Occupant Comfort, Control, and Satisfaction in Three California Mixed-mode Office Buildings

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Abstract

This report outlines the results from an occupant survey of satisfaction with thermal comfort and air quality in three California mixed-mode office buildings. Mixed-mode refers to the relatively new design strategy of explicitly integrating natural ventilation with mechanical cooling and ventilation services. Each of the research sites includes operable windows along with a complete HVAC system. Survey results indicate that access to operable windows has a significant positive impact on reported satisfaction with air movement, ventilation, and air quality. Occupants also indicate that they are more likely to use operable windows for air movement and air quality control than for temperature control.

Introduction: What exactly is Mixed-mode?

"Mixed-mode" (also called "hybrid ventilation") refers to providing building ventilation and cooling services using a combination of natural (passive) and mechanical (active) systems. Typically, the natural ventilation system consists of operable windows, either manually or automatically controlled, while the mechanical ventilation system includes air distribution equipment and often (but not always) refrigeration equipment for cooling.

Traditionally, buildings have been classified by their ventilation and cooling services as either naturally ventilated (NV) or air-conditioned (AC). In NV buildings the envelope serves as the primary climate modifier, filtering the amount of ambient heat, air, and light that enters the building. The indoor conditions of a NV building are, therefore, closely linked to outdoor climate. Occupant control over operable windows is key to inducing ventilation, while occupant controlled window shades are important for controlling daylight and limiting solar heat gain. In AC buildings, deeply tinted and sealed curtain wall systems typically isolate the building interior from outdoor conditions. Electric lighting systems provide a continual amount of internal lighting and air-conditioning systems maintain a consistent thermal environment.

In AC buildings, internal conditions are more predictable and controllable than in NV buildings. This control, however, comes at a significant capital cost, energy consumption, and environmental impact. Recent studies have demonstrated that occupants of NV buildings are comfortable over a wider range of thermal conditions than occupants of AC buildings, in part because NV occupants' expectations and thermal preferences are influenced by having greater control over the indoor thermal environment (de Dear & Brager 1998). Since no single set of indoor conditions can satisfy all individuals at all times, AC buildings often expend significant capital, energy, and facility management resources providing conditions that are only acceptable to most building occupants, most of the time (which is exactly what a lot of good naturally ventilated buildings provide at a fraction of the expense).

In the last several years, mixed-mode (MM) has emerged as a new class of buildings that seek to find a more robust solution to cooling and ventilation by taking advantage of the best features of NV and AC buildings. MM buildings are designed to integrate the use of mechanical systems when and where it is necessary with the use of natural ventilation whenever it is feasible or desirable. An analogy with lighting systems is appropriate, as it is quite common to integrate daylighting strategies with electrical lighting systems in an effort to improve visual comfort while minimizing energy consumption.

Mixed-mode buildings can provide several advantages over conventional buildings, including reduced HVAC energy, reduced lifecycle costs, increased adaptability of building functions, and, in particular, improved occupant comfort. Mixed-mode strategies, however, also have the potential to add cost and complexity to a building, and in the worst case might yield frustrated occupants and excess HVAC energy consumption.

Mixed-mode systems have existed in the shaky middle ground between fully naturally ventilated and fully air-conditioned buildings for some time. In recent years, however, building researchers and designers have begun discussing, designing, and analyzing buildings explicitly intended to operate as mixed-mode. In 1999, The International Energy Association (IEA) launched a three-year "research annex" to explore control strategies and occupant comfort issues for hybrid ventilation systems[1]. This project (dubbed "HybVent") includes researchers from Denmark, Australia, and Japan among many other international participants (Heisleberg et. al. 1999). Several well known "green" buildings have adopted mixed-mode systems, including William McDonough's Gap corporate office building in San Bruno, CA[2], and Norman Foster's Commerzbank headquarters in Frankfurt[3] (figure 1). Mixed-mode buildings are most common in Continental Europe, the United Kingdom, and Japan. For a variety of reasons the US building industry has not widely embraced the strategy, and the vast majority of commercial buildings in the US are sealed and air-conditioned.

Figure 1: Commerzbank Headquarters, Frankfurt; and Gap Building, San Bruno, CA.

[1] More information on IEA – EECBS Annex 35, "Hybvent", can be found at: http://hybvent.civil.auc.dk
[2] For more information on the Gap 901 Cherry Street building go to: http://www.mcdonough.com
[3] For more information on the Commerzbank Headquarters go to: http://ww.commerzbank.com

Research Method

This study identified three California office buildings that include both mechanical air-conditioning systems and occupant controlled operable windows. Each of these buildings can be considered "traditional" in their approach to mixed-mode ventilation, as opposed to the more innovative and experimental mixed-mode approaches found in some European buildings (Bordass & Jauzens 1996).

The study sought to explore occupant satisfaction with thermal comfort and air quality in each of these buildings. At each research site, we administered an occupant survey based on an "Indoor Environmental Quality Assessment" tool developed by the Center for the Built Environment (CBE), who sponsored this work[4]. The occupant survey was administered via the Internet, with respondents filling in responses and comments through their web browser and the data collected to a database maintained by CBE. The majority of the questions on the survey asked about overall satisfaction with various aspects of the indoor environment, using a seven-point scale ranging from "very dissatisfied" to "very satisfied", as demonstrated in Figure 2. Other questions asked about the use of operable windows and personal HVAC controls. Each section of the survey also provided an opportunity for respondentd to write in open-ended comments.

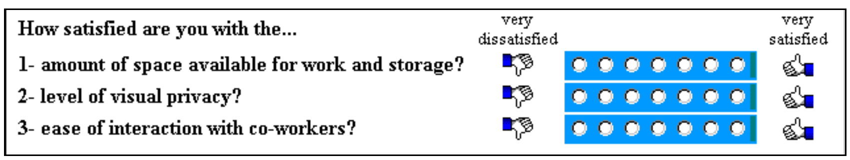


Figure 2: Example Questions from On-line Occupant Survey

Although the survey is a general assessment of indoor environmental quality, our analysis focused on the reported use of operable windows and personal HVAC controls, and how different survey groups reported their satisfaction with temperature, air movement, ventilation, and air quality (odors and humidity).

For any given survey question, we categorized the responses into three bins: "dissatisfied" (the bottom two points on the seven point scale), "neutral" (the middle three points), and "satisfied" (the top two points), as shown in Figure 3. For this analysis, we compared different groups of survey respondents based on the relative percentage of dissatisfied, neutral, and satisfied responses for any given question. Statistical significance of the differences in the response profile for various survey groups was evaluated using the Mann-Whitney non-parametric test (the U-test) for two populations of different sizes[5].

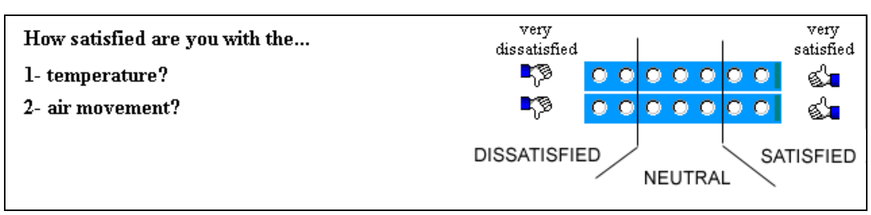


Figure 3: Response "Bins" for Occupant Survey

[4] More information about the occupant survey is available at: http://www.cbe.berkeley.edu/survey
[5] See Sigel, Chapter 6 page 116, for more information on the Mann-Whitney U test.

Research Sites

We identified three California office buildings for this study, all of which were built in the 1990s and include occupant-controlled operable windows along with mechanical cooling, heating, and ventilation systems. In each building, operable windows were included in an effort to optimize occupant comfort, control, and satisfaction. The buildings are different, however, in many other ways including the design of the HVAC systems, interior space layout, organizational culture, and prevailing climate.

Palo Alto

The Palo Alto building (PA) is a 5-story, 164,000 sf academic instructional, office, and computer lab building completed in 1996. The 5-story "L-shaped" building houses approximately 350 university faculty, staff, and graduate students. The building includes small (180 sf) private offices along the perimeter of each wing, most of which are shared by two or more occupants. Interior space is largely devoted to common work areas, storage, and core services, although there are also a few offices in the interior.

Figure 4: Palo Alto Research Site

The building mechanical system is a conventional, single-duct VAV system with every office zoned independently. Thermostats in each office allow occupants to control the HVAC services provided to the office. Micro-switch sensors located in the operable windows deliver a control signal to shut off the zone terminal box if a window in the office is open. The PA building can, therefore, be considered a "change-over" mixed-mode system (i.e. if natural ventilation is employed in an office, then air-conditioning is not available).

The facility management at PA is, well trained, well-funded, and quite responsive to occupants concerns and complaints. Maintenance requests and hot/cold complaints can be handled on-line through a departmental web site. Both occupant thermal comfort and energy consumption of the building also benefit from the generally mild, coastal climate in Palo Alto.

Private sector donors to the university financed the construction of the building. It is a state-of-the art instructional and computer lab facility, billed as "the most advanced computer science building on any college campus in the U.S. to date", and was built at a premium cost of around $240/sf (hard construction costs)[6].

[6] Hard construction cost estimates for all three facilities are based on interviews with project architects along with other published information, when available. The cost estimates do not include the cost of land, site improvements, permitting and design fees, or contractor overhead and profit

San Rafael

The San Rafael (SR) building is a 3-story, 75,000 sf office building completed in 1998. A developer built the facility to suit the needs of a growing software company, which pre-leased the upper two floors. Approximately 150 permanent employees and another 50 contract employees work for the software company. The "U-shaped" building includes a combination of open-plan offices (approximately 2/3 of employees) and small private offices (approximately 1/3). All of the private offices and much of the open plan space have access to operable windows. The first floor of the building was not included in this study.

The design of the building is intended to optimize occupant comfort and control. The software company is very concerned with its ability to recruit and retain qualified employees. The architect's design intent was to provide a narrow building with a large number of operable windows, extensive daylighting possibilities, and many small HVAC zones. San Rafael's temperate climate supports use of natural ventilation through the operable windows.

Figure 5: San Rafael Research Site

The HVAC system for the building is a water-source heat pump loop. The 50,000 sf occupied by the software company includes 72 heat pump units, or approximately one unit per 800 sf. Individual thermostats in the occupied space control the heat pump units. Opening and closing windows has no direct impact on the operation of the HVAC systems, and as such the building can be considered a "concurrent" mixed-mode system. Due to the abundance of small heat pump units, many employees (particularly those in open plan arrangements) may be affected by multiple heat pump units, which independently switch on and off, and which may have somewhat different thermostat settings. Survey comments indicate that this is a common source of frustration and that many would prefer the units turned off as often as possible. The heat pump units also produce a fair amount of undesirable background noise.

Although the building was built to suit the needs of the software company, it is essentially a speculative office building. It was built on a fairly typical budget for Class A office space in the area of $140/sf hard construction costs, including tenant improvements.

Sacramento

The Sacramento building (SAC) is a 4-story, 208,000 sf, owner-occupied office building completed in 1996. Approximately 550 employees work in the building, and all of the office space is open-plan with partitions of various heights. The "H-shaped" facility contains four, narrow wings radiating from a central lobby. The entire design of the building was intended as a showcase of energy efficient design including an underfloor air distribution system, a high-efficiency central plant including thermal energy (ice) storage, and a sophisticated and well-regarded daylighting scheme.

Figure 6: Sacramento Research Site

The HVAC system delivers supply air via a pressurized floor plenum. Occupant-controlled, passive floor registers control the amount of air delivered to any given area. A second dual-duct VAV system provides supplemental heating and cooling at the building perimeter, with supply registers located in the window soffits. The operable windows are equipped with sensors intended to shut off the dual-duct VAV box serving a perimeter zone anytime a window in that zone is open. It is unclear, however, whether this control strategy has ever been implemented. The primary (underfloor) conditioning system operates regardless of window status.

The interior space plan of SAC was originally designed so that circulation would occur at the perimeter of each wing, with offices at the core. This concept was abandoned, however, when the interior space was fitted out with partitions and furniture. In most perimeter offices in the building, occupants must reach 2 –3 feet, across their desk and across a significant window soffit in order to open the window. A combination of factors, including distracting street noise, the robust HVAC system, and the relative difficulty in operating the windows, all lead to a situation in SAC where windows are utilized infrequently. Sacramento also has a more extreme climate than the other two research sites with hotter summers, cooler winters, a generally large diurnal temperature swings.

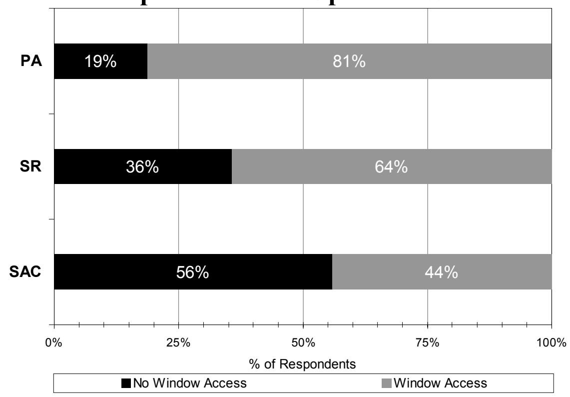
SAC was built to be a "100-year" building showcasing energy efficiency and providing high levels of occupant comfort. The hard construction budget was around $180/sf.

Occupant Survey Results

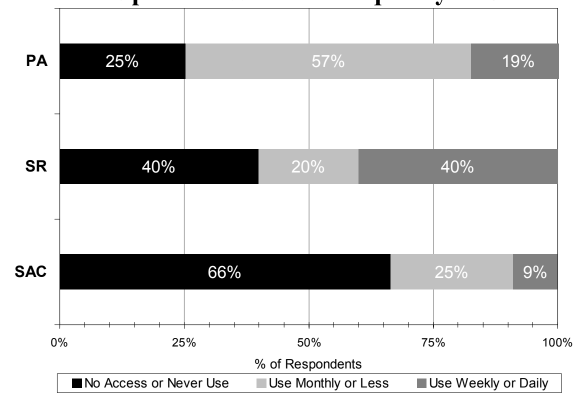
Response rates to the survey varied among the three research sites from San Rafael (70/150, 45%) to Sacramento (179/550, 33%) to Palo Alto (63/350, 18%). The reasons for this variation in response rate are not clear. The survey was completely voluntary and anonymous. Our analysis necessarily assumes that the respondents for each site represent a random sample of all building occupants. We acknowledge that we did not demonstrate that each sample of respondents is random and representative, which unfortunately is very difficult to do and rarely done in field surveys of occupant satisfaction.

