

The contextual factors contributing to occupants' adaptive comfort behaviors in offices — a review and proposed modeling framework

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Abstract

Occupants play an unprecedented role on energy use of office buildings and they are often perceived as one of the main causes of underperforming buildings. It is therefore necessary to capture the factors influencing these energy intensive occupant behaviors and to incorporate them in building design. This review-based article puts forward a framework to represent occupant behavior in buildings by arguing: occupants are not illogical and irrational but rather that they attempt to restore their comfort in the easiest way possible, but are influenced by many contextual factors. This framework synthesizes statistical and anecdotal findings of the occupant behavior literature. Furthermore, it lends itself to occupant behavior researchers to form a systematic way to report the influential contextual factors such as ease of control, freedom to reposition, and social constraints.

1 Introduction

Occupant behavior has been recognized as a major source of building performance uncertainty. Its role has risen further in relative terms, as lighting, building envelopes, and heating, ventilation, and air-conditioning (HVAC) equipment have improved in efficiency; meanwhile comfort expectations have increased [1]. Occupants typically have an even greater impact on

passive buildings because of the active role that they take in improving their personal comfort [2]. It has been reported that occupant behavior can impact energy performance of offices by a factor of two or more [3-5]. Even higher levels of uncertainty have been reported in residential buildings [6-11]; which can be attributed to (1) greater control over the indoor climate (e.g., HVAC appliance choice and use habits, full thermostat control), (2) less behavioral diversity (i.e., fewer occupants to offset the adverse behaviors of a minority of occupants), (3) greater power over purchased appliances and equipment, and (4) other energy-intensive tasks (e.g., hot showers, cooking, and clothes washing/drying). However, the current paper focuses on office buildings only.

Uncertainty of energy-intensive occupant behaviors can be troublesome for building designers in an era when building energy codes and targets are aggressively escalating and absolute energy targets like net-zero energy are becoming a reality in many jurisdictions [12, 13]. In numerous cases, building designers have made optimistic assumptions about occupant behavior [e.g., 14, 15] and occupants have been attributed to lower-than-expected performance of buildings [e.g., 16, 17, 18]. Designers often expect occupants to act simply, rationally, and logically as per their own set of beliefs and understanding of buildings — some of which assume a form of energy conservatism [19]. In contrast, through decades of first-hand experience with post-occupancy evaluations (POEs), Leaman [20] made the following generalized observations (reported by Cole and Brown [19]) that occupants:

- “act in response to random, external events

- take decisions to use switches or controls only after an event has prompted them to do so (rather than in advance of it)
- often wait for some time until taking action and typically when they reach a ‘crisis of discomfort’
- over-compensate in their reactions for relatively minor annoyances
- operate the controls or systems that are most convenient to hand, rather than those that would logically be the most appropriate
- take the easiest and quickest option rather than the best, for their immediate benefit
- consciously or otherwise, leave systems in their switched state, rather than altering them back again later, at least until another crisis of discomfort is reached.”

It is evident that these tendencies do not parallel the hopeful behaviors that building designers anticipate; yet it is still hard to argue that occupants are completely irrational. In line with this, numerous researchers have begun developing occupant models based on field studies or experiments to better represent human behavior in building performance simulation (BPS)-based design [21]. Particular concentrations have been on occupancy (occupant presence) [22-25], window-opening [26-28], light-switching [4, 29], blind-adjusting [30-32], and clothing level adjustments [33, 34] as a function of one, and sometimes multiple, environmental variables (e.g., indoor air temperature and vertical daylight illuminance). In most of these models, solely the system’s previous (as in Markov Chains) or current (as in Bernoulli Processes) environmental state is incorporated.

In contrast to these the aforementioned models, many observational studies revealed that subtle contextual factors, along with environmental variables, can significantly influence occupant behavior [35]. For this paper, these contextual factors were sorted in nine categories, as follows: (1) availability of personal control, (2) accessibility of personal control, (3) complexity and transparency of automation systems, (4) presence of mechanical/electrical systems providing alternative means of comfort, (5) view and connection to the outdoors, (6) interior design, (7) experiences and foreseeable future conditions, (8) visibility of energy use, and (9) occupancy patterns and social constraints. These categories were chosen as the factors over which designers have the greatest control. This excludes culture, age, gender, and other personal factors that are unlikely be known during design. Subsequently, this paper proposes a review-based conceptual framework to represent occupant behavior in terms of these contextual factors — as well as the environmental variables — for BPS-based design. Furthermore, findings in the literature — on the contextual factors influencing occupant behavior in office buildings — were assessed; limitations reported in these studies were discussed and recommendations for future work were developed.

2 Contextual factors influencing occupant behavior

This section, the core of the paper, examines a comprehensive list of factors contributing to adaptive occupant behaviors with evidence from the literature and case studies. Statistically significant results —when available— are presented. However, even relevant anecdotal evidence is reviewed as an impetus for further research.

