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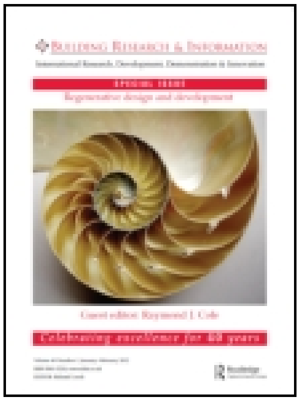

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RESEARCH PAPER

Window signalling systems: control strategies and occupant behaviour

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Signalling systems that tell building occupants when to open and close windows have become a popular strategy for balancing the comfort benefits of manual windows with the efficiency benefits of automation in mixed-mode buildings. Data from surveys, interviews and site observations in 16 US buildings reveal a diversity of design objectives, control sequences and circumstances to anticipate when designing buildings with window signalling systems. The signals had the strongest influence on occupants' use of windows when they were visible, the logic behind the controls algorithms was clearly understood, and they were seen as an informational device linked to an explicit internal policy that has to do with efficient and comfortable building operation. Lower levels of participation occurred when occupants tend not to pay attention to their windows, or the signals, unless they are uncomfortable, at which point it matters little what the signals indicate. However, occupants who do discover value in the signals are more likely to be more satisfied with their personal control. Occupants' reasons for opening windows may include the desire for fresh air or air movement, which is as important to them as temperature adjustment, but admittedly difficult to program into the controls' algorithms.

Keywords: adaptive behaviour, agency, feedback, mixed-mode, natural ventilation, occupant satisfaction, personal control, windows

Les systèmes de signalisation qui indiquent aux occupants des immeubles quand ouvrir et refermer les fenêtres sont devenus une stratégie en vogue pour trouver un équilibre entre les avantages des fenêtres manuelles en termes de confort et les avantages de l'automatisation en termes d'efficacité dans les immeubles à mode mixte. Les données issues d'enquêtes, d'entretiens et d'observations sur place réalisés dans 16 immeubles des Etats-Unis révèlent une diversité d'objectifs de conception, de séquences de contrôle et de situations permettant de prévoir quand concevoir des immeubles équipés de systèmes de signalisation des fenêtres. La plus forte influence des signaux sur l'utilisation des fenêtres par les occupants a été constatée lorsqu'ils étaient visibles, que la logique sous-tendant les algorithmes de contrôle était clairement comprise et qu'ils étaient perçus comme un dispositif informationnel lié à une politique interne explicite visant à une exploitation efficace et confortable des immeubles. Des niveaux plus faibles de participation ont été obtenus lorsque les occupants avaient tendance à ne pas faire attention à leurs fenêtres, ou aux signaux, à moins qu'ils ne fussent mal à l'aise, auquel cas peu importe ce que les signaux pouvaient indiquer. Cependant, les occupants qui découvrent vraiment l'intérêt de ces signaux sont plus susceptibles d'être davantage satisfaits de leur contrôle personnel. Les raisons qu'ont les occupants d'ouvrir les fenêtres peuvent inclure le désir d'air frais ou de souffles d'air, ce qui est aussi important pour eux que le réglage de la température, mais est, il faut bien l'admettre, difficile à programmer dans les algorithmes de contrôle.

Mots clés: comportement adaptatif, agence, retour d'information, mode mixte, aération naturelle, satisfaction des occupants, contrôle personnel, fenêtres

Introduction

The urgency of climate change requires civil society to rethink comfort, building response and control strategies. Concerns over climate change have at least three levels of impact when it comes to designing for thermal comfort in buildings. First, the urgency of climate change mitigation creates an imperative to reduce the carbon impact of buildings by dramatically reducing energy use. Naturally ventilated buildings have a key role to play in mitigation by either eliminating or reducing the need for mechanical cooling.

In addition to the struggle to reduce carbon emissions and slow the progression of climate change, adaptation and resiliency are also needed to respond to the various future climate change scenarios. The second level of impact needs to address buildings' performance in the face of more hazardous weather events which are already occurring with more frequency. Severe weather events (*i.e.* hurricanes, or the heat waves in Chicago in 1998 and in Europe in 2003 that collectively killed thousands of people who lacked adequate buildings) make it clear that buildings are vulnerable. Natural ventilation is a key strategy for passive survivability, allowing buildings to maintain liveable conditions in the event of extended power outages.

The third level of impact has to do with rising temperatures themselves, and the impact on indoor thermal conditions. It is no longer viable to consider occupants as passive recipients of automated, predictable, centrally controlled environmental conditions. Occupants' previous expectations that the thermal environment will be steady over all time, uniform over all space, and held within a relatively narrow deadband were dependent upon an enormous cost and consumption of energy. Instead, occupants need to be active participants in their environment, and be provided with sufficient adaptive opportunities to have personal control, enabling them to be more tolerant and perhaps even prefer wider ranges of conditions. Again, operable windows in naturally ventilated buildings are one form of personal control that is greatly valued by occupants.

One of the central challenges of natural ventilation is how to integrate it with mechanical modes of cooling and heating, and associated building control strategies. There is a broad, ongoing debate about the relative merits and challenges of manual versus automatic building controls, particularly applied to operable windows. These tradeoffs become even more complex when the building integrates operable windows with mechanical cooling, referred to as 'mixed-mode' design. From the perspective of thermal comfort, there is a great deal of literature establishing a strong basis for improved thermal perception in buildings with operable windows, resulting from some extent to the greater sense of personal control and connection to the outdoor environment (Baker & Standeven, 1995; Brager & Baker, 2009; de Dear & Brager, 1998; Hellwig, Antretter, Holm, & Sedlbauer, 2008; Huizenga, Abbaszadeh, Zagreus, & Arens, 2006; Paciuk, 1990). There is also an indication that operable windows may offer improved indoor air quality (Seppänen & Fisk, 2001). But trying to optimize the integration of operable windows with mechanical systems to achieve their full benefits for energy performance remains an unresolved challenge, often best achieved by downsizing cooling equipment and/or offsetting fan-driven ventilation (Daly, 2002; Emmerich, 2006; Rowe, 2003; Ogden, Kendrick, & Walliman, 2004). Overall, the benefits of operable windows are acknowledged by national building standards based on the adaptive comfort theory (de Dear & Brager, 1998), and the Leadership in Energy and Environmental Design (LEED) rating system has embraced the operable window as a workplace quality amenity. But the key question still remains: how does one balance manual versus automatic window control?

Fully automated windows or vents are sometimes seen as more reliable and predictable; but they can also raise costs and remove the amenity of local, manual control. Another approach is to allow users to operate their windows at will, but to install sensors and controls that shut off the heating, ventilation and air-conditioning (HVAC) system when a window is opened. This strategy works best in buildings where each occupied space is individually controlled, usually a prohibitive cost in office buildings. Signalling systems that advise occupants about when to open and close their windows (such as red/green lights or lighted signs) represent a compromise between the extremes of fully automated versus fully manual windows. They have become a popular, low-cost solution that attempts to balance the benefits of manual and automatic control, and are based on the premise that information from the building can effectively influence behaviour while retaining the fundamental benefits of personal control. However, little research has been done to characterize how these systems operate in practice, and whether they influence how occupants use their windows.

An investigation of signalling systems builds on two active fields of research. The first involves ongoing attempts to model window-operating behaviour (Humphreys, Nicol, & Tuohy, 2008; Inkarojrit & Paliaga, 2004; Rijal *et al.*, 2008; Warren & Parkins, 1984), some of which include investigations of temporal and social dynamics that strongly influence window use patterns in offices (Haldi & Robinson, 2008; Herkel, Knapp, & Pfafferott, 2008; Yun, Koen, & Baker, 2008). The second relates to research regarding the role of occupant education and information feedback in energy efficiency; feedback includes both 'dashboard'-style information, the importance of giving people positive feedback for their actions (Brown, Dowlatabadi, & Cole, 2009; Leaman, Bordass, & Cassels, 1998), and the idea of a psychological 'forgiveness factor' when people have greater feelings of control of the conditions in their building (Leaman & Bordass, 2007).

This project takes a broad look at window signalling systems in existing buildings in the US by investigating projects across the country to understand better (1) why and how 'open windows' signals are designed and implemented; and (2) the extent to which the signals play a role in occupant behaviour and response. The study does not monitor window-opening behaviour or measure the energy-savings impact of window signals. As the project discovered in its building recruitment phase, applications of window signals as a mixed-mode control are more varied in design and implementation than the existing literature acknowledges. The results from this project are intended to inform designers of best practices when considering signalling controls for operable windows, as well as to guide future research into the dynamics of manual and automatic controls in buildings that help integrate operable windows with mechanical systems. In addition, the signals provide an opportunity to investigate the ability for informational devices (or occupant education, more broadly) to bring design objectives and occupant control behaviours related to comfort and energy into better alignment.

Methods

The process began by identifying and recruiting 16 office and mixed-use buildings in the US, drawing from existing databases of high-performance buildings and by collaboration with the authors' industry partners (Figure 1). The type of workplace and size of subject population varied widely building to building. Data collection included occupant surveys, interviews, site observations and specifications of control algorithms. Table 1 lists which methods were applied in each building.

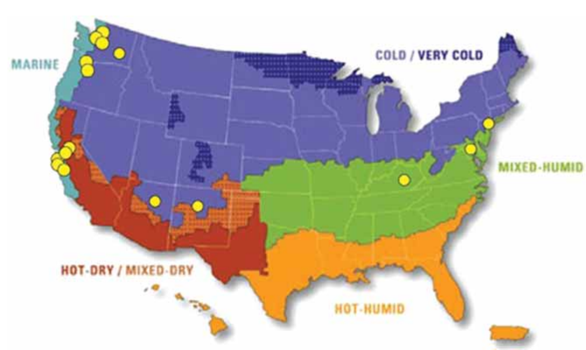

Figure 1 Locations of 16 study buildings (basemap: US Department of Energy)

Occupant survey

A new survey module was developed as a part of the Center for the Built Environment's (CBE) online Indoor Environmental Quality (IEQ) Survey, and was administered in ten of the 16 buildings. While the survey was offered to each building free of charge, for some it was not possible (or practical due to the number of staff) to get permission to survey the occupants. A total of 604 occupants were surveyed, with response rates of at least 60%. The number of subjects surveyed in each building ranged from 19 to 156, with a median of 42. Only the full-time office employees were surveyed.

The core survey asks questions about office layout, office furnishings, thermal comfort, air quality, lighting, acoustics, and building cleanliness and maintenance. All satisfaction questions are answered with a seven-point scale with the end points identified as 'very dissatisfied' and 'very satisfied'. During the analysis, these are translated to numerical values ranging from -3 to $+3$. An additional survey module asked occupants specifically about the signalling systems, including:

- how frequently they actively respond to the 'open' and 'close' signals
- how likely they are to open the window even in 'close' mode
- whether the signals interfere with their sense of personal control
- to describe any conflicts that arose between the system and their own preferences.

CBE's IEQ survey, and the authors' building scorecard, can both be seen on the CBE website (http://www.cbe.berkeley.edu/research/survey.htm). The additional survey module is shown in the Appendix (which is available in a separate file from the journal's website).

Interviews

For all 16 buildings, at least one member from the design team (architect and/or engineer) and at least one representative of the building (building coordinator, manager or operator) were interviewed and they were asked to describe the design intent and known operating issues. Most of these interviews took place by telephone, but some were during site visits where possible.

Site visits

Visits were made to 13 of the 16 buildings, and observations were recorded about the building, the office space and the placement of the signalling devices. In six of the buildings, survey data were supplemented with

Table 1 Buildings included in the study (ordered by methods achieved and location)

Building	Location	Year built	Total occupancy[a]	Office type	Users	Interview	Visit	Survey ID
654 Minnesota, UCSF	San Francisco, CA	2007	100	Open floor office	Full-time university staff	✓	✓	✓
Orinda City Hall	Orinda, CA	2007	40	Private and small open office pods	Municipal government	✓	✓	✓
Boora Architects	Portland, OR	2008	60	Open floor office	Architects	✓	✓	✓
ZGF Architects	Portland, OR	2009	175	Open floor office	Architects	✓	✓	✓
NBBJ Architects	Seattle, WA	2003	300	Open floor office	Architects	✓	✓	✓
Savery Hall, University of Washington	Seattle, WA	2009	200	Private offices	University faculty	✓	✓	✓
ARD Facility, Northern Arizona University	Flagstaff, AZ	2007	50	Private offices	Environmental research lab	✓	✓	✓
Kroon Hall, Yale School of Forestry	New Haven, CT	2009	60	Private offices	University faculty	✓	✓	✓
Compton Union Building	Pullman, WA	2008	25	Small open office	University faculty	✓		✓
Lincoln Hall, Berea College	Berea, KY	2002	60	Private offices	University faculty	✓		✓
Kirsch Center, de Anza College	Cupertino, CA	2005	8	Private offices	University faculty	✓	✓	
Hewlett Foundation	Menlo Park, CA	2002	150	Private offices	Foundation	✓	✓	
Zoomazium, Woodland Park Zoo	Seattle, WA	2003	1	Small open office	Part-time staff/ exhibit docent	✓	✓	
Thornburg Headquarters	Santa Fe, NM	2004	175	Private offices and open floor	Financial group	✓	✓	
Boalt Hall, University of California – Berkeley	Berkeley, CA	2009	n.a. (all transient)	Small open office, classroom, lounge	Law students	✓	✓	
Chesapeake Bay Foundation Merrill Center	Annapolis, MD	2000	50	Small open office spaces	Environmentally focused foundation	✓		

Note: [a]Occupancy refers only to office inhabitants expected to regard signals and does not include transient occupants, except where noted.

brief, informal interviews with a total 22 occupants, about evenly divided among the six buildings, in which they were asked whether the signals played a role in how they use windows, and to elaborate as to why or why not.

Control algorithms

The as-designed control algorithms were collected for each of the 16 buildings, and these were verified as the as-operated sequence in all but four of the buildings. As part of the project, a graphic tool was developed to visualize the differences among control strategies based on the main temperature criteria employed (see Figure 2).

Results: design and operation of signalling system

Reasons for choosing signalling controls

The interviews revealed differences in how the design teams understood the benefits and liabilities of operable windows, and these can be summarized into three primary reasons a signalling device was chosen:

- *Moderating personal control*
  The client or architect valued operable windows as a workplace amenity, but they were a hard sell to engineers or facilities managers without some measure of oversight.

- *Cost-effective natural ventilation*
  The design team intended for windows to offset mechanical cooling and ventilation, but automated controls were deemed too expensive and/or value engineered out of the project. Three projects decided on a signalling strategy post-design development.

- *'Green' message*
  The client or design team thought the signals would make operable windows more visible to occupants or visitors. This was not a primary reason in any project, but it had equal importance in three projects.

Algorithms to define 'open window' mode

In virtually all projects the algorithm for 'open' mode was written based on outdoor temperature criteria, and some projects included additional criteria for indoor temperature limits and, in just a few cases, CO_2, humidity and wind speed. How air was delivered during 'open' mode was another major difference among applications. As part of the analysis, a graphic tool was developed to compare these different control approaches, and for simplicity seven distinct examples of these are shown in Figure 2, grouped into four general approaches. The 'open' mode is denoted by a green zone confined by indoor (y-axis) and outdoor (x-axis) temperature limits. The blue hatching indicates whether or not air is mechanically supplied to the zone. Where there is green and no blue hatching, this means the air supply is shut off. A more detailed explanation and comparison of these strategies is available in Ackerly & Brager (2011).

All four approaches have the potential to reduce mechanical cooling hours by allowing windows to dampen the effect of internal gains and delay mechanical cooling operation for as long as outdoor temperatures are below acceptable indoor temperatures. As in any building, raising the cooling set-point (the horizontal dashed black line in the diagrams) will further reduce cooling energy.

The use of outdoor temperature as the primary indicator for when it is appropriate to use the windows reflects a view that the outside air is a resource for comfort. In one sense, windows are treated like an air-side economizer, which saves energy in buildings during cooling mode when the internal loads are high, but when outside air is cooler than the recirculated air, thereby avoiding the use of the chiller.

The use of outdoor temperature also reflects the view that the windows are seen as an amenity for occupants rather than just as a form of building control, and the signals are telling them when outdoor conditions are in a range where their personal desire to use the windows, for whatever reason, will not have an adverse effect on building operation. This is most explicit in buildings that fall into Group 1, in which the windows are intended to supplement, rather than replace, the building's normal economizer cycle.

Figure 3 shows the variation in acceptable outdoor temperature ranges used in the algorithms for establishing 'open' mode in the signals. The chart roughly differentiates strategies in which open windows are understood as part of the economizer mode (allowing window use at cooler temperatures), and strategies that adopt adaptive comfort principles (allowing higher indoor temperatures). These strategies are not always mutually exclusive. Naturally, the set-points also differ according to building size, climate and system design. For example, the highest limit that was used was 27.8°C (82°F) (for both indoor and outdoor temperatures). This was in a renovated historic building in Portland, Oregon, with perimeter fan coil units operated by occupants and no perimeter ventilation. Cooling set-points of 25.6 and 26.7°C (78 and 80°F) were used in more conventional open office spaces successfully, also located in the Northwestern US.

Buildings that associated window use with the building's economizer (all on the West Coast) used outside temperature as a proxy for simplicity, even if the economizer has enthalpy control. Another approach, demonstrated in one building in Santa Fe, New Mexico, was to tie the open and close signals directly to the mechanism that initiates active cooling (chilled water supply). While clear and legible, this strategy encountered difficulty during Santa Fe's spring and fall, in which frequent cycling of the chilled water supply (and thus the signal, confusing occupants), prompted the building manager to disable completely the green light between November and April.

Depending on the extent to which the design team wanted the building to operate like a 'change-over' mixed-mode system (*i.e.* the building switches between being either exclusively naturally ventilated, and being sealed with mechanical cooling), some approaches shut off all mechanical systems during 'open windows' mode (Group 2). In these cases, all workstation zones were within 20 feet of the perimeter and windows were assumed to be adequate for ventilation. For three of these buildings, the engineer felt

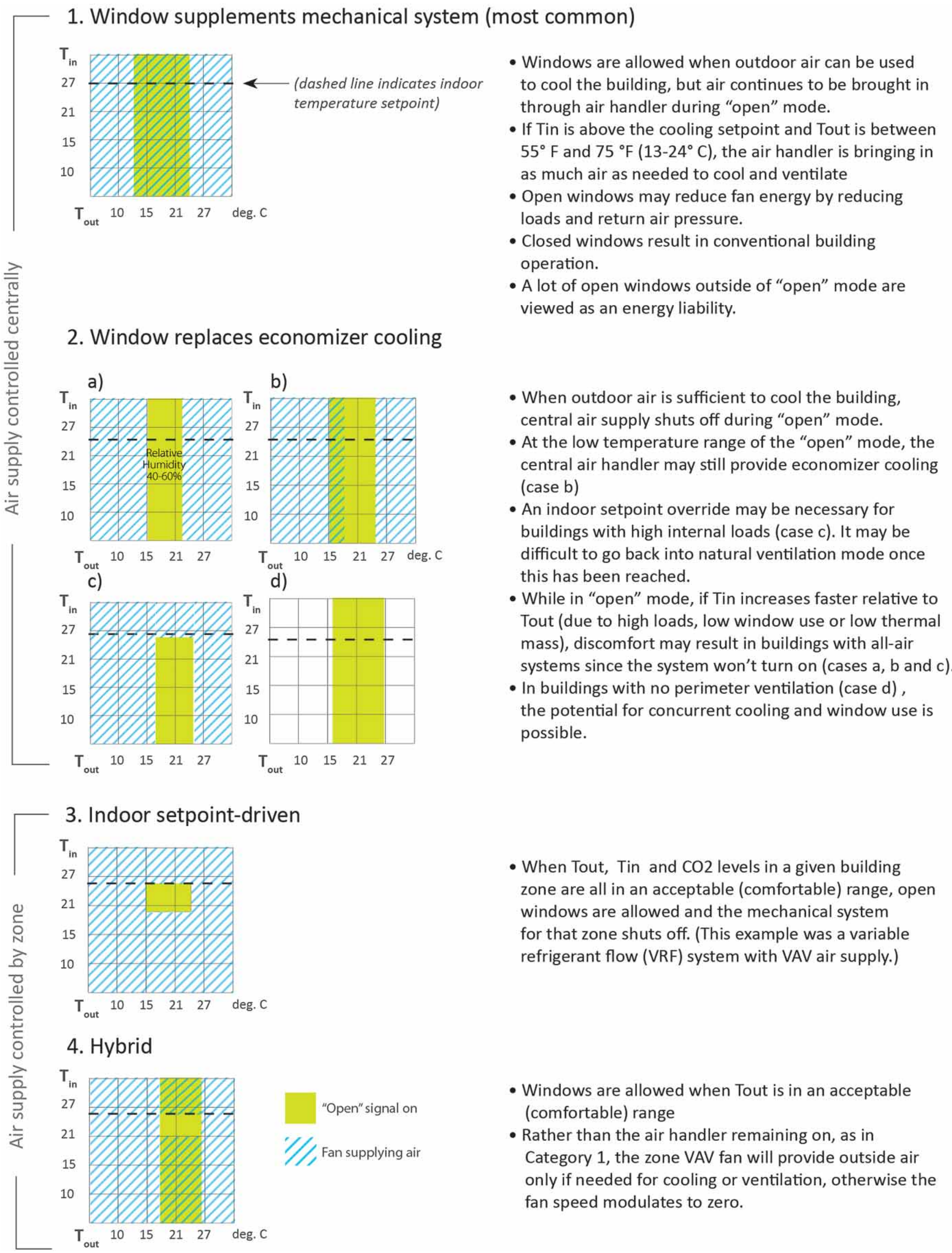

Figure 2 Distinct approaches for setting signal control algorithms

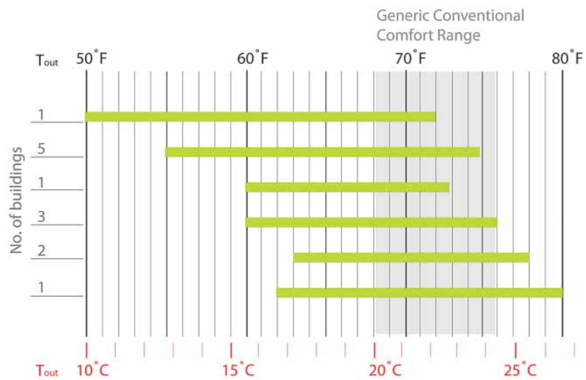

Figure 3 Variation in acceptable outdoor temperature ranges for opening windows

it important to include additional indoor temperature limits (case 2(c) in Figure 2).

In four buildings, outdoor relative humidity, wind speed and indoor CO_2 were additional environmental criteria that could override temperature inputs for ‘open windows’ mode. For example, in one building the wind speed must also be below 24 km/h (15 mph) for a period of five minutes for the green light to go on. In another building, a separate blue light indicates to occupants if CO_2 levels are high enough to warrant opening the windows for air quality reasons. In some buildings that associate windows with economizer mode, demand control is used to modulate fan speed for efficiency and air quality. Only in one building does CO_2 directly influence the status of the red and green light. In this situation, CO_2 sensors in each zone may override natural ventilation mode and trigger air supply, switching the indicator from green to red.

There were several ways in which outdoor temperature limits were combined with indoor temperature criteria and air supply in the algorithms for ‘open’ mode. It is important to note that control algorithms were not based on a narrow view of thermal comfort criteria. Rather, they reflected a more complex relationship of different ways in which designers understood the benefits and liabilities of operable windows. Typically, when the same engineers worked on different projects they tended to use the same strategy for all the projects in which they used signals. This suggests that the algorithms might more strongly reflect a way of thinking, rather than sophisticated building-specific analysis.

Signal design and placement

The range of signal designs is shown in Figure 4. Of the 16 projects, eight use unlabelled red/green or amber/

Figure 4 Signal interface types

green indicator lights; three use indicator lights with explanatory text; two use unlabelled on/off green indicators; and three use on/off 'open windows' signs. Typically, signals were distributed somewhat sparingly throughout open office floors, spaced anywhere from one per bay to one per floor. For buildings with private offices, signals were installed in individual offices in all but two, in which signs were posted in the corridors.

The findings about the design process behind these signalling systems were particularly revealing. Interviews suggested that in most cases there was little systematic discussion about the design of the signalling device; instead, decisions were made either by impromptu judgment, cost or previous experience. The vast majority of interviewees also indicated that the signals were intended as 'guidance', as opposed to an imperative, which is important to note when later interpreting the findings about occupant use patterns. The survey did not find any relationship between the presence of text and the percentage of occupants who report being aware of the signals. In terms of occupant response, the results suggest that all interface types were more or less equally likely to be overlooked unless occupants were given a compelling reason to regard them by way of briefings, periodic e-mails or regular, less formal reminders from the building or office manager.

Education of occupants

Interviews suggested there were three 'tiers' of education methods that were used to explain the purpose of the signals. At the base tier, the majority of projects (ten of the 16) relied solely upon an initial staff notice, usually in the form of an orientation given by the design team or building manager, which described the signalling system as one of the building's 'green' features, intended to save energy through natural ventilation. This explanation is very common, given that this is how the idea came about in the design process. In the next tier, a few buildings provided more targeted one-on-one explanation of the control strategies through a new-hire orientation with the building manager. In the third, highest, tier, a building or office manager was active in an ongoing discussion with occupants, either in person or by e-mail, regarding what was going on with the building. In one case it was found that frequent e-mails sent automatically by the building management system were easily regarded as spam and ignored.

Results: occupant behaviour

The survey assessed occupant engagement with windows and the signalling systems as a part of a larger set of standard questions evaluating indoor environmental quality, which included their perceptions about thermal comfort and indoor air quality.

General comfort satisfaction

Indoor environmental quality assessment for the buildings in this study represent a range of occupant satisfaction scores, as shown in Figures 5(a–c). Figure 5(a) shows the average performance of the buildings included in the study (including those surveyed previously) compared with all buildings of a similar vintage (constructed since 2000) and the scores show a consistent, minor improvement on average, particularly in general satisfaction, thermal comfort and air quality.

These results coincide with the findings of Brager & Baker (2009), who use a subset of this data to demonstrate high occupant satisfaction scores for mixed-mode buildings. Their findings are reproduced in Figures 5(b–c) including the added records generated for this study (mixed-mode buildings shown as black circles and other mixed-mode buildings depicted as white diamonds, both sets compared with the curve for the entire CBE database as compiled in late 2009). Overall, the mixed-mode buildings are performing very well compared with the overall database, particularly with regard to perceived indoor air quality. The new records of buildings with signals occupy a similar range of the distribution curves compared with the mixed-mode buildings without signals, with the exception of a couple negative outliers in the thermal comfort category (in both cases, the buildings were having serious issues with the sizing of the cooling system – one being a corrected mistake that the occupants simply had not recovered from at the time of the survey – caused severe over-heating). It should be noted that the base curve for these figures includes the entire CBE database, not just buildings of the same vintage.

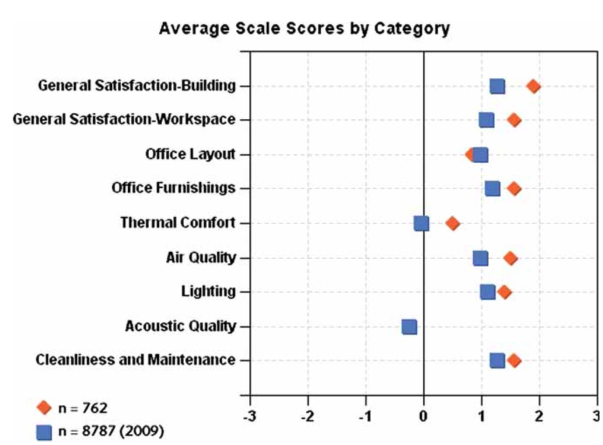

Figure 5(a) Occupant satisfaction scores compared with the CBE IEQ survey database

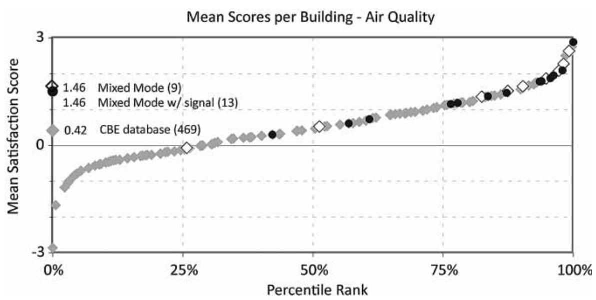

Figure 5(b) Benchmark database versus mixed-mode buildings with and without signals – thermal comfort

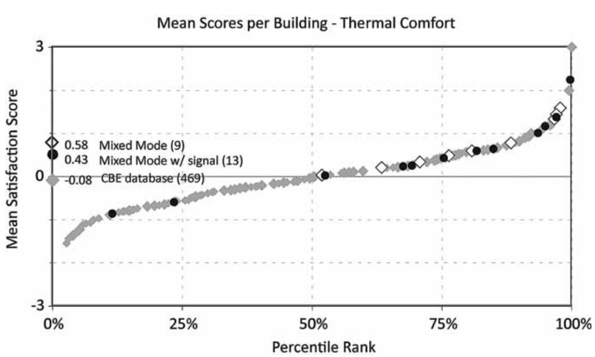

Figure 5(c) Benchmark database versus mixed-mode buildings with and without signals – indoor air quality

Personal reasons for using windows

The survey revealed that, although respondents consistently value operable windows very highly, people use windows for different reasons. As shown in Figure 6, the desire for cooler and fresher air are by far the most common reasons people open their windows, with a desire for increased air movement closely following. A similar percentage of people cited connection to the outdoors or the signals themselves as a reason, although this average varies widely across buildings.

Similarly, of the 22 subjects interviewed during the authors' site visits as a follow-up to the survey, seven (30%) said the signals played a role in how they use their windows, while 15 said they did not. The most common reason for not using the signals was simply a stated tendency not to pay attention to windows – or the signals – because they are generally comfortable and focused on other things.

Of the seven people interviewed who said the signals *did* play a role in how they use their windows, four expressed a general tendency to like to have their windows open for psychological reasons, and as a result were more likely to see the 'open' signal as a 'good reminder' or 'a treat'. Likewise, they were more likely to acknowledge the 'close' signal (or wonder why it was on). Others found particular value in following directions, whether it was an opportunity to take a break from work, a reminder that it was nice outside, or a belief that following the system is important for the operation of the building.

Reported responses to the signals

In the survey, in seven of the ten buildings, a consistent minority of respondents (10–20%) reported actively opening their window when the 'open' signal was on, as shown in Figure 7. ('Active' occupants are defined as those who report acting on the signals 'always' or 'usually'.) This pattern seems to be independent of what control strategy and interface is used in a particular building, and the percentage of respondents who say they are unaware. Three buildings (1–3) stand out for having over 50% actively engaged with very low percentages of respondents in the 'not aware' category, and these examples offer important lessons for future applications in that they share the characteristic of having some mechanism for ongoing reinforcement. In at least one of the buildings, occupants were unusually familiar with the intent of the system since they were an architect's office and were involved in the design; in the other two buildings, managers made an ongoing effort (tier 3) to share the importance of the signals.

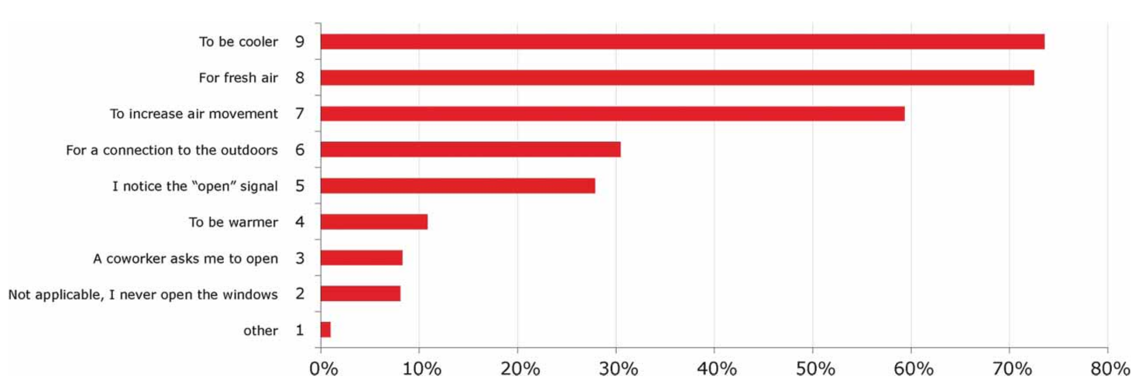

Figure 6 Reasons for opening windows

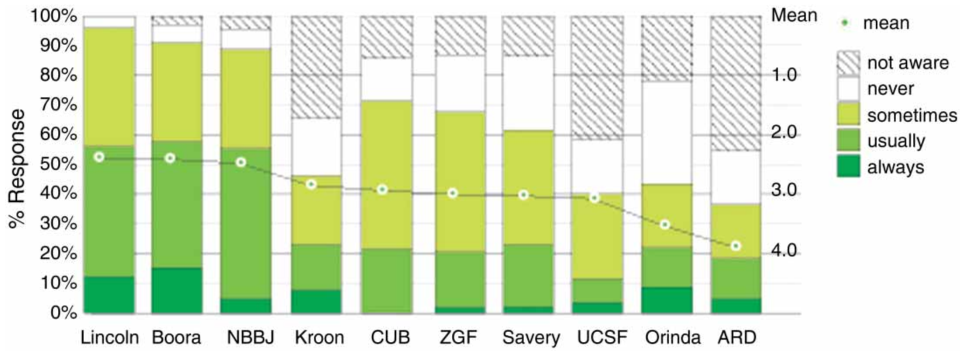

Figure 7 Occupant response to the 'open' signal

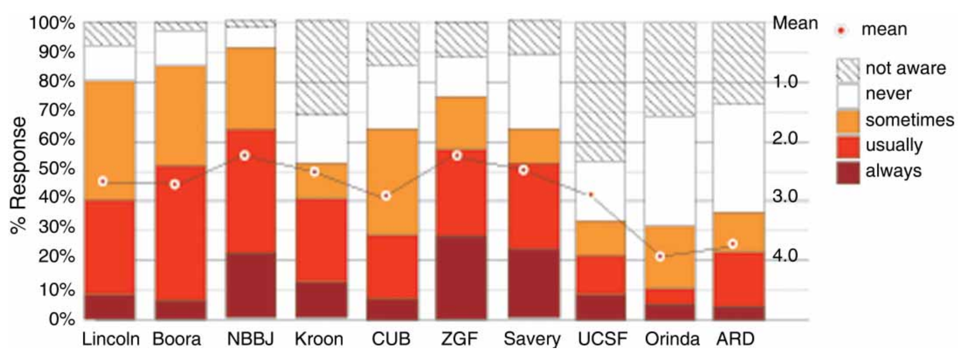

Figure 8 Occupant response to the 'close' signal

Overall, the mean responses for acting on the 'close' signal are higher and more variable, as shown in Figure 8. The projects for which 'closing' responses are significantly lower than 'opening' responses are those without a 'close' signal (that is, 'green only' signals that turn on and off: buildings 1, 2 and 9). Those for which the importance of closing windows was particularly emphasized to occupants does show relatively higher response rates (buildings 6 and 7).

Occupants were also asked how likely they would be to open a window if they wanted to, even if they know the signal indicates otherwise (*i.e.* assessing their willingness to act against the 'close' signal). As shown in Figure 9, responses in the buildings represent a full spectrum of tendencies, from over 70% reporting being compliant in one building, to less than 10% in another. With the exception of these few extreme cases, generally 40–60% of occupants in any given building report adjusting windows as they see fit.

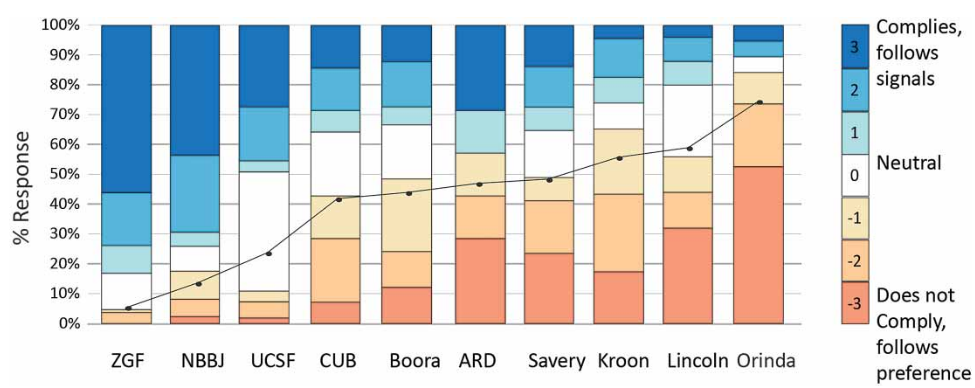

Figure 9 Willingness to open on the 'close' signal

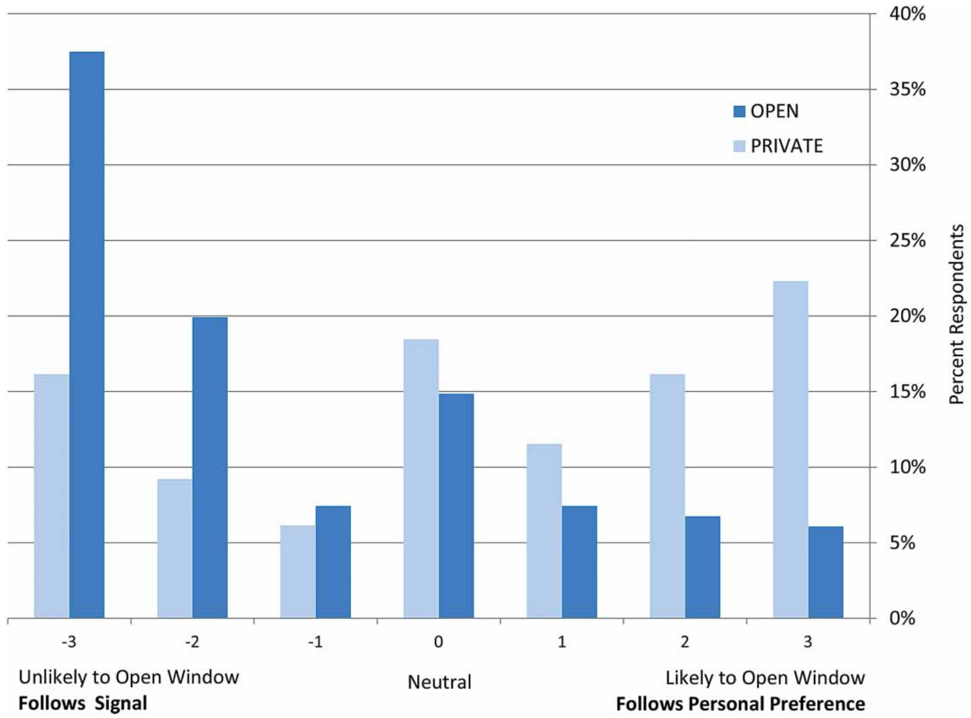

Figure 10 Open versus private offices: willingness to disregard the signals

Open versus private office spaces

The results demonstrate that the mean responses range significantly building to building. Because the buildings are quite different in terms of which ones have open-plan versus enclosed private offices, further analysis investigated the potential influence of office layout, as shown in Figures 10–13. In addition to the histograms, additional tests were conducted and the results were

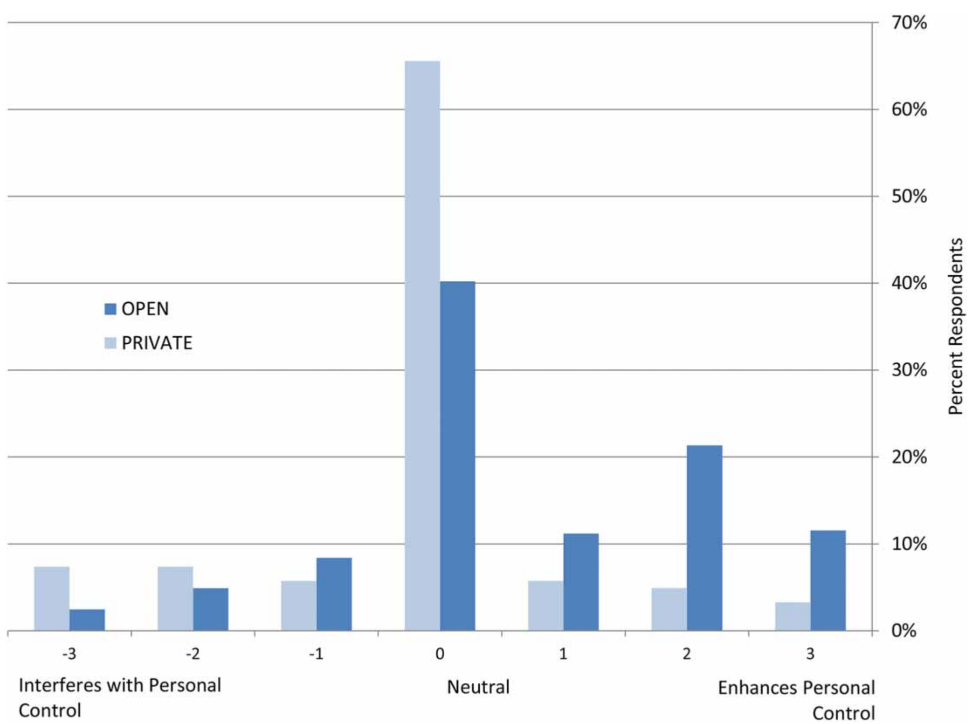

Figure 11 Open versus private offices: personal control

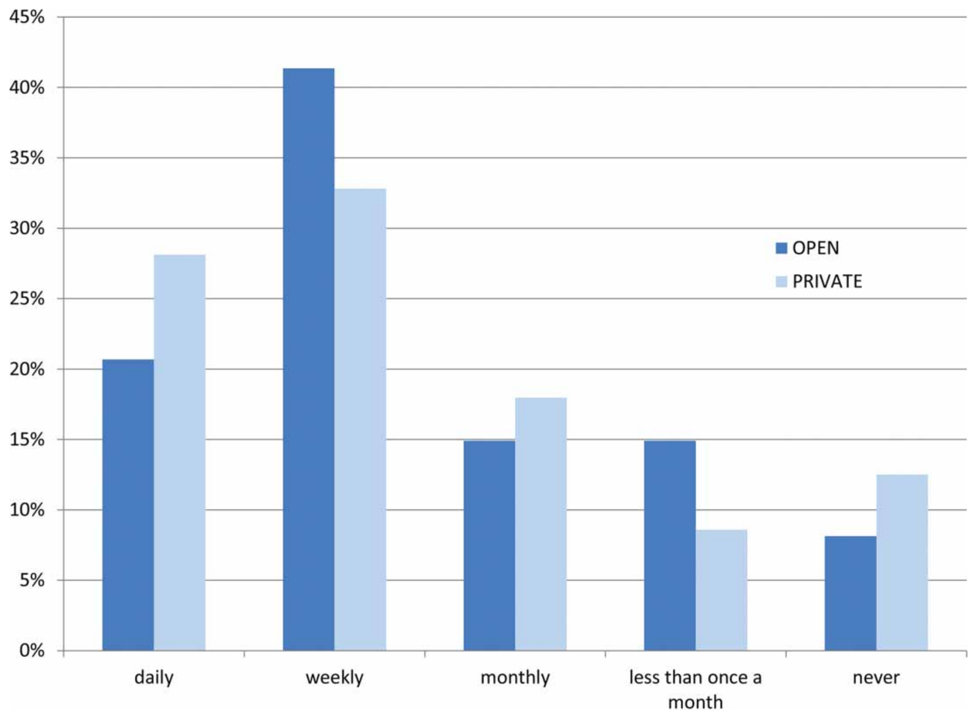

Figure 12 Open versus private offices: frequency of window use

considered statistically significant when $p < 0.05$ (which may partially be due to small sample sizes). In general, these findings suggest that general ambivalence among workers may be reduced somewhat in open offices, where the 'active' users end up taking responsibility for a group of co-workers who share window access. It is also easier for building managers to walk through and correct for windows accidentally left open.

Overall, as shown in Figure 10, people in private offices were less likely to respond actively to the

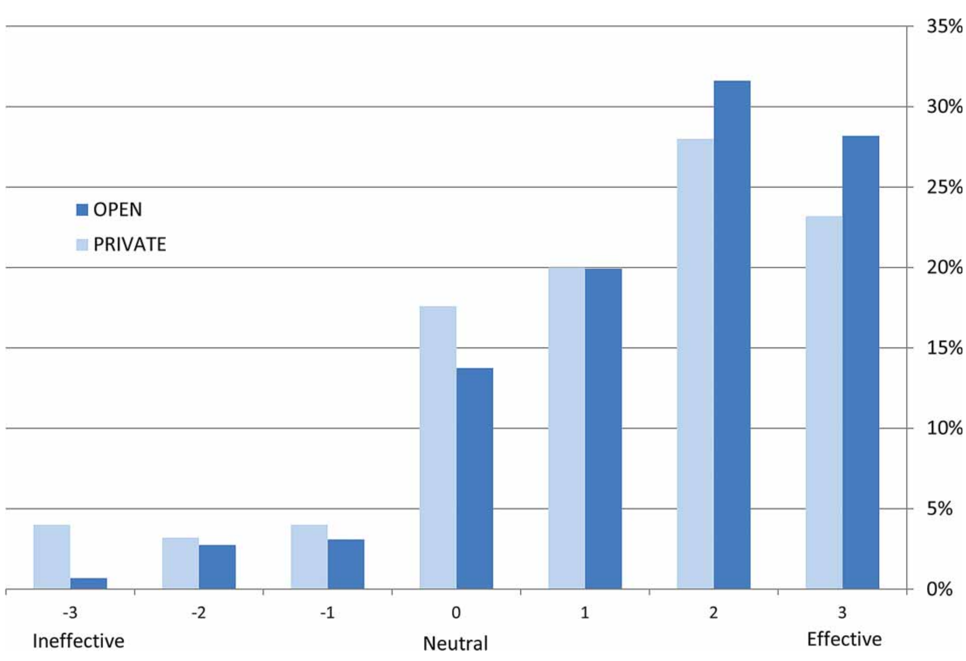

Figure 13 Open versus private offices: effectiveness of windows

signals, even though they generally had better access to both windows and an indicator installed within view. In comparison, open office inhabitants were much more likely to obey the signal than those in private offices. There are a number of possible explanations. Presumably, people with private access to a window will use it whenever they want, whereas window use in open offices is inherently more tied to the signals or other directives from co-workers. Social reinforcement in open-plan offices is likely stronger during 'close' mode (when an open window is perceived by co-workers as 'breaking the rules') than in 'open mode' (which simply validates the behaviour of those who naturally like to have their windows open).

Figure 11 addresses the question of whether the signals enhanced or interfered with occupants' sense of personal control, and it can be seen that most people selected 'neutral'. But among those who did have an opinion, people in open offices were much more likely to say that the signals enhanced their personal control.

For the data in both Figures 10 and 11, the statistical significance was tested by the Wilcoxon rank-sum test (known also as Mann–Whitney *U*-test), which is applicable when the variables have an ordinal character (Siegel, 1956). The differences between responses in open versus private offices were statistically significant both for willingness to obey ($W = 11\ 388$, $p < 0.001$) and occupants' sense of personal control ($W = 21\ 704$, $p < 0.001$).

It is important to point out that this relatively positive response in open offices does not necessarily imply more frequent window use; in fact, people in private offices were more likely to report that they personally opened their windows daily (Figure 12), while people in open offices were more likely to open their windows seldom and never. This finding is not unexpected, since people in open-plan offices may be sensitive to how their actions might affect their neighbours, and negotiating shared control is not standard practice in most office buildings. That said, people in both office types felt the windows were roughly comparable in terms of effectiveness (Figure 13), with people in private office giving only a very slightly higher rating. During interviews with occupants, a few open-office workers commented that the signals acted as a 'neutral third party', giving permission to window users who would otherwise be concerned about disturbing their co-workers. In a sense, signalling systems may work in open offices, not by promoting increased window use, but by leveraging the behaviour of those who regularly use windows, even if they are a minority.

For the data in both Figures 12 and 13, the statistical significance was tested by the Chi-squared test. The differences between responses in open versus private offices were statistically significant both for frequency of use (Chi-squared 10.7, d.f. = 4, $p = 0.03$) and the effectiveness of the windows (Chi-squared 6.13, d.f. = 2, $p = 0.03$).

Factors contributing to participation

The wide distribution in the mean responses reported building to building does not necessarily indicate a failure of signalling systems. Instead, these results point to the importance of finding out why individuals observe or disregard the signals, and then determining which of these factors are in the control of the design team or building management. The basic differences in how people use windows are perhaps the most important factor. Attitudes, interfering circumstances and other conflicts that contribute to participation are discussed in the next section.

The survey asked occupants to comment on whether the signals coincided with their 'own sense of when to open/close windows', and reviewed, coded and tallied the most common issues. A total of 274 comments were offered (roughly 20% of total survey participants), and responses were normalized by the number of occupants surveyed in each building (Figure 14). The following key factors were identified as influencing how people used their windows in relationship to the control signals:

- *How often the 'close' signal is on*
  Next to simply dismissing the signals, the most recurring reported issue was that the 'close' signal was frequently on at times that seemed nice enough to use windows (15% of comments). In five buildings, a malfunction, mis-translation of the design intent or operator adjustment resulted in the 'close' signal always being on. In other words, almost one-third of the buildings studied (including three of the ten surveyed) were not operating according to design specifications. For signals that were functioning as intended, this type of comment usually referred to the space being too warm and stuffy during times windows were not allowed, or simply that occupants preferred using windows to chilled air. These comments point to the relative influence of indoor versus outdoor conditions in determining comfort expectations and window-opening behaviour. In a naturally ventilated building, where indoor temperatures are allowed to drift out of the comfort zone, it makes sense that the *action* of opening a window would correlate better with indoor temperature, as has been shown in the literature. However, in a mixed-mode building, where there may be a different expectation, or an indoor set-point is set to limit 'open' mode, the *idea* of being able to open a window may have more to do with outdoor

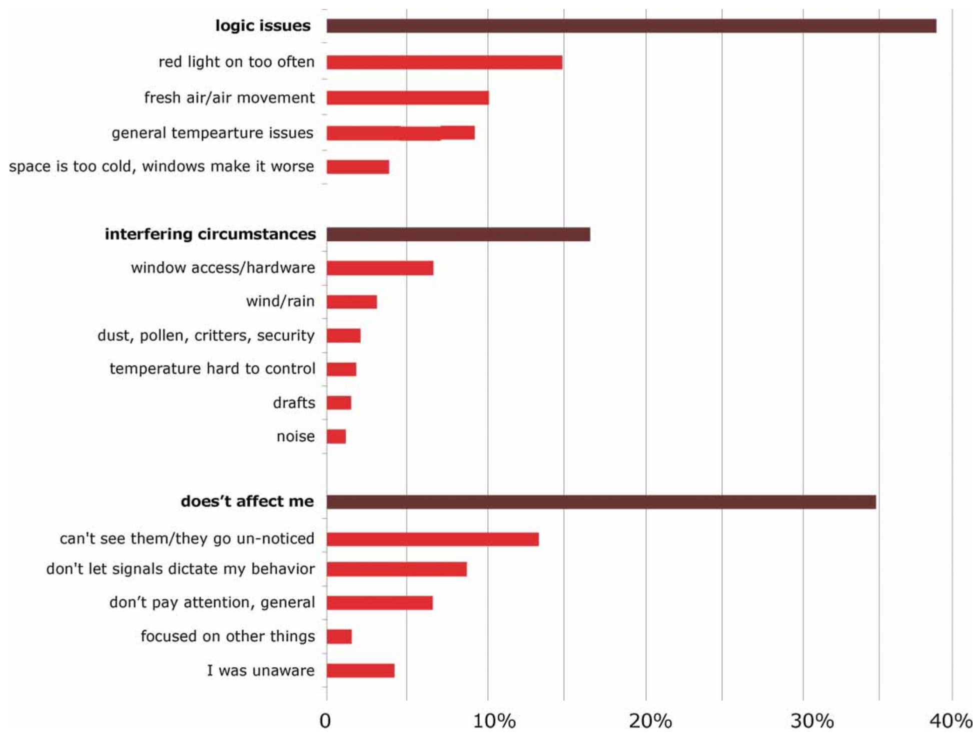

Figure 14 Top conflicts reported in open-ended survey questions

temperature and climate, along with a host of workplace factors that cause occupants' interests to fall out of alignment with designers' assumptions.

- *The desire for fresh air*
  In the survey, the desire for fresh air rivals the desire for temperature adjustment when using windows. This trend has been seen in previous studies by the authors and by others, but the relative priority of using windows for thermal comfort versus fresh air may differ in naturally ventilated versus mixed-mode buildings and is something that might be studied in the future. As a result, it was not surprising that 10% of reported conflicts between behaviour and signal instructions referred to the desire for fresh air when the 'close' signal was on. In most cases, air movement and fresh air were coupled in the comment. This finding supports research that has shown a relationship between the perception of 'stuffiness' and thermal conditions including air movement, humidity and temperature (Arens *et al.*, 2008; Fang, Clausen, & Fanger, 2000).

- *Visibility from workstations*
  Another 10% who offered comments about conflicts remarked that they may pay more attention if the signals were more visible from where they sat. This seems obvious, but the added cost often drove designers to install as few devices as possible. However, what is considered 'visible' can be highly contextual; according to one case, computer task bar icons, which are low-cost and highly accessible, can easily blend into other desktop icons and get overlooked.

- *Unique situations*
  Most of the comments, even if they are not shared by other respondents in the study, point to the diversity of attitudes and preferences among office occupants as well as the range of local circumstances that affect comfort. Unfortunately, the traditional basis for control algorithms, behavioural models and workplace policies only address average responses of occupants, rather than treating them as individuals. Perhaps this can be improved through greater clarity and validation of the initial design assumptions about how people will behave. There are also opportunities to use more sophisticated stochastic control algorithms that have the ability to learn and optimize for the aggregate tendencies of a group of window users. Although stochastic models offer the potential for helping one predict people's behaviour, it remains untested if and how they could be used to control the signals that are intended to influence that behaviour. Aside from personal disposition, mood and personality, this study documented extrinsic interfering circumstances including the location of furniture, the location of the thermostat, the presence of draughts from floor air

diffusers (noted by several occupants), proximity to the facade, conditions directly outside (such as noise, wind or pollen), surface temperatures, and direct sun exposure. In theory, these circumstances are the very justification for providing measures of personal control like operable windows. However, in many buildings, how the meaning of the signals is described to occupants does not go far enough to make allowances for these circumstances.

Discussion

These findings suggest that the programming of the system is less important than making sure they are visible and communicate a clear message. This way, occupants know how to manage their unique circumstances, which is critically important to maintain a sense of personal control, while also trying to manage the overall environmental conditions and energy use in the building. The survey results suggest that occupants' reasons for opening windows may include the desire for fresh air or air movement, which is as important to them as temperature adjustment, but admittedly difficult to program into the controls. The hybrid approach (option 4 in Figure 2) is a good way to ensure good air quality during 'open' mode, since air supply is modulated by zone based on need, and 'open' mode corresponds to outside air temperature only. The fact that the mechanical system is making sure the space is comfortable may, however, prevent occupants from adapting to using their windows more.

Beyond better communication between building managers and occupants, improving control algorithms comes down to how temperature set-points are established and how predictably and frequently the signals switch between 'open' and 'closed' modes. For buildings in mild, dry climates, signal algorithms based only on outdoor temperature allows the signal to communicate clearly the principle of when outdoor conditions are (or are not) sufficient for occupants to open the window as desired without adverse effects on energy use. In warmer or more humid climates, the algorithms may necessarily need to be more complex, such as using indoor and outdoor enthalpy rather than simple dry bulb temperature as a control variable.

The idea of exclusively using an 'economizer' logic for the window signal algorithms can be problematic, because (1) the quantity of airflow is not as precise with windows; and (2) it can be uncomfortably cool to open windows at 13–16°C (55 or 60°F), even if occupants know it may minimize internal gains and cooling needs later in the day. For the cooler temperature range, problems could be mitigated by considering the configuration of the window, or possibly considering strategically placed trickle vents rather than operable windows for ventilation.

It is important that the signals are programmed so that the effective result is not a default to 'close' mode if occupants do not participate according to plan. In most cases where the 'close' signal was on all the time or way too often, this was a result of programming errors, adjustments and overrides. However, including indoor comfort criteria limits in the operation of the signals may also result in the 'close' signal being on too often (as in the indoor set-point-driven approach; option 3 in Figure 3).

In all but one of the buildings using the option 2 approach, occupants were expected to act as 'human actuators' for mode change-over, and operate windows that were not directly located in their own workstation, either in large banks or at clerestory level. This is an acceptable approach if occupants are well informed, mode changes are reasonably predictable and frequent, and the building is built to dampen temperature swings enough to be resilient to low participation. But expecting high participation for windows not directly 'owned' by an occupant (*i.e.* associated with their own workstation) is probably not feasible for a conventional office.

For the most part, none of the buildings studied was 'allowed to get uncomfortable' by design, although a few used relatively high set-points that approach the temperatures one might find if the building did not have a cooling system. Given the tendency for occupants to ignore their windows unless they are uncomfortable, one engineer said that going through a period in which occupants are exposed to a new routine with warmer conditions may be necessary to make signals truly meaningful as a way to prevent discomfort. Understanding how window signals might help occupants adapt is an interesting question for further research. It may be useful to conduct more detailed research on the following:

- The option #2 (Figure 2) strategy, in which the central mechanical system shuts off entirely based on outdoor temperature only. Where occupants are not expected to be human actuators, in what mixed-mode design scenarios do they learn to use their windows to avoid high indoor temperatures, and how does that behaviour differ from buildings that are purely naturally ventilated?

- Adding an upper limit for 'open' mode. In a building like option 2(c) (Figure 2), when the open signal turns off if indoor temperature gets too high, how high can the cooling set-point be set to get people to adapt but not be dissatisfied? Can more sophisticated algorithms or technologies like modelpredictive control be used to strike a balance between adaptation and discomfort?

Turning now to occupant behaviour, the survey results are as problematic as they are promising. Even in the most successful applications of the system, there is likely to be a substantial portion of people who are either unaware or ambivalent about the system; meanwhile, even in the least successful buildings there is also a steady minority that does participate. This latter result could be an artefact of the survey method, in which subjects may report 'good behaviour' even if it is not entirely accurate. However, the limited number of occupant interviews suggests that occupants' reasons for using windows is important.

In general, it appears to be typical for signals to be disregarded because the majority of office inhabitants have a tendency not to pay attention to their windows unless they are uncomfortable. So when they are comfortable, they are likely to maintain the status quo and not react to the signals. When they are uncomfortable, it matters little what the signals say. Therefore, it is the non-comfort factors – the psychological and social factors – that play a greater role in determining how occupants participate. In an open office, the signals appear to leverage and validate the behaviour of those who tend to like to have their windows open, and to discourage 'bad' behaviour.

Despite these trends, the informal interviews suggest that it is possible for occupants who normally would not think about their windows to change their behaviour if they find a meaningful link between the signal operation and the comfort routine they experience throughout a typical day. One hypothesis is that such a change in behaviour is probably associated with an increase in personal control and persistence, since those who follow the signals do so because they have discovered *personal* value – rather than an altruistic one – in the system related to comfort. In a well-designed building, if the occupants are knowledgeable about how to use the controls available to them and these controls are sufficient, ideally there should be no need to appeal to altruistic goals of being 'green' to motivate behaviour change.

Conclusions and recommendations

This study provides a closer look at both the range of circumstances to anticipate when designing with operable windows as well as how successful an information system is in moving occupant behaviour towards design team expectations.

Ultimately, signalling controls are used to balance competing objectives of energy and comfort, and building designers resolve tradeoffs differently. None of the designers that were interviewed assumed that everyone in the building would follow the signals perfectly. By necessity, each building is designed so that window use transgressions do not pose any serious performance risks. As one building manager put it, 'if you're serious about natural ventilation, you cannot leave it up to the occupants.' In times when building technologies were simpler, the authors might have disagreed. But commercial buildings have become sufficiently complex that successful solutions require coordination between engineering-based and occupant-based solutions.

So why propose a signalling system at all, and how is money and time best invested? If a building owner decides a signalling system is an advantageous compromise to fully automated controls, then the following recommendations (based on the research findings) will help to optimize this strategy.

Simplify and test the control algorithms

Ideally, the 'open' signal should have a very clear meaning associated with simple criteria based on outdoor temperature and other meaningful conditions so that the building does not default to 'close' mode. Once the building is occupied, adjusting the setpoints and surveying occupants for their response would maximize effectiveness. Changes between signal modes should be routine not too frequent, and it is particularly important that the logic behind the controls algorithms, and the connection to the underlying design intent, is clearly communicated to building operators and occupants alike. The case studies reveal a number of further considerations for the control algorithms:

- *Economizer logic and minimum acceptable temperatures*
  For buildings in mild, dry climates, controlling signals based on outdoor temperature is a clear, simple strategy. The potential downside is that the control of the quantity of airflow is not as precise as with an economizer. The 'windows-as-economizer' approach takes two forms in the set of case studies. In one approach, buildings allow the use of windows during economizer mode, offering some supplementary benefit depending on the sophistication of air supply zoning and demand control. In the second approach, windows are also sometimes used *in place* of the economizer, *i.e.* they are entirely relied upon for cooling over a similar outdoor temperature range. The chief advantage of the first approach is its resilience to the uncertainties of occupant participation; however, there are greater liabilities in areas where people actively open windows even during 'close' mode. The second approach may

require more diligence in occupant education, since they are serving as human actuators for the windows, and therefore need to be well-informed and relatively responsive to the signals

- *Upper set-points for cooling system 'changeover'*
By using an *indoor* temperature criterion for window use, this approach differs from economizer-driven control logic in two ways. First, outside air is still supplied to the zone by the air handler when temperatures may be too low for occupants' taste. Second, the energy savings during natural ventilation mode in these buildings relies primarily on maintaining a higher indoor comfort limit, based on applying the climate-specific adaptive comfort zone.

- *Localized control*
The combination of windows with other local thermal control features existed in only a few of the case study buildings, but they revealed both advantages and potential pitfalls. The most obvious advantage is the potential to modulate operating modes based on local conditions or personal preferences. This involves the assumption that occupants will decide to use their windows (and/or ceiling fans) and thermostats in the right sequence. Signals alone cannot influence these decisions, but they can provide useful guidance if designed well. Potential pitfalls include the increased complexity with local control, or whether overheating in one location has the potential to initiate mechanical cooling for an entire floor. Solutions include tying the signals to mechanical system operations zone by zone, or linking the signals only to outside temperature

- *Combining signals with thermal mass and other control strategies*
There are several controls that could theoretically be combined with signalling systems to enhance the use of natural ventilation, including sensors or actuators that could provide alarms or automatic overrides in order to address windows left open over night or during critical periods. In practice, however, none of the study buildings involved such controls because they were deemed too expensive. Instead, the use of thermal mass to dampen or buffer against temperature swings and reduce loads stands out as the most robust way to increase the viability of manually operated windows, given the inevitable diversity of occupant tendencies and unique circumstances.

Make signals secondary to a stated policy

Interviews about the design process revealed that signalling systems are often understood as a part of the building's mechanical system controls, *e.g.* as an alternative to window actuators. This research suggests that a more realistic approach is to take advantage of signalling systems as an informational device supporting an explicit internal policy that has to do with efficient and comfortable building operation. Without a policy to support, the signals lack meaning.

There are a number of reasons that a signalling system should be secondary to a management strategy. First, as has been shown by others (Brown et al., 2009), the occupant learning curve for unconventional building systems in office spaces in particular is steep, and some strategies, such as wider deadbands, may require a shift in occupant expectations or routines. Second, internal policy and education is the only way to address the unforeseen interactions among thermal, visual, acoustic, and other conditions and preferences unique to a specific workstation.

For example, in one large office building project of which the authors were aware, the client opted not to install red/green lights. Instead, they spread the word to faculty not to open windows if the temperature is above 26.5°C (80°F) outside, as this actually increases the load on the building. The implication is that even if occupants are not following the policy to be 'green', they learn over time that it is best for their own comfort.

Depending on the building and climate, the policy that is most important for changing control behaviour may have nothing to do with outdoor weather patterns. For instance, in a faculty office building, where occupants have irregular schedules, making sure windows are closed when people leave their office can be more important than whether they open their windows between 18.5 and 23°C (65–78°F). Whatever the policy, it should be established during new hire orientations, or through periodic contact/reminders from the building manager.

Link the system to tangible benefits

In the majority of projects, the signals were presented to occupants as a 'green' feature designed to save energy by providing natural ventilation and/or avoiding energy waste. It has been found that generic values like 'saving energy' or 'being green' seldom motivate behaviour change (Abrahamse, Steg, Vlek, & Rothengatter, 2005; Campbell *et al.*, 2000; Gardner & Stern, 1996; McKenzie-Mohr & Smith, 1999; Staats, Harland, & Wilke, 2004; Stern, 2002). Therefore, in establishing the kind of policy described above, it is important that the underlying message be communicated in terms of what occupants need to know so that *their* needs are met, rather than the building's needs. (Assuming the building is designed well, these would coincide.) Connecting the meaning of the signal to 'green building' is not likely, by itself, to influence substantially the majority of occupants. This may be particularly true in private offices where there is less social reinforcement of 'doing good' or 'breaking the rules'. Based on input from the occupant interviews, the following personal benefits (well known by researchers) could be highlighted when explaining the purpose of the signals to occupants:

- a better understanding of how windows provide comfort (*e.g.* 'if it is warmer than 26.5°C (80°F), opening the window may actually make things worse')
- the ability to *avoid* discomfort ('if you let the cool air in now, it will prevent overheating later')
- the opportunity to take a mental break from work by opening the window
- an enhanced knowledge of the outdoor environment.

Make signals visible from individual workstations

Assuming people have found value in the system, direct visual access to the signal is important for taking action. Many occupants said explicitly in the survey that they would probably use the signals more if they could see them from where they sat. Given that most people are occupied with their work, it seems reasonable that the signals should be understood as 'reminders' of something they already buy into. Signal visibility can be connected to the idea of educating occupants about the logic behind the controls. For example, there was one case study building in which a digital temperature monitor was very simply wired to each 'open windows' sign and installed by the window at eye level.

In conclusion, although this project appears to be the first systematic study of these signalling systems, it should be viewed as merely one step forward in the ongoing enquiries into occupant behaviour in buildings with operable windows. The buildings in this study together provide a useful set of best practices for implementing signalling controls, but no project stands out as a model application. For instance, one building's control strategy may be particularly robust, but the signals are not visible to occupants; or occupants are particularly well informed and engaged with the system, but the control sequence happens to be faulty or confusing.

This project combined multiple methods in order to collect as much information as possible about a technology that has been little studied. Future research could go in several directions:

- monitoring of actual window use behaviour to understand better the influence of a signalling device compared with other environmental stimuli or physical characteristics in an office (open, private, distance from window)
- intervention studies that monitor window use behaviour before and after targeted policies, campaigns or interfaces are introduced (may or may not be associated with a signal)
- field monitoring of fan operation in 'open' mode resulting from window use compared with demand control ventilation or compared with window–HVAC interlock controls
- field studies incorporating both physical measurements and surveys to test acceptable upper temperature limits in natural ventilation mode
- investigating the use of signals in combination with other building information feedback tools, such as dashboard systems

Based on the interviews with practitioners, the authors believe that signalling strategies hold great promise for balancing the tradeoffs between manual and automated building controls in mixed-mode buildings, and deserve further attention by both researchers and the building industry to understand better the extent to which behaviour is influenced by signals, or how signalling devices impact fan and/or cooling energy.

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