Building to Building Comparison: Window and HVAC Control Usage

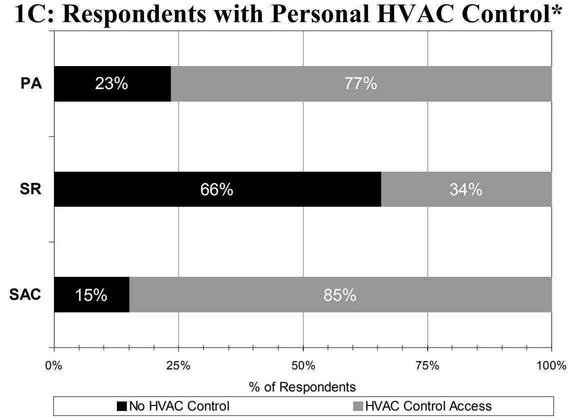
1A: Respondents with Operable Windows



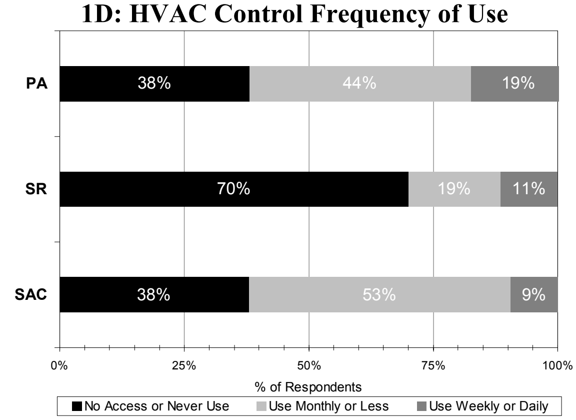
1B: Operable Window Frequency of Use



1C: Respondents with Personal HVAC Control*



1D: HVAC Control Frequency of Use



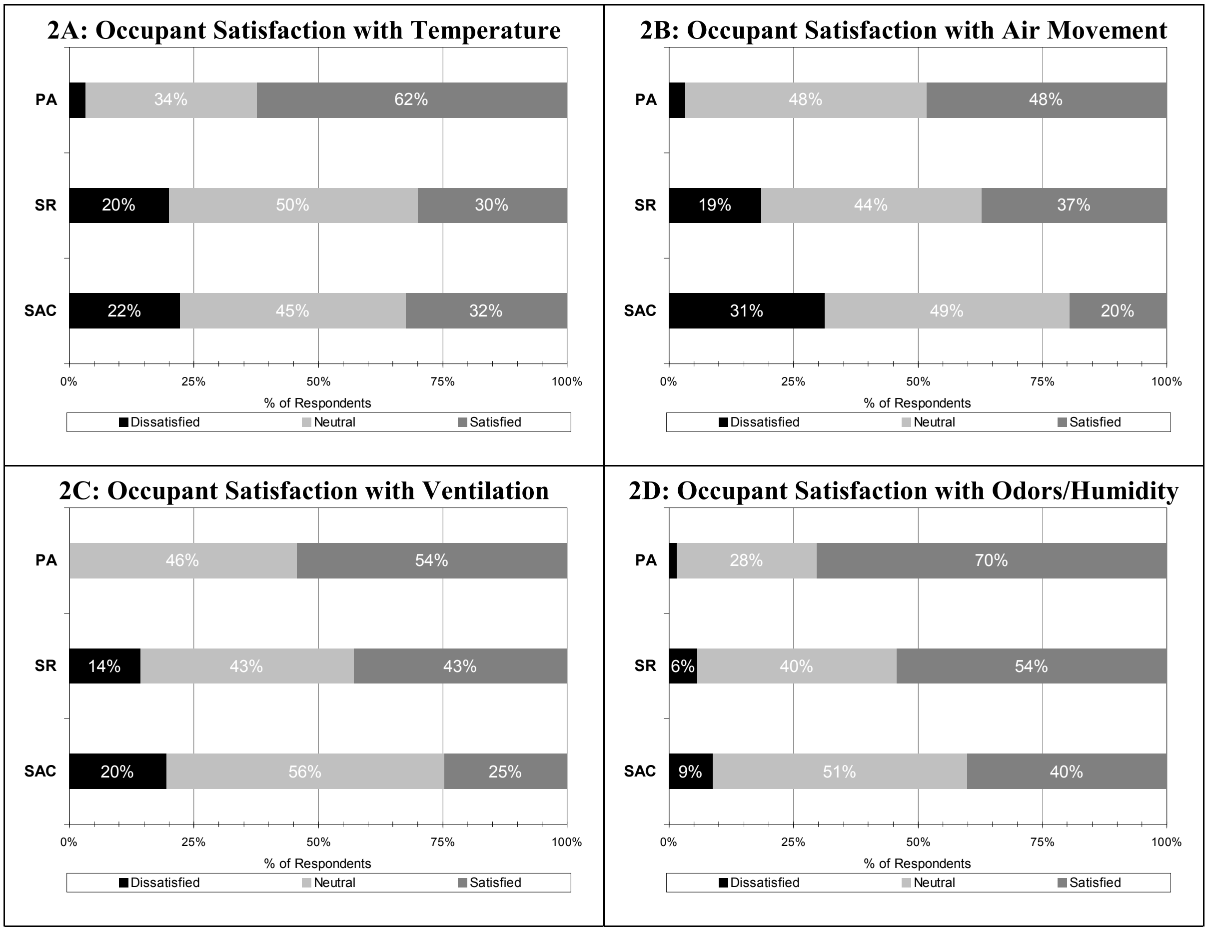
*Personal HVAC controls are thermostats for PA and SR, adjustable diffusers for SAC

We asked people whether they had access to operable windows or personal HVAC controls and, if so, how often they used them. Although the highest percentage of occupants with access to operable windows occurred in PA (n = 64, Chart 1A), occupants of SR (n = 70) reported that they utilize their windows most frequently (1B). This may be due to the limited opportunity for HVAC control and relative nuisance that the HVAC system in SR creates. The prevailing climate and the facility management staff in SR both support frequent use of the operable windows.

SAC (n = 179) reported the lowest percentage of occupants with access to windows (1A), and the lowest frequency of window usage (1B) among the three sites. Anecdotal evidence, site observations, and survey comments all indicate that space planning decisions in SAC make it difficult or impossible for many occupants to operate the windows.

PA and SAC both demonstrated a similar percentage of occupants with access to personal HVAC controls (1C) and use of those controls (1D). SR reported much less personal control over HVAC systems (only 34% of occupants report that they have access to a thermostat). Among those with access to windows and/or HVAC controls, occupants of SR reported that they adjust thermostats much less often than they use windows. SAC occupants reported using windows only slightly more often than adjusting air diffusers, while in PA occupants reported that window use and thermostat use have similar frequency.

Building to Building Comparison: Thermal Comfort and Air Quality

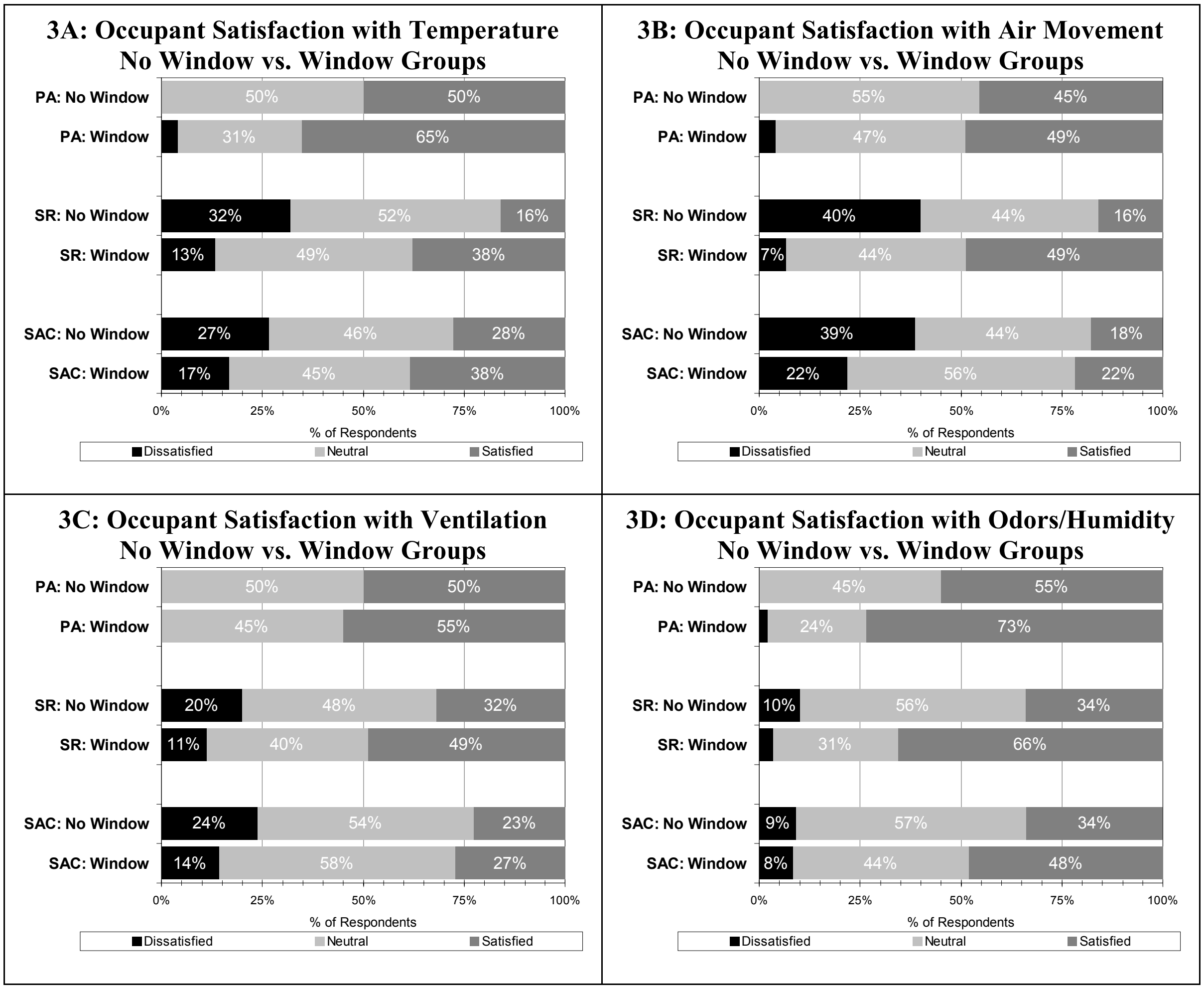


We asked subjects to rate their satisfaction with temperature, air movement, ventilation, and odors/humidity. The charts above demonstrate statistically significant differences ($p \leq 0.05$) in the responses to these questions collected at each site, with the exception of temperature satisfaction for SAC and SR, which is nearly identical.

PA reported much higher temperature satisfaction than SR or SAC (2A). This may be due to the fact that PA has a high level of occupant control over both windows and the HVAC systems, along with a facility management team that addresses thermal comfort complaints promptly. SR and SAC occupants reported similar patterns of temperature satisfaction. In both buildings, around 20% of occupants are dissatisfied with the temperature, with roughly equal numbers of those dissatisfied reporting that they are "too hot" versus "too cold". It is interesting to note that this is consistent with the goals of ASHRAE Standard 55, which specifies indoor thermal conditions that 80% of occupants should find acceptable.

The data for air movement (2B), ventilation (2C), and air quality (2D) satisfaction each show a pattern similar to Chart 1A (the percentage of building occupants with access to operable windows). The data on Chart 1A is well correlated with the data on Charts 2B, 2C, and 2D. This limited sample would seem to indicate that there is a strong relationship between access to windows and occupant satisfaction with air movement, ventilation, and air quality.

Window Users to Non-Window Users Comparison

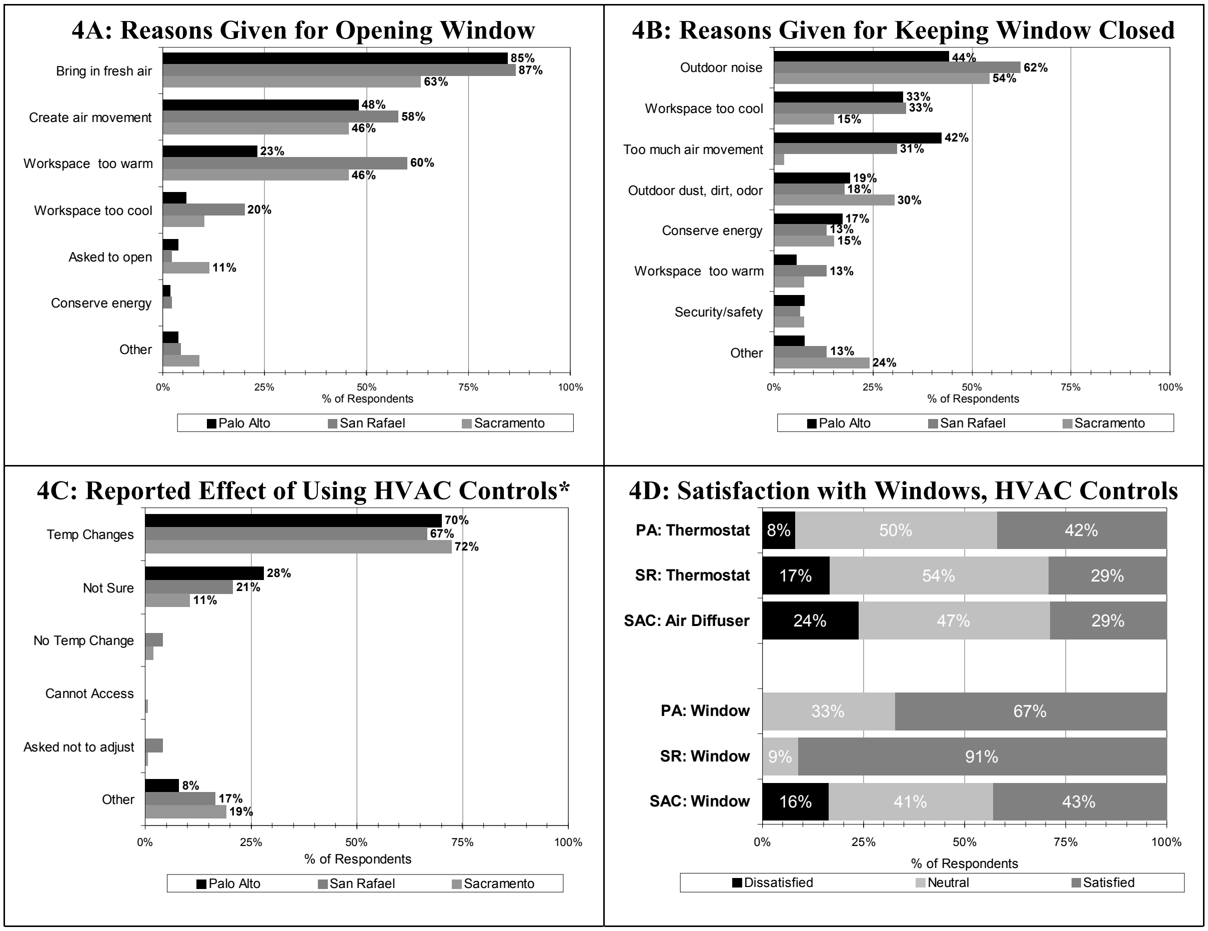


We also analyzed the thermal comfort and air quality satisfaction data separately for respondents who indicated, and who did not indicate, access to windows. For PA, the population that reported they do not have access to a window is quite small (n = 12). This group shows no statistically significant differences in satisfaction with thermal comfort and air quality compared to the larger group who reported that they have access to an operable window (n = 52).

In contrast, the occupants of SR showed quite a different pattern. For SR, there is a clear difference in reported satisfaction with thermal comfort and air quality between the "window" group (n = 45) and the "no window" group (n = 25). SR was also the site with the most reported use of the windows (1B). The difference in satisfaction for the SR "window" and "no window" groups are all statistically significant ($p \leq 0.05$), except for ventilation, which is not quite significant ($p = 0.12$).

A similar pattern was found in SAC, where the "window" group (n = 78) reported somewhat higher satisfaction for temperature, air movement and ventilation, significant to the 90% confidence level ($p \leq 0.10$), compared to the "no window" group (n = 101). The difference in satisfaction between the "window" and "no window" groups in SAC, however, was not as strong as found in SR, where windows are used much more often.

Use of and Satisfaction with the Operable Windows and HVAC Controls



*Personal HVAC controls are thermostats for PA and SR, adjustable diffusers for SAC.

Occupants who reported access to an operable window were asked to select from a list of reasons for opening the windows and for keeping them closed (4A, 4B). The most common reasons given for opening a window (4A) were bringing in fresh air and creating air movement, followed by thermal issues. Not surprisingly, the building with the least robust HVAC system (SR) reported opening the window for thermal reasons more often than the other two buildings (PA or SAC). Among the most frequent reasons given for keeping the windows closed (4B) were outdoor noise, dust, dirt, and odors.

Approximately 2/3 of occupants in all three sites reported that their HVAC controls are effective at changing the temperature in their work space (4C). Overall satisfaction with HVAC controls was relatively similar in SR and SAC, and somewhat higher in PA (4D). However, there was no statistically significant relationship between having access to HVAC controls and satisfactions with thermal comfort and air quality.

Satisfaction with the windows was extremely high for SR, where the windows are used most frequently, and also quite high for PA (4D). In both of these sites the reported satisfaction with operable windows was higher than for any other survey question. Occupants of SAC reported relatively low satisfaction with the windows compared to the other two sites, but SAC respondents still reported higher satisfaction with the operable windows than with the adjustable air diffusers.

Discussion and Conclusions

For the three mixed-mode office buildings we investigated, access to operable windows was generally well correlated with increased occupant satisfaction for air movement, ventilation, and air quality. Occupants of these buildings consistently reported that 'creating air movement' and 'bringing in fresh air' were the primary reasons that they opened their windows. Researchers found similar results in occupant surveys performed at mixed-mode office buildings in the United Kingdom (Williams, et. al. 1997). Conventional HVAC systems tend not to provide occupants with opportunities for personal control over air movement, ventilation, and/or air quality. Operable windows, on the other hand, provide occupants with some measure of control with these environmental factors, generally leading to increased satisfaction.

The relationship between indoor air quality and operable window use, however, can be both positive and negative. Survey comments indicate that while many occupants use operable windows to create more air movement, induce fresh air, or purge odors from their work space, others complain about outdoor dust, dirt, odors, and allergens that enter their work space via operable windows. Despite these complaints, however, survey respondents in all three sites reported much higher satisfaction with operable windows than with personal HVAC controls.

In interviews, designers and facility managers at the three research sites generally seemed uncomfortable with the idea that significant amounts of unfiltered, unconditioned air may enter the building via the windows. In the Sacramento site, the mechanical systems are designed to pressurize the building enough so that opening a window will increase exfiltration, but will not allow unfiltered outdoor air into the building. Ironically, survey respondents in SAC selected 'bring in fresh' more than any other reason, when asked why they use their windows. This suggests that perceived effectiveness of operable windows may play a stronger role than actual physical changes. Meanwhile, at the Palo Alto site, a "facility handbook" urges occupants to close their office doors whenever they have windows open, warning that open windows will allow "unfiltered air into the building (that) may increase dirt and pollen within the room." It is not objectively clear whether, for any given situation, conditioned indoor air or "fresh" outdoor air is preferred by the occupants. Distracting outdoor noises is also a consistent problem associated with the operable windows in the office buildings analyzed. From all of this, a clear design caveat arises: designers of mixed-mode office buildings must remain acutely aware of the noise and air pollution sources near the site.

It is not conclusive from this study to extent to which access to personal HVAC controls affected occupant satisfaction with thermal comfort and air quality. In some cases, there seemed to be a strong positive impact on satisfaction by having access to a thermostat or adjustable air diffuser. Much of the data, however, showed no significant difference in reported satisfaction between those with and without access to HVAC controls.

Based on the data collected from the research sties, the relationship between window access and temperature satisfaction is not as strong as the relationship between window access and air movement, ventilation, or air quality satisfaction. Indoor temperature is certainly influenced by operable windows, but the operation of HVAC systems and the cooling/heating load characteristics of the building may more significantly impact temperature. We suspect that occupant temperature satisfaction is largely determined by the operation of HVAC systems in mixed-mode buildings, and that temperature satisfaction may be quite different in facilities that operate primarily in a naturally ventilated rather than air-conditioned mode.

HVAC systems are typically designed and controlled for maintaining stable temperature conditions. Operable windows, it would seem, are adept at addressing the more ephemeral environmental qualities of air movement, ventilation, and air quality. Providing extensive opportunities for operable window access, therefore, should be a central goal of designers who seek to optimize occupant satisfaction in mixed-mode office buildings.

About the Center for the Built Environment and the Authors

The Center for the Built Environment (CBE) is an industry-university collaborative research center, established in May 1997 at the University of California, Berkeley. CBE's mission is to provide timely, unbiased information on promising new building technologies and design techniques. The research is funded by annual contributions from fifteen industry partners, while the National Science Foundation underwrites administrative costs. Faculty, research staff, and graduate students at UC Berkeley, perform the bulk of the research. More information can be found on-line at: www.cbe.berkeley.edu.

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