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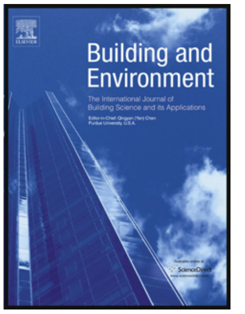

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Manually-operated window shade patterns in office buildings: A critical review

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1 ABSTRACT

Despite the significant impact that the position of movable window shading devices has on building energy use, peak loads, and visual and thermal comfort, there is a high degree of uncertainty associated with how building occupants actually operate their shades. As a result, unrealistic modeling assumptions in building performance simulation or other design methods may lead to sub-optimal building designs and overestimation or underestimation of cooling loads. In the past 35 years, researchers have published observational studies in order to identify the factors that motivate building occupants to operate shading devices. However, the diversity of the study conditions makes it is difficult to draw universal conclusions that link all contributing factors to shade movement actions. This paper provides a comprehensive and critical review of experimental and study methodologies for manual shade operation in office buildings, their results, and their application to building design and controls. The majority of the many cited factors in office buildings can be categorized into those affecting visual comfort, thermal comfort, privacy, and views. Most office occupants do not operate their shades more than weekly or monthly and they do so based on long-term solar radiation intensity and solar geometry trends rather than reacting to short-term events. They generally operate them to improve visual conditions rather than thermal conditions. Occupants in offices with automatically-controlled heating and cooling tend to be less diligent about using shading devices to improve their comfort.

Keywords: occupant behavior, window shades, thermal comfort, visual comfort, energy use, advanced façade design

Nomenclature

d	solar profile angle
D_{solar}	solar penetration depth (m)
H_{sp}	height of window spandrel, if any (m)
H_{win}	height of window (m)
H_{wp}	height of workplane (m)
MRT	Mean Radiant Temperature
MSO	Mean Shade Occlusion (%)
N	number of shades that were moved between two discrete times
p	percentage closed of a shade (%)
P(x)	probability of the shade being opened (or closed)
SMR	Shade Movement Rate (%)
Y	model input (i.e., the value of the environmental variable)
Greek letters	
α	regression coefficient
β	regression coefficient
Subscripts	
i	shade index number

n	total amount of shades
t	timestep

2 INTRODUCTION

As buildings become more energy efficient, not only does their total energy use decrease, but there is also a shift in the distribution of energy end uses, such that occupant behavior plays an increasing role [1]. The actions that occupants take, such as switching on lights, moving window shades, operating windows, and switching on equipment significantly affects their comfort and building energy use. These actions also add considerable uncertainty in predicting how a building will perform, during design.

Window shading devices, which include roller shades, venetian blinds, vertical blinds or louvers, and which can be interior, exterior, or between window panes, (all referred to as "shades" herein) provide significant control over daylighting, thermal and visual comfort, views and privacy, while also affecting heating and cooling loads. Tzempelikos et al. [2] reported a 31% reduction in total secondary energy use (lighting, heating and cooling) when both active lighting and shading control were applied to a perimeter zone of a university office building. The active shading control consisted of closing the shades when beam solar radiation on the window exceeds 20 W/m^2. Lee et al. [3] examined active shade control and achieved cooling and lighting energy reductions of 21% each and a peak cooling load reduction of 13% on a sunny summer day. Dubois [4] reported that shades can reduce cooling energy by between 23% and 89%. Using measured data from an experimental office, Reinhart et al. [5] showed that the Venetian blind position can affect the useful contribution of daylight in an office by between 10 and 60 percentage points, depending on the distance from the façade. In addition to reducing energy use and protecting occupants from glare, shades also have the potential to significantly improve thermal comfort by means of improving the operative temperature and radiant asymmetry [6]. Newsham [6] found that the presence of manually controlled shades (versus none) had the potential to reduce the mean Predicted Percentage of occupants Dissatisfied (PPD) from 22% to 13%. This, in turn, can reduce energy use because occupants are less likely to compensate by increasing or decreasing the air temperature setpoint.

Compared to fixed shades, operable ones provide control freedom [7] allowing occupants to better adapt to their environment without additional energy expenditures. It is important to note that occupants tend to report a greater level of comfort when they have a perception of significant control over their thermal environment [8]. Finally, shades provide privacy from the outside, when needed.

Building performance simulation (BPS) is a valuable tool for quantifying the potential benefits of shades under certain assumed controls, among other building features and technologies. Yet occupant behavior, which can have a significant impact on building performance, has not advanced to nearly the level of detail and accuracy to which heat transfer through building envelopes and other physical phenomena have been modeled [1, 9]. Studies have found shades to be passively operated and in sub-optimal ways [10]. Thus, building designers may overestimate the benefit of shades through optimistic or simplistic assumptions. Shades are often considered to have a low "operational effectiveness" relative to fixed and automated shading [11]. For simulation-supported design, occupancy-based inputs into models are based on very rigid schedules (e.g., people are present in the building from exactly 9:00 to 17:00) or controls (e.g., all shades close if the exterior solar radiation on the façade exceeds 100 W/m^2) [1, 12]. Conversely, designers may oversize HVAC equipment using design days in which all shades are assumed to be in the most adverse positions – a situation that is improbable in reality. ASHRAE Standard 90.1's performance approach [13] does not allow any potentially advantageous shading control to be modeled unless, in fact, automated motorized shades are in the design.

An emerging expectation of BPS and its practitioners is that it should be able to predict performance for the use in standards (e.g., LEED^{TM} [14]) and absolute target levels (e.g., net-zero energy [15]). Therefore, there is a strong need for a universal model that realistically and accurately predicts how occupants react to different environmental factors, if possible. If automated shade controls are developed, it is important that their movement closely reflects the shade positions that occupants prefer. Current automated shade controls often fail to recognize when conditions change to being undesirable (e.g., glare), or worse, may move shades to a less desirable position (e.g., close them when daylight conditions were already too dim) [16]. Thus, developing a deep understanding of preferred shade positions is critical to both design and controls of buildings.

Since the decision-making process of whether an occupant changes a shade position is complex, a common research approach has been to observe shade use relative to numerous factors and attempt to create correlations or more complex models that can be applied to controls or BPS [17]. Weather conditions, time of day, time of year, and façade orientation are the most commonly examined factors. However, the universality of the results is put in question, due to the wide variation of these and other factors among the studies [9, 17-19].

Complementary research topics include the study of occupant control of window openings [20] and electric lighting events [21, 22]. However, the current work is concentrated on manually controlled shades, while recognizing the interdependence, where necessary.

The objective of this paper is to review previous shade use observational and study methodologies on office buildings, their findings and how these results can be applied to practical applications such as BPS, automated shade controls, and façade design. Future research needs are identified in all major sections of the paper. The long-term objective of this research project is to develop occupant behavior models for shading controls that can be universally applied to building performance models and better shade controls. Such models will allow designers to make better design decisions in order to reduce energy use and peak loads, while maintaining occupant comfort.

3 EXPERIMENTAL AND STUDY APPROACHES

A comprehensive literature review revealed that 12 major observational studies have been performed on the manual operation of shades, starting in 1978. Their objectives were to gain an understanding of, or develop a mathematical relationship between, one or more factors (e.g., exterior solar radiation, work plane illuminance) and occupants' shade movement actions. A list of factors, their categorization, and relationship with each other is summarized in Figure 1. The significance of this figure is that it illustrates possible interdependencies between factors that influence shade operation.

The following section assesses the advantages and disadvantages of the various experimental approaches used for the observation of the manual operation of shades. All major studies are summarized in Figure 2.

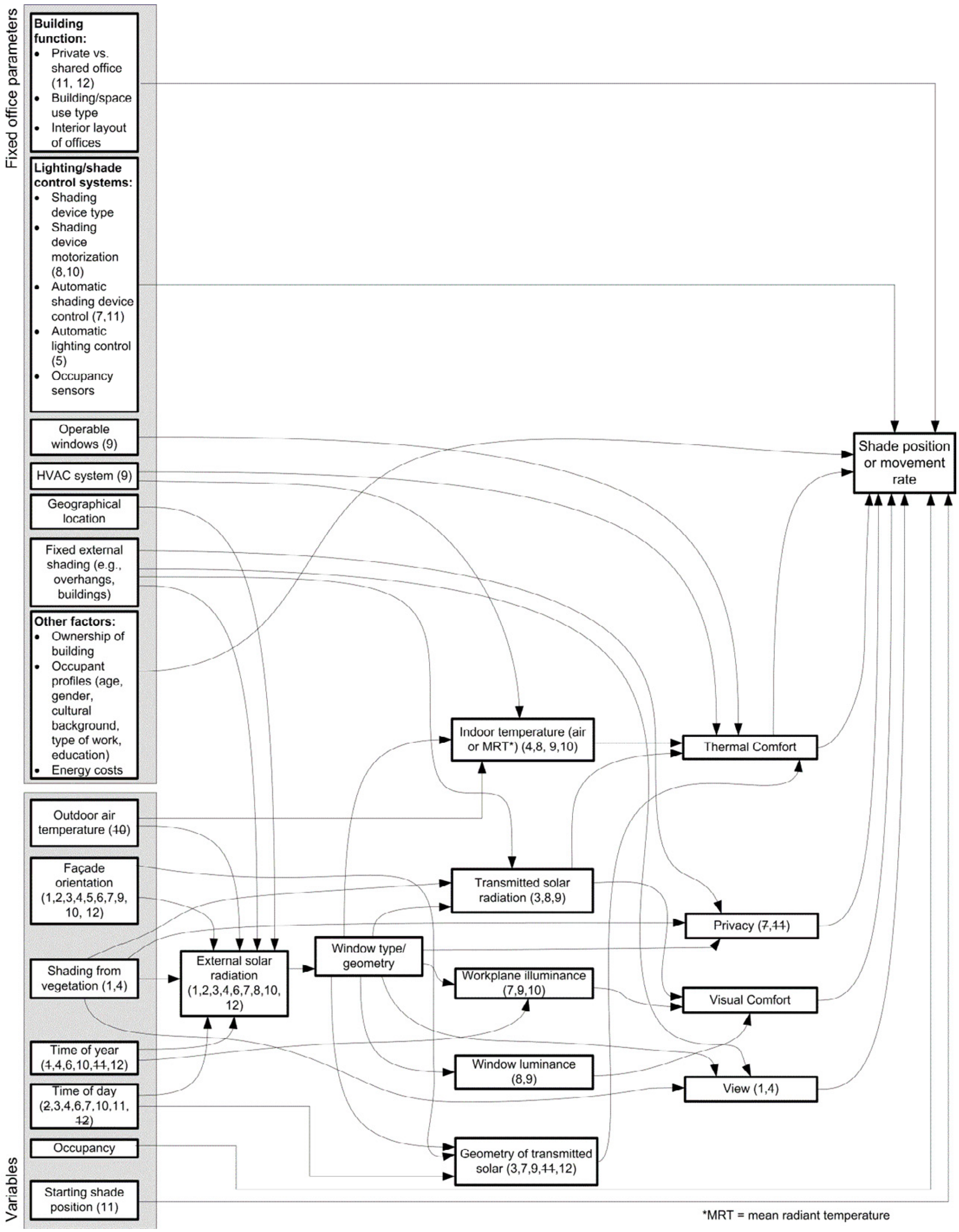


Figure 1: A map of the factors that could affect occupants' behavior regarding manual shade operation. The bracketed numbers correspond to the studies that found a particular factor to be significant (as deemed by the studies' authors); those that were explicitly reported to be insignificant factors are crossed out. The study numbers correspond with Figures 2 and Table 1.

3.1 Shade position metrics

There are two main metrics consistently used throughout the literature: mean shade occlusion and shade movement rate [23]. Mean shade occlusion (MSO) is defined as the average fraction that the shades are closed for some group of windows (e.g., if there is one window with the shade up and three windows with shades down, the mean shade occlusion is 75%). MSO is most useful for feeding occupant behavior models directly as it is representative of the preferred shade positions and ultimately indicates the mean thermal properties of a façade. Note that MSO is not necessarily indicative of the interior daylight levels since daylight levels are sensitive to each individual shade position; not merely the mean position (e.g., if there is one shade open and one closed different daylight levels will result than if there are two half-open shades).

The shade movement rate (SMR) is defined as the fraction of shades that were moved between two discrete times. It is useful for identifying the triggers that may have caused occupants to adjust their shades, but is not as useful in direct use in occupant behavior models and does not indicate the direction of the average shade position change.

$$MSO_t = (1/n)\sum_{i=1}^{n}(p_i)_t \qquad (1)$$

$$\mathrm{SMR_t} = (1/\mathrm{n})\sum_{\mathrm{i}=1}^{\mathrm{n}}(\mathrm{N_i})_\mathrm{t} \qquad (2)$$

$$(N_i)_t = countif\left(\frac{dp_i}{dt} \neq 0\right) \qquad (3)$$

where n is the total number of windows, p is percentage closed of shade i at time step t, and N is the number of shades that were moved between time steps.

Several studies [17, 24] presented the shade position data in greater resolution, such as a frequency distribution in all positions in 20% increments. Ideally, researchers of future studies provide data in an online database where it can be post-processed. The nature of reported data in many of the past studies is aggregated to the extent that it has limited applicability.

3.2 Observation techniques

Three major techniques used to capture shade positions are: i) time-lapse photography of the exterior of the façade(s), ii) sensors that directly measure shade position and iii) internal visual inspection (walkthroughs) of the offices. Photography offers the most promise of obtaining large sample sizes in a non-invasive and relatively inexpensive way, but it does not provide information about the indoor environment.

Most of the reviewed photographic procedures involved taking photographs or video of one or more facades with a sampling frequency of between hourly and daily, for a period lasting between a single day and a year. The photographs were manually analyzed and the shade position data was translated to a database. A limitation of this method is that in the case of Venetian blinds, slat angles are often not discernible from photographs [12, 18, 19, 24, 25]. Even if individual slats are identifiable, it is difficult to determine if they are tilted upwards or downwards. This difference can affect the amount of transmitted daylight by a factor of 10 [19]. Lindsay et al. [19] proposed a method for overcoming this by mounting three cameras (though two would be sufficient) pointed at the same façade but from different angles (i.e., one tilted up and the other tilted down). Other challenges associated with the photography technique include visual obstructions [24, 25], insufficient photograph resolution [12, 19, 24], rainy weather [24], uncertainty about whether offices are occupied [23], veiling reflection, the restriction of only taking photographs during the day when there are sufficient light levels, and the amount of effort to manually post-process shade positions [18]. Rea [18] used random sampling to reduce the number of photographs that were analyzed and found the associated error to be acceptably low.

Several studies [17, 26, 27] have involved the use of electro-mechanical sensors to detect shade position. This technique is advantageous because of the reduction of human error, efficiency of data collection, and the possibility to record slat angles as well as shade deployment level. It also eliminates the challenge of external obstructions. However, it is limited to buildings with such sensors present; installing them for the purpose of monitoring alone would be impractical for large-scale studies. The studies that used this technique were among the smallest, in terms of number of windows. However, the technique did allow Haldi et al. [17] to perform the study for six years – over four times longer than the next longest study.

Another technique used, involved somewhat irregular building walkthroughs to observe and record shade position [26, 28]. While this is time-consuming [28], it allows blind slat angles to be recorded and occupants to be interviewed or observed directly. Hand-held sensors were used to measure visual and thermal comfort metrics; thus avoiding the cost of installing instrumentation in each office. It is also useful for diagnosing any unexpected behavior. For instance, Inkarojrit [25] found that MSO was about 10 percentage points less than expected because venetian blinds tend to rattle if they cover an open window.

3.3 Sample size, frequency and duration

Given that shade positioning is frequently considered a stochastic process rather than a precise relationship [25, 29], large sample sizes (number of windows with shades) are highly-desirable. The existing studies used sample sizes of 10 [27] to 700 [24]. The photographic approach allowed for the largest number of shades to be studied, while position sensors were used for the longest periods, but for much fewer shades. The walkthrough studies were smaller than the others in terms of duration and number of shades studied. However, this technique allowed the researchers to directly survey occupants for their motivation on the shade positioning. Haldi et al. [17] paid particular attention to variability between individual occupants under the same environmental conditions and suggested that a sample size of greater than 22 windows with shades would be necessary.

Sampling frequency varied greatly among the studies from effectively continuous (using sensors or video) to weekly, with the majority occurring once every one or two hours, during occupied hours. As the Nyquist sampling theorem suggests, *the sampling frequency must be at least double the frequency of the phenomenon being measured.* The sampling frequency should be high enough to capture sufficient information to determine which external factor may have motivated movement. However, the studies' results indicated that most causes for shade movement were not sudden events but rather gradual. Lindsