepancies between the calculated PMV values and observed thermal sensation votes. While the trend of the discrepancies between the predicted and observed mean thermal sensation votes does not follow the classic assumptions concerning adaptive opportunities it is believed that one reason for these discrepancies was the effect of elevated solar irradiation on the occupants in the perimeter zones of the spaces where a majority of the surveys were returned from. The effect of short wave radiation on the human body heat balance can be considered, e.g. by appropriate modifications of the mean radiant temperature [20]. Although the solar irradiation levels were not measured in the surveys, on all 3 days when discrepancies between observed and predicted thermal sensation votes were most significant (16 March 2005, 22 April 2005, 17 June 2005, see Fig. 4) occupants' voted to reflect perceptions of increased light levels (Fig. 7).

Occupants' perceptions of air movement, which would cause local discomfort, indicated mean votes from surveys closer to 'neutral' than calculated DR predicted on a number of occasions. Occupant mean air movement votes were more consistently similar than DR values. Higher DR values appeared to be the result of adaptive intervention by occupants opening windows or the BEMS opening the NV grilles to increase ventilation in response to increasing internal temperatures. This appears to lend support to the premise that where there are adaptive opportunities occupant perceptions will be closer to 'comfortable/neutral' than calculated values using a static model.

While the absorption of solar radiation by occupants is expected to have a direct impact on their thermal states from the calorimetric point of view, an objective statistical analysis indicated that there was no monotronic relationship between occupants' sensations of temperature and lighting levels ($r_s = 0.23$). Similar conclusions were drawn for the correlation between the thermal sensation and air movement votes ($r_s = 0.39$).

When asked to make an overall assessment of their 'comfort' occupants' responses appeared more stable, as the combined mean thermal and visual comfort vote varied less than the mean thermal sensation vote. There appeared to be very weak relationships between the combined thermal and visual votes and perception of lighting levels ($r_s = 0.12$), air movement ($r_s = 0.01$) and thermal sensation votes ($r_s = 0.16$).

The relationship between mean thermal sensation votes and the number of environmental measurements (mean external temperature, mean internal air and operative temperature, mean relative humidity, mean air velocity, mean DR), as independent variables, found the strongest relationship was with mean internal air temperature ($r_s = 0.54$) rather than internal operative temperatures ($r_s = 0.52$) and mean diurnal external temperature ($r_s = 0.48$). It was, however, short of the 5% significance level (when plotted onto a Spearman rank correlation graph). In contrast the objective relationship between mean combined thermal and visual comfort vote and the environmental measurements indicated the strongest relationship was with mean diurnal external temperature ($r_s = 0.6$). Although this fell just short of the 5% significance level it seems to support results from larger survey sources described in studies such as by Humphreys and Nicol [13] and McCartney and Nicol [6]. The relationships with mean internal operative temperature ($r_s = 0.4$), internal air temperature ($r_s = 0.39$) and mean relative humidity ($r_s = 0.4$) were weaker.

8. Summary and conclusions

The main finding from this study is the suggestion that active adaptive opportunities should be made an important part of future refurbishment strategies for existing office buildings. They offer some of the best low energy opportunities for building occupants to remain comfortable in a period of changing of environmental conditions. In the study, occupants' comfort votes expressed their strong support for adaptive opportunities, although further studies of the weak statistical relationships found between these active adaptive opportunities would be beneficial.

The building occupants surveyed in this study voted positively for those active adaptive opportunities such as opening windows, manually controlled external shading for controlling both solar glare and solar gains, which also contribute towards reducing energy and CO_2 emissions. The use of localized switching for turning lights on or off also appeared to be strongly supported. Its use in conjunction with any automatic controls to reduce energy loads and heat gains from lighting should be, however, carefully considered as automatic lighting controls were not supported by the occupants surveyed.

Interestingly, little support was found for intervening in the type of cooling system installed. This might be a reflection of the type of system used—a chilled beam radiant cooling system which appeared not to be perceived as uncomfortable. In general, radiant cooling systems result in 15% less CO_2 emissions than traditional solutions, e.g. fan–coil air conditioning systems [21]. Unlike other cooling solutions (which are often more difficult to install and/or require sealed buildings) radiant cooling systems can be combined with other low-energy strategies and adaptive opportunities such as the use of natural ventilation systems and opening windows.

Also passive interventions need to be included in future refurbishment strategies in order to save both energy and reduce carbon emissions during a period facing significant climate change. Increasing levels of insulation and reduced air leakage, for example, can contribute to improved occupant comfort by providing more homogeneous indoor thermal climates reducing localized discomfort from temperature asymmetries. Failure to implement some of the passive adaptations, proposed in this article, seem to have contributed to the higher energy use than originally targeted for the building studied [8]. It also appears, however, that changes in clothing could be of less importance to building occupants than generally assumed and the relationship between the need to adapt clothing and cultural influences of fashion, on dress codes, need further consideration.

It has been demonstrated that refurbishment of existing buildings has both lower environmental impacts and whole life costs than comparative redevelopment solutions and similarly the adoption of NV solutions rather than installing air conditioning [22]. It appears that occupant spatial or temporal control strategies, along with occupants changing their clothing, should not be relied upon in future refurbishment strategies for maintaining comfort conditions. The inclusion of active adaptations such as opening windows, occupant control of external and internal blinds, localized switching to turn lighting on and off do need to be made central to refurbishment strategies as measures perceived as contributing to improved occupant comfort while reducing buildings' energy consumption and CO_2 emissions. In addition strategies should also meet the expressed support for occupant active adaptation of heating and ventilation systems (whether natural or mechanical) which are currently centrally controlled by BEMS.

Future education of architects and service engineers will need to focus more on 'human aspects' and indoor climate research to better understand the principles of thermal adaptation and occupant comfort in order that they can include intelligent adaptive opportunities within their refurbishment strategies. They will also need to understand how these environmental systems can be controlled by small groups of people, how this form of adaptation will interact with individual desires in a practical way and how this will feed into the overall perception of occupants' comfort levels as a large group [23,24].

References

[1] C.H. Pout, F. MacKenzie, R. Bettle, Carbon Dioxide Emissions from Non-domestic Buildings: 2000 and Beyond: BR442, CRC Ltd., London, 2002.

[2] K. Steemers, Establishing research directions in sustainable building design, Technical Report 5, Tyndall Centre for Climate Change Research, Norwich, UK, 2003.

[3] S. Clarke, J. Kersey, E. Trevorrow, R. Wilby, S. Shackley, J. Turnpenny, A. Wright, A. Hunt, D. Crichton, London's Warming: The Impacts of Climate Change on London, Summary Report, The London Climate Change Partnership, 2002.

[4] Energy Consumption Guide 19: Energy Use in Offices, Energy Efficiency Best Practice Programme, Watford, UK, 2000.

[5] M. Hulme, G.J. Jenkins, J.R. Turnpenny, T.D. Mitchell, R.G. Jones, J. Lowe, J.M. Murphy, D. Hassell, P. Boorman, R. McDonald, S. Hill, Climate Change Scenarios for the United Kingdom: The UKCIP02 Scientific Report, Tyndall Centre for Climate Change Research, Norwich, UK, 2002.

[6] K.J. McCartney, J.F. Nicol, Developing an adaptive control algorithm for Europe, Energy and Buildings 34 (6) (2002) 623–635.

[7] BSEN ISO7730, Moderate Thermal Environments—Determination of the PMV and PPD Indices and Specification of the Conditions for Thermal Comfort (Incorporating Amendment No. 1), British Standards Institute, London, 1996.

[8] Feedback User Group, Case Study (by I. Carmona): West End House, Reid Architecture, 2004. Available: http://www.usablebuildings.co.uk/rp/index.html.

[9] B. Boardass, A. Leaman, Making feedback and post-occupancy evaluation routine 3: Case studies of the use of techniques in the feedback portfolio, Building Research & Information 33 (40) (2005) 361–375.

[10] G.S. Brager, R.J. de Dear, Thermal adaptation in the built environment: a literature review, Energy and Buildings 27 (1) (1998) 83–96.

[11] R.J. de Dear, G.S. Brager, Thermal comfort in naturally ventilated buildings: revisions to ASHRAE Standard 55, Energy and Buildings 34 (6) (2002) 549–561.

[12] N. Baker, M. Standeven, Thermal comfort for free-running buildings, Energy and Buildings 23 (3) (1996) 175–182.

[13] M.A. Humphreys, J.F. Nicol, An adaptive guideline for UK Office Temperatures, in: F. Nicol, M. Humphreys, O. Sykes, S. Roaf (Eds.), Standards for Thermal Comfort: Indoor Air Temperature Standards for the 21st Century, Chapman & Hall, London, 1995.

[14] J.F. Nicol, M.A. Humphreys, Adaptive thermal comfort and sustainable thermal standards for buildings, Energy and Buildings 34 (6) (2002) 563–572.

[15] Energy Consumption Guide 19: Energy Use in Offices. Energy Efficient Best Practice Programme, BRESCU, BRE, Watford, 2000.

[16] J. Townend, Practical Statistics for Environmental & Biological Scientists, John Wiley & Sons Ltd., Chichester, England, 2002.

[17] B.W. Olesen, Introduction to the new revised draft of EN ISO7730, in: Proceedings of Moving Thermal Comfort Standards into the 21st Century Conference, Windsor, United Kingdom, 2001.

[18] A. Procter, B. Fennell, A National Survey of Total Office Costs, City University Business School, London, 2001.

[19] D.S. Fishman, S.L. Pimbert, Survey of subjective responses to the thermal environment in offices, in: Proceeding of WHO Conference, Indoor Climate: Effects of Human Comfort, Performance and Health in Residual, Commercial and Light Industrial Buildings, Copenhagen, 1978.

[20] P.O. Fanger, Thermal Comfort—Analysis and Applications in Environmental Engineering. McGraw-Hill, New York, pp. 148–149 (Chapter 5), 1973.

[21] Good Practice Guide 291: A Designer's Guide to the Options for Ventilation and Cooling, Energy Efficiency Best Practice Programme, Watford, UK, 2001.
[22] J. Anderson, K. Mills, Information Paper 9/02, Part 1, Refurbishment of redevelopment of office buildings? Sustainability Comparisons, CRC Ltd., London, 2002.
[23] D. Robinson, Some trends and research needs in energy and comfort prediction, in: Proceedings of Comfort and Energy Use in Buildings—Getting them Right Conference, Windsor, UK, 2006.
[24] J.A. Clarke, I.A. Macdonald, J.F. Nicol, Predicting adaptive responses—simulating occupied environments, in: Proceedings of Comfort and Energy Use in Buildings—Getting them Right Conference, Windsor, UK, 2006.