2.1 Availability of personal control

Numerous researchers [36-39] have observed a strong relationship between occupants' perception of control over their environment and productivity. This was interpreted as: the availability of means for adaptive comfort can improve comfort [40, 41]. In fact, a common industry practice is to place placebo controllers (e.g. thermostats) to give occupants the illusion of control [42]. Nicol and Humphreys [43] explained that: "[occupants] with more opportunities to adapt themselves to the environment or the environment to their own requirements will be less likely to suffer discomfort". Occupants readily adapt themselves or their environment to regain comfort under uncomfortable circumstances [26]. Thus, "discomfort is increased if control is not provided, or if the controls are ineffective, inappropriate, or unusable" [43]. In such circumstances, occupants have often been observed to develop their own solutions. These are difficult to anticipate and can lead to considerable uncertainty in energy use. For instance, consider Figure 1 which shows examples of semi-permanent 'MacGyvered' solutions when occupants presumably deemed adaptive measures to be inadequate for their needs [44]. Another potentially energy-intensive solution is installation of portable heaters (even in summertime in over-cooled buildings) which may be left activated after occupancy and are not centrally controlled. Such solutions have not been widely studied compared to the level of intentional adaptive measures (e.g., lights).

In addition to developing physical solutions to discomfort, occupants may exercise psychological coping mechanisms, such as ignoring or tolerating the source of discomfort [44]. However, this is thought to have health (e.g., headaches and stress) and productivity [45]

implications; although occupants may habituate to repeated long-term exposure to a certain set of indoor environmental conditions [46].



Figure 1: A shield was mounted to the top of a cubical wall to protect the adjacent occupant from a beam of light that penetrated through a gap in the shading system (left); a sheet of foil was used to cover a window to either block light or solar radiation (right).

2.2 Accessibility of personal control

“People who are uncomfortable want quick and easy solutions to the discomfort, and do not want to spend a lot of time and effort” [44]. Assuming adaptive measures are available, functional, and all other factors are equal, we expect those which are easiest to use to be used more frequently under uncomfortable circumstances.

The location of control interfaces has been frequently cited as influencing occupants’ propensity to exercise them [47-49]. In a field study of single-occupancy offices, Maniccia, et al. [50] found that occupants were significantly less likely to dim the lights if they only had wall-mounted controls versus desktop controls, whereby they did not have to interrupt their work

[51] or stand up [48]. These results also suggest that occupants rarely turn lights off midday and only as they are leaving their office when the light switch is easy to access [52].

Occupants opt for controls interfaces that are easier to use. Sutter, et al. [53] observed that remotely-controlled motorized shades were adjusted three times more often than manually-powered shades. Such controls often require a start-stop sequence of actions, but without pressing the “stop” button, shades will fully open or close [31]. Thus, motorization could lead to a bias of fully open or fully closed shades since the occupant can simply push a button once instead of holding it. In contrast, manually-controlled/non-motorized shades have been frequently observed to be only partially closed [54]. Sze [55] collected self-reported blind/shade use from 183 teachers at nine public schools in New York and found that frequency of use was quite low because the aging cords were knotted and difficult or impossible to use. Furthermore, poor furniture positioning can make it difficult to reach interfaces [56-58]. Day, et al. [56] reported that poor office design and furniture layouts required many occupants to climb over desks or crawl under them to reach blind controls; others asked the maintenance department to move the cord to the other side of the window to improve accessibility. One interviewed occupant stated ‘sometimes I leave them closed more often than I like because it’s (sic) hard to reach’.

2.3 Complexity and transparency of automation systems

The last century has seen a surge in buildings that are completely reliant on energy-intensive and tightly-controlled electrical and mechanical systems to maintain a comfortable indoor environment [19, 59-61]. There has been a trend towards sophisticated automation systems

that theoretically improve comfort and energy use; but in reality may do the opposite [62, 63]. Complex controls are defined here as those which are not intuitive to understand nor to operate in order to achieve the expected and desirable outcome. For instance, automatically controlled window blinds may not address immediate occupant comfort needs or improve views, but instead be controlled to reduce adverse solar gains or predicted glare.

The highly-controlled approach in buildings is now deep-rooted in design practice and building performance codes[64]. Consequently, the value of adaptive controls (e.g., operable windows) and their ability to relax strict comfort conditions, despite the emerging exemplary examples [65, 66], is not fully appreciated by the design community and often not incorporated into design.

Use of these sophisticated automation systems runs the risk of reducing satisfaction through a poorer perceived sense of control. Furthermore, these systems may be misused by occupants who do not understand them [7, 67]. User misunderstandings can range from lack of technical vocabulary to failure to understand the thermal dynamics of the building. Urban and Gomez [7] listed common occupant misconceptions of thermostats: “thermostat is an on/off switch; thermostat is a dimmer switch; thermostat is an accelerator; and, turning down the thermostat has little or no effect on energy consumption”. A comparative analysis by Karjalainen [68] between offices and homes found that the lack of understanding of how office HVAC systems function relative to those in homes detrimentally influenced the comfort perception in the offices. Complexity of controls interfaces (e.g., cryptic symbols, illogical button placement) and its discouragement from use is also widespread [58, 69, 70]. Meier, et al. [70] reported that

only about thirty percent of the programmable thermostats are used as intended by the manufacturer; they attributed this to lack of understanding of the system.

A recurring finding in the literature is that rapid feedback to inform occupants that conditions are improving and that the system is functioning is crucial for perceived comfort and satisfaction with systems [58, 61, 68]. The intuitive and immediate nature of operable windows to improve comfort results in a considerably wider range of acceptable conditions than in air-conditioned buildings [71]. Leaman and Bordass [36] found that quick-responding building operators are also important to perceived comfort. Feedback to occupants to confirm that a system is functioning is particularly crucial for thermal systems, which normally experience a lag between control input and a change in the indoor environment [72].

A further risk of complex controls, which has not been recognized in current occupant models, is permanent overrides of controls. For instance, occupants have been observed to cover illuminance sensors with tape to effectively convert lighting controls to manual mode [44]. In another anecdote, a graduate student encountered frequent deactivation of motion-sensed lighting controls. Thus, he positioned a Drinking Bird™ to permanently keep the lights activated — at the cost of energy (Figure 2). A more centralized approach to this problem may occur as building operators disable the complex controls because they do not understand them or want to avoid occupant complaints [73].



Figure 2: One occupant's solution to under-sensitive motion-activated lighting controls.

2.4 Presence of mechanical/electrical systems

Previously, it was stated that building designs have been trending towards higher levels of automated control and taking occupants out of the control loop. But what impact does this have on occupants' likeliness to use adaptive measures?

Most studies that have considered this question have found that occupants rely less on adaptive behaviors -either by choice or necessity- when HVAC and lighting systems are readily available. While window blinds are overwhelmingly used to improve visual comfort [74], Inkarojrit [32] observed that occupants in a building without air-conditioning were more likely to use blinds to control the thermal environment as well. Pigg, et al. [75] observed that occupants in offices without occupancy sensors for lighting control were more likely to turn off lights before leaving for the day. Schweiker, et al. [76] found that window opening behavior in a Japanese office with air conditioning was significantly different than window opening behavior in a Swiss office building. The occupants of the Japanese offices relied on air-conditioning when the outdoor air temperature was warm; although culture may have also played a role in these

differences. Busch [77] found that occupants wore an average clothing level of 0.07 clo less in naturally-ventilated building than air-conditioned buildings in Thailand. However, Schiavon and Lee [33] found that occupants in Californian naturally ventilated offices wore 0.03 clo more than their counterparts in mechanically-cooled buildings. This dampened effect could result from dress codes (see Section 2.9).

Findings reported by Reinhart and Voss [30] revealed that automated systems can encourage occupants to exploit daylight instead of electric lighting. In this long-term observational study, they found that occupants were more likely to open window blinds to admit daylight if they had daylight-based lighting control instead of manual control. This was likely as a result of the electric lighting, which provided a maximum of about 400 lux on the workplane.

2.5 Views to and connection with the outdoors

Views and connections to the outdoors are widely accepted to be important for occupant well-being [78-80] and property values [81]. This has been recognized by green building standards, such as LEED (Leadership in Energy Efficient Design), which give credit for buildings that provide a view to for majority of occupants from their seated position. Like many of the contextual factors that influence occupant behavior, views are difficult to quantify because of their subjectivity. Further complexity arises from the frequent presence of daylight (and possibly glare) when occupants are provided with a view [82]. Quality of view is a combination of both geometry (field of view and distance) and content in the view (e.g., natural versus urban landscape). Several methods were used to quantify the quality of view as a function of one or more of these variables [83, 84]. Aries, et al. [79] used a survey to assess view based on quality,

type, and distance from workstation to the window. They found that view independently affects comfort perception.

Research on the potential influence of view and connection to outdoors on occupant behavior is somewhat limited. Inkarojrit [32] and Sutter, et al. [53] provided some anecdotal evidence that occupants may be more tolerant to glare if they have access to a view. Day, et al. [56] reported that an occupant with poor access to blinds simply left them open and tolerated glare for the sake of maximizing view and daylight. Thus, the glare threshold above which occupants may take adaptive actions to avoid glare (e.g., close blinds) is likely higher if they have a desirable view. Inkarojrit [32] found improving views to the outdoors to be the second most common reason for occupants to open blinds after increasing daylighting. Rubin, et al. [85] attempted to correlate blind position to quality of view; while they found it to be statistically significant, it was only a minor factor. Ackerly and Brager [86] reported that 30% of surveyed occupants open windows to improve their connection to the outdoors. In line with these observations, Haldi and Robinson [31] incorporated unshaded window fraction as the main variable to predict window shade opening behavior. This suggests that occupants' desire to maintain view and connection to outdoors represents a primary motivation to open window shades.

2.6 Interior design

Interior design can have a profound influence over comfort and, in turn, occupant behaviors [56]. Flexibility for occupants to maneuver and rotate has been found to be a viable means to prevent glare. In a simulation study, Jakubiec and Reinhart [87] predicted that discomfort glare

can be reduced by 97%, if occupants can change their position or their view direction. Heerwagen and Diamond [44] reported that occupants in a field study used repositioning themselves as the most common response (49%) to glare on their computer monitor. In a study of nine office buildings, Osterhaus [88] found that the prevalent monitor orientation was normal to the window — the theoretically ideal orientation to avoid glare [89]. From an energy perspective, flexibility for occupants to rotate or shift is highly desirable because it allows occupants to avoid longer term adaptations that may reduce future daylight exploitation [74]. Similarly, careful thought must be given to room dimensions and furniture positioning such that occupants are not forced to be zones of greater discomfort (e.g., glare or draughts) [82, 90]. Despite this, the majority of occupant behavior models that have been developed neglect furniture layout or occupant orientation for simplicity. Occupant models used in energy modeling could credit office designs that provide occupants with better opportunities to reposition and mitigate discomfort.

Type of office chair can have a very significant impact on effective clothing level (about 0.15 clo), depending on whether they are breathable or heavily upholstered [71]. Thus, the importance of maximizing annual comfort through chair selection is evident.

Furniture and surface finishes can influence daylight controls commissioning. For example, the sensor calibration and placement often occurs before occupancy and the placement of the furniture; and these sensors remain fixed for the life of the building [91]. The literature suggests that occupants are not merely effected by gross daylight effects; small specularly reflective surfaces (e.g., metallic window frames) positioned in the path of beam solar radiation can cause

significant glare [56]. In contemporary offices, computer monitors are becoming the prevalent working surface. Glare on monitors is a major driver of occupant behavior with regards to blind and light use [53, 88]. The National Renewable Energy Laboratory's Research Support Facility exhibits a thoughtful interior design; whereby the cubicles are positioned with a gap from the south-facing windows such that the beam solar radiation is precisely blocked at the time of lowest solar altitude during occupied hours.

2.7 Experiences and foreseeable future conditions

It has been reported that the occupants react by undertaking an adaptive behavior only when some escalating source of discomfort occurs [92]. Leaman and Bordass [61] reiterated this, stating that most adaptive measures are undertaken based on current discomfort — rather than in anticipation of a foreseeable future discomfort. If occupants react to the cumulative magnitude of discomfort, as these researchers suggest, this could have a profound effect on occupant behavior modeling methodologies. Parallel to these arguments, Haldi and Robinson [31] reported that occupants do not undertake adaptive actions over window shades predictively. They found that occupants tend to use their window shades frequently upon arrival; however no significant variation was noted in their behavior from occupancy to departure period.

In contrast to occupants' reactive nature while undertaking adaptive actions (deciding whether or not to undertake the action), anecdotal evidence suggests that they act predictively while choosing the adaptive states. For example, occupants tend to overcompensate for their dimmable electric lighting and interior shadings to supplement daylight —rather than fine-

tuning the current lighting conditions knowing that daylight illuminance could decrease in the near future [52, 93]. Similarly, Bordass, et al. [49] reported that occupants often position window blinds to mitigate worst-case visual conditions — especially in open-plan offices. Morgan and de Dear [34] studied clothing levels in Australian shopping malls and offices; they found that outdoor weather conditions over the past seven days and weather forecast for the current day are statistically significant predictors of clothing level. Schiavon and Lee [33] developed occupant models that predict occupants' clothing level by correlating the outdoor temperature in the morning and the current indoor temperature.

Contradictory to these observational studies, most existing occupant behavior models solely incorporate current environmental conditions to predict adaptive state (e.g. blind position). However, adaptive occupant behaviors in offices can be captured as: (1) occupants decide to react based on the current conditions causing discomfort and; (2) occupants use their previous experience to anticipate future discomfort and choose the adaptive states accordingly.

Certain adaptive measures cause non-environmental consequences that may occur immediately or in the future. Such risks can influence the choice of adaptive measures. For instance, fans or open windows can cause papers to shuffle [94], but would be less problematic in paperless offices. Leaving windows open upon departure can represent security [95-98] and rainfall [26, 98] related risks. Yun, et al. [99] described the importance of having a secure method for natural ventilation for the sake of night-time ventilation after occupants have departed. A review of window-opening behavior by Fabi, et al. [35] found most office windows are closed at night, whereas between 25 and 50% of residential windows are left open at night.

It is not clear whether this is a result of security concerns, perception of ownership over comfort, or lack of occupants' predictions (see Section 2.7). Veitch, et al. [100] found concern for plants' survival near windows was a leading reason for homeowners to leave window blinds open; though this could apply to the workplace as well. Another risk associated with blind control includes fading of dyes/paints [101]. While the above consequences to using adaptive measures may influence occupant behavior, there is little quantitative evidence of this.

2.8 Visibility of energy use

The visibility of the environmental and economic impacts of energy use represents another significant contextual factor influencing occupant behavior [102]. Visibility of energy use can be increased by various occupant feedback strategies, such as utility bills, static signs, memos or mail, digital dashboards, training sessions or workshops, and simple indicators like a light to advice occupants to take a certain action.

Staats, et al. [103] performed a study whereby they attempted to modify two behaviors — thermostat use and diffuser covering — using pamphlets, posters, and personal letters. The combined tactics yielded a modest 6% savings in energy use, though some of the behavior modifications lasted over a year after the study. Galasiu and Veitch [90] found that e-mails reminding occupants to use lighting wisely resulted in very modest energy savings. Ackerly and Brager [86] surveyed occupants in 16 buildings with window opening signal systems and found them to increase occupants' likeliness to operate windows; though not consistently.

The majority of the studies on direct communication to occupants to reduce energy use has been focused on the residential sector [104, 105]. These approaches have shown inconclusive

results and some systems have been found to lose the novelty over time if repeated feedback is not provided [105]. Several key elements of building performance display systems established by the literature include: real-time information, interactive and customizable displays, individualized/sub-metered data, context (e.g., historical context), and aesthetics.

The impact of an individual's energy consumption cost on their energy-related behaviors is fairly well-documented [106]. While adding sub-meters to dwellings has been shown to achieve as much as a 30% reduction in energy use [107, 108], it is less clear whether this is paralleled in commercial buildings — particularly if employees only benefit indirectly from cost savings (i.e., reduced energy costs do not necessarily increase employee salary) [109]. It has been suggested that building occupants for small businesses would face a similar cost-consciousness to homes due to the greater connection between employees and the employer [110].

It is not clear how the presence of feedback mechanisms could be incorporated into occupant behavior models, as the literature indicates that their effectiveness is far from consistent.

2.9 Occupancy patterns and social constraints

Significant evidence suggests that occupancy patterns influence adaptive behaviors and predicted vs. measured energy savings (e.g., for light switching). It is widely accepted that occupants adapt the indoor conditions or adapt to these conditions when they enter their workplace [31, 35, 111]. This could be caused by a combination of two factors: (1) they are exposed to a sharp gradient between indoor and outdoor conditions; and (2) the ease of accessibility to controls as they walk in. For some occupant behaviors (windows closing and light switch-off) the time-interval just before the departure, similar to the arrival period, was

also noted with a discernible increase in frequency. Several researchers [30, 75] reported that the duration of absence followed by the departure as the primary predictor for light switch-off action. It is therefore necessary to classify observed occupant behaviors in accordance with the occupancy intervals (just after arrival, intermediate, just before departure) during which the observations were acquired.

Occupants are profoundly affected by the presence of others when taking adaptive comfort measures. And despite the diversity in the preferred conditions of occupants [112], shared spaces often impose the requirement that multiple occupants endure similar environmental conditions. On the contrary, occupants may also be exposed to different conditions because of their position in a room or activity; thus, adaptive comfort measures may benefit some occupants at the detriment to others. Ideally general comfort conditions would be provided by a centralized system but all occupants would have the ability to fine-tune the indoor environment to suit their personal needs [72]. However, most existing controls in shared spaces make such fine-tuning difficult (e.g., just one light switch and one thermostat per area). The desire for individualized control is so strong that occupants would often choose it over theoretically better conditions but no personal control [113].

Heerwagen and Diamond [44] reported that occupants in private offices were more likely to make environmental or behavioral changes to regain comfort, whereas occupants in open-plan spaces rely more on psychological coping mechanisms (e.g., tolerating or ignoring discomfort). The latter form of adaptive measures was deemed much less effective and often resulted in health problems (e.g., headaches, eye-strain, and stress). Despite the apparent comfort

advantages of private offices, open-plan offices have gained popularity because of the reduced real-estate cost per occupant as well as to promote collaboration [114, 115]. Furthermore, open-plan offices facilitate many energy-saving strategies including greater daylight penetration depth and better cross-ventilation [116].

Numerous studies have reported that occupants are consistently more comfortable in private offices than they are in open-plan spaces [44, 57, 68, 79, 117, 118]. Most occupant behavior models do not distinguish between single and multiple-occupancy spaces [35]; yet, this effect has been widely cited and quantified [e.g., 31]. Borgeson and Brager [119] eloquently stated that “Unspoken assumptions of preference, varying personal criteria, and various forms of social etiquette can produce occupant behavior that is substantially different from modeled personal preference”. Two complementary explanations are provided by the reviewed literature to explain the distinct observations collected in shared and private office spaces.

(1) Concerns for causing discomfort to others by taking adaptive measures and violating social norms:

In numerous studies, it was observed that the frequency of adaptive actions significantly decreases in shared spaces compared to private offices [35, 90, 120]. This was attributed to individuals’ timidity to undertake an adaptive measure which may end up annoying other occupants [40, 51, 121]. Further complexity is added to analyzing occupant behavior in shared offices because the impact of adaptive actions can affect environmental conditions differently by location (e.g., occupants beside windows are more prone to daylight glare [82]). Thus, the lack in granularity of environmental controls may require settings that satisfy all occupants (e.g.

lights on even if daylight is adequate in part of a space). Some occupants have better access to controls, causing them to be more likely to take adaptive actions [56]. But despite this convenience, a small number of occupants typically assume the role of primary controllers [29]. Boyce [29] observed that individual occupants in an open-plan office tended to control only the lights above their desk unless daylight conditions allowed lights in the entire space to be turned off. In a study of 14 single and double-occupancy offices, Haldi and Robinson [31] found that the occupants in single offices closed blinds at a much lower workplane illuminance threshold (around 30% lower) than their counterparts.

Another interesting social element of adaptive comfort is clothing. In a simulation-based study, Newsham [122] found that modeling occupants as having flexible clothing levels versus fixed clothing reduced the thermal discomfort instances substantially, resulting in 41% HVAC energy savings. Despite clothing's significant impact on comfort and occupants' ability to adapt to their environment, social pressures to dress socially appropriately rather than appropriately for the environment are strong in office environments. Morgan and de Dear [34] studied clothing levels in both shopping malls and offices; they found shoppers to be much more responsive to seasonal weather conditions than office workers. The workers' clothing level was clearly influenced by the dress codes imposed by their employers (e.g., casual Fridays resulted in an average drop of about 0.2 clo in the summertime). Morgan and de Dear [34] stated: "Corporate dress codes, as found in the present office environment study, all but extinguish clothing adaptive opportunity". Notably, private office occupants may not have the same level of control over clothing as they do for lights or blinds because they normally interact with other occupants at some point during the day (e.g., meetings or in common areas). Thus, improving adaptive

opportunities related to clothing use may not be a design issue but rather one of corporate policy or culture. A successful program in a country where formal clothing is the norm (Cool-biz in Japan) involved informing occupants about the benefits of modifying their clothing levels in the workplace during summer. Not only were tips given for achieving greater comfort in clothing that still appeared formal (breathable pants, starched collar), but they also attempted to influence attitudes about appropriate clothing level. A follow-up program advised workers to wear thicker clothing in the winter [123].

Ackerly and Brager [86] reviewed 16 buildings with automated indicators (e.g., lights) that inform occupants of when it is advantageous to open or close windows. They found that the presence of the signals tended to give occupants in shared spaces the validation for opening or closing windows. Thus, occupants in shared spaces had a greater sense of personal control in the presence of these signal systems.

(2) Reduced perceived ownership:

Shared office spaces often suffer from diffusion of responsibility, whereby individuals assume that someone else will take action (e.g., turn off the lights at the end of the day) [29]. This is similar to the effect of automated systems where occupants do not feel they play as significant a role in maintaining comfort. Reinhart [4] and Galasiu, et al. [113] have reported similar findings. Accordingly, spaces without individualized lighting control consume considerably more lighting energy [113, 124]. Dorn and Schnare [125] anecdotally reported that natural ventilation was less effective in open-plan offices than private offices because occupants do not feel ownership over operable windows in the large offices. A reduced perception of control in

shared office spaces as a result of the presence of others has been widely reported [57, 68, 79, 96, 118, 126].

3 Discussion and recommendations for future work

The current review identified the main contextual factors that influence occupants' behavior that have been documented. However, these influential factors have been largely neglected in occupant behavior models. This is partly because their significance may be misunderstood and difficult to measure or quantify, but also due to the cost of observational studies. The difficulty of quantifying contextual factors transcends to BPS where many indoor environmental properties and office characteristics (e.g., noise and furniture position) are not readily available or specifiable – especially early in design.

In order to confidently construct an occupant model that incorporates contextual factors, ideally two populations (e.g., buildings or floors) with nearly identical properties except for the contextual factor being of interest (e.g., shared vs. open-plan offices and venetian blind vs. roller shade) would be studied. This has proven difficult in practice. The next best alternative is for the research community to collectively construct a database with tens or hundreds of studies that measure environmental variables, occupant response, and contextual factors, such that statistical significance and the effect of contextual factors can be isolated. However, this will require significantly more detailed and consistent reporting. Much of the existing literature has failed to report some of the most basic building parameters (e.g., window construction) [74]. Furthermore, there is vast diversity in reported occupant behavior metrics (e.g., blind position and blind movement rate) and environmental variables (e.g., workplane illuminance

and vertical illuminance on the façade). The authors anticipate that the occupant behavior research field will standardize observational studies, though a centralized standard and database (for instance, coordinated by International Energy Agency Energy in Buildings and Communities Annex 66: “Definition and Simulation of Occupant Behavior in Buildings”) could greatly facilitate this effort.

In order for designers to confidently implement occupant behavior models into design, the models should reflect some of the most significant contextual factors explored in this paper. While the one-model-fits-all has been favored in the past decade because of limited observational studies, it is clear that several sub-models will have to be developed to incorporate major contextual factors (e.g., number of occupants in space and ease of using controls) —which forms the basis of the modeling framework presented in the current paper.

Even once occupant behavior models are established, there are challenges for implementing them in BPS (building performance simulation) tools. The reviewed literature suggests that numerous indoor environmental variables influence occupant behavior (visual, thermal, acoustic comfort), while many BPS tools are focused on energy use, equipment sizing, and basic comfort parameters. Furthermore, most BPS tools are spatially coarse and assume that air is fully-mixed in zones and that there are no interior furnishings, despite the much finer resolution that would be required to capture many of the issues outlined in this paper. Similarly, most behavior models with regards to lighting and blind control focus on illuminance on the workplane or façade; but these are not necessarily indicative of visual comfort [127]. Furthermore, acoustics is not incorporated into most BPS tools despite the fact that it is

emerging as one of the poorest performing categories of indoor environmental quality [128, 129] and a contributing factor of occupant behavior [32, 130]. Finally, only a few tools lend themselves to easily incorporating occupant behavior models (i.e., open source tools or tools that allow some custom modules to be developed). In particular, many existing tools do not easily facilitate implementation of more advanced models (e.g., stochastic and multi-variable).

An issue that remains largely unaddressed is the order of use of adaptive measures. Nicol and Humphreys [43] suggested that a greater number of adaptive measures can improve comfort. Order of use can be tremendously influential on energy [131, 132] — as high as a factor of 3.3. But existing occupant behavior models mostly focus on a single adaptive measure. Haldi and Robinson [133] provided insight on the order of adaptive measures used by office workers based on self-reported behavior. A key result was that office doors were much more likely to be opened if the window was already open.

Recent research has recognized the diversity of occupant behavior [30, 31, 134, 135]. (Note that diversity here refers to the range in occupant responsiveness to environmental variables). It is therefore essential to ensure that building design and operation is not optimized for identical occupants but for a reasonable range of occupants. It also allows sensitivity of building design to be determined on the basis that occupants are diverse (e.g., O'Brien [136]).

Based on the discussion above, a framework to observe and model occupant behavior in office spaces is proposed, as shown in Figure 3. This framework suggests that occupants' decision-making mechanism is triggered upon a change in the indoor climate [92]. Subsequently, occupants evaluate whether or not an adaptive action is necessary to restore their comfort.

This decision is significantly influenced by the contextual factors discussed throughout this paper. In this framework, these contextual factors are coarsely discretized to recognize their influence. Furthermore, it is also intended that a systematic way of classifying contextual conditions will lead to the development of occupant behavior models that are transferable to other buildings. These contextual factors could be available as built-in options in BPS tools. For example, the EMS application of EnergyPlus has shown great potential to incorporate occupant behaviour models in BPS and it has already been exploited in a number of studies [136-139]. Similarly, stochastic occupant behavior models by Rijal, et al. [140] and Yun, et al. [141] were integrated in the BPS tool ESP-r. Furthermore, a research project by the authors is underway to incorporate existing occupant models in the EMS application of EnergyPlus and make them publicly available. These examples indicate the feasibility of integrating occupant behavior models in the BPS-based design process. However, it was also noted that the existing modeling methodologies were vastly fragmented such that their validity is restricted to a number of contextual factors. This framework, by preserving the general structure of the occupant behavior models in BPS, puts forward a systematic way to report observational studies in order to develop occupant models transferable to other buildings with similar contextual factors.

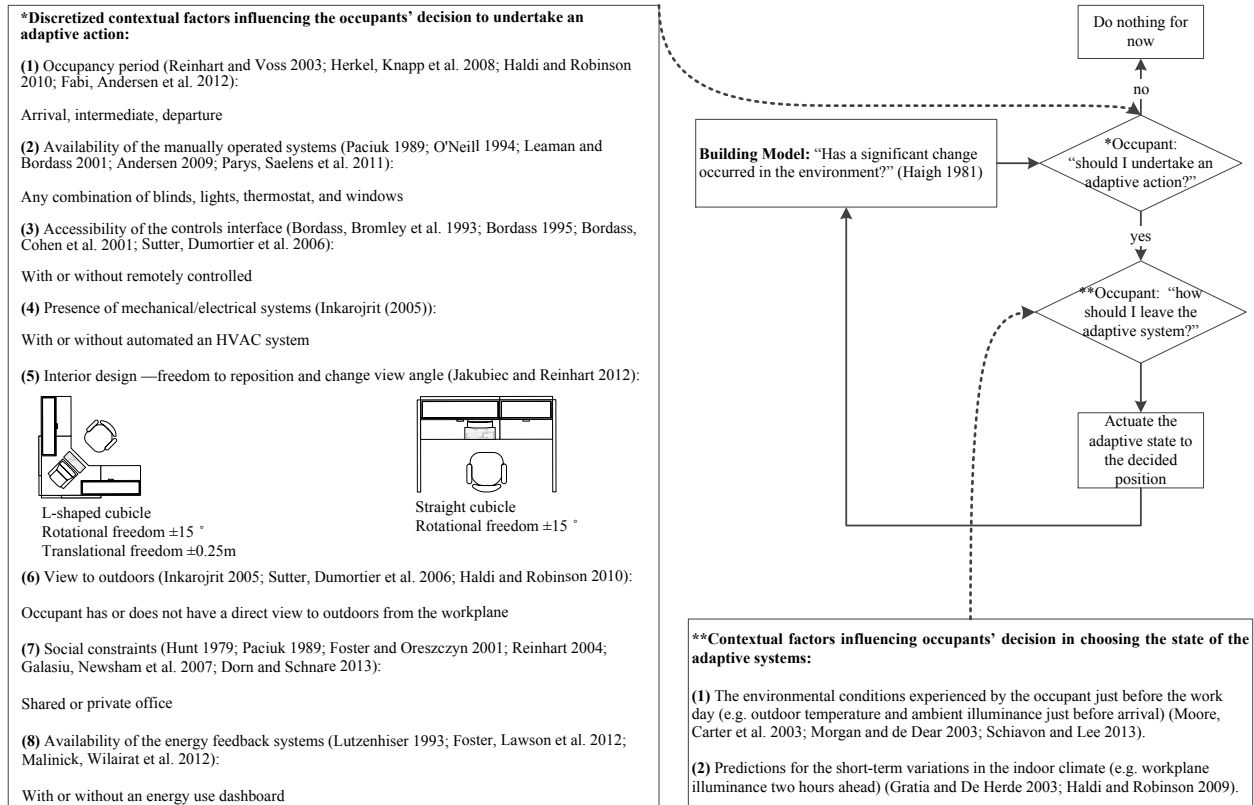


Figure 3: Framework for incorporating contextual factors in occupant behavior models

The first contextual factor is the occupancy period. The choice of this contextual factor is mainly influenced by Haldi and Robinson [31] and Reinhart and Voss [30], where they observed that the likelihood of behavioral adaptation can notably vary between different periods of the occupancy and developed distinct occupant models for each of the occupancy period. Therefore, it is recommended that observed behaviors be classified in terms of the occupancy period that they are acquired (e.g. arrival, intermediate, departure). The second contextual factor is the availability of the occupant controlled adaptive systems. This contextual factor is mostly influenced by Andersen's [131] work whereby the influence of the co-existence of different adaptive opportunities in tandem was investigated. In line with this, in the current framework discretization of the observational datasets in any combination of the manually operable adaptive systems available in an office (e.g. light switches, interior shades,

thermostats, and operable windows) is recommended. The third contextual factor is the accessibility of the adaptive controls. This factor is mostly influenced by Sutter, et al. [53] who observed that the motorized blinds were used three times more frequently than the manually controlled blinds. Thus it is here recommended that controls of the adaptive states be discretized ("with remote control" (e.g., web-application-based controls, wireless remote controls) and "without remote control" (e.g., thermostats fixed on a wall, roller blinds with pull-cords). The fourth contextual factor is the presence of mechanical/electrical systems. The choice of this factor is mostly influenced by Inkarojrit [32]. In that study it was noticed that occupants use their blinds mainly for visual comfort, if an air-conditioning system is available; while in absence of an air-conditioning system, occupants use their blinds also for their thermal comfort. It is therefore recommended to classify the observations acquired in buildings depending on the presence of these mechanical/electrical systems (e.g., with/without air-conditioning). The fifth contextual factor is related to interior design. The choice of this factor is mainly inspired by the adaptive zone concept introduced by Jakubiec and Reinhart [87]. Parallel to this work, it is recommended to classify the cubicle and desk styles as it can be argued that it accounts for the freedom to reposition and change view direction; e.g. "L-shaped cubicle" or "straight cubicle". The sixth contextual factor is the view and connection to outdoors. The choice of this factor is influenced by three studies [31, 32, 53]. These studies pointed out the significance of the view and connection to outdoors on the behavioral adaptation. Therefore, it is recommended to classify the observations depending on occupants' view to outside from their cubicles; e.g. "occupants that have direct view from the workplane through the fenestration" and "occupants that do not have direct view to outdoors from their cubicle". The

seventh contextual factor is the social constraints. The choice of this factor is inspired by numerous studies [30, 40, 51, 113, 125] reporting noticeable variations in occupants' behavioral adaptation between the observations collected in private and shared offices. Parallel to this, in this framework it is recommended that observations are classified as those acquired in shared offices and as those acquired in private offices. The eighth factor is the availability of energy-use feedback systems. The choice of this factor is mainly influenced by the studies carried out by Galasiu and Veitch [90] and Ackerly and Brager [86] where they studied the influence of providing direct feedback about the environmental impact of their adaptive behaviors. Thus, that reporting observations separately if there is a permanent source of feedback (e.g., energy-use dashboards) is recommended. Furthermore, once occupants decide to undertake an adaptive action —using current environmental variables and contextual factors as predictors— the actuation level of the adaptive state needs to be determined. To this end, the current framework suggests using the environmental conditions experienced by the occupants prior to the workday [33, 34, 93] and the foreseeable environmental conditions following the decision making instant [98, 142].

Ultimately, the appropriate coarseness and inclusion or exclusion of the discretization of the contextual factors must be determined through future work. There is considerable expense in collecting data and developing models to account for all typical building and occupancy variations. Thus, future research must balance accuracy with practicality.

4 Conclusions

This paper attempts to demonstrate that existing occupant behavior models — stochastic or deterministic — can be overly-simplified in that they focus on a very small number of environmental variables as the main drivers of adaptive behaviors. Designers and researchers have noted that occupants often behave unlike these simple models and thus *unexpectedly* or *illogically*. However, the numerous anecdotes and statistically-significant results from the reviewed field studies and experiments indicate that many other contributing factors to occupants' decision-making exist. These include availability and accessibility of adaptive measures, interior design and mechanical/electrical systems, social factors, and views, among others.

From a modeling perspective, the current review clarifies the importance that monitoring studies, at minimum, thoroughly reporting all major contextual factors, and ideally controlling for some of them such that they can be included in the models. In order to confidently extend one occupant model to a different building of the same type, building type, or location, the context must be carefully reported. To this end, this review-based study puts forward a conceptual framework that captures occupants' behavioral adaptation in a two-step process: (1) When a significant change occurs in the indoor climate, an occupant decides whether or not to undertake an adaptive action. This decision is influenced by the current environmental variables and several contextual factors. These contextual factors were coarsely discretized to promote systematic reporting in the future observational studies. Furthermore, it is also intended that this systematic way of reporting will lead to the development of the occupant behavior models transferable to other buildings, should these contextual factors be available as

a drop-down list of options in the BPS tools. (2) Once an occupant decides to undertake the adaptive action, the actuation level of the adaptive state (e.g., how much should I lower my blinds?) should be predicted using the conditions experienced prior to the workday and the foreseeable environmental conditions following the instant when the decision is made.

Some of the contextual factors discussed in this review may not be suitable for mathematical models, but are nevertheless important to incorporate into design. Designers must understand the guiding principles of occupant decision-making processes and look to successful case studies rather than assuming that occupants will behave as designers hope.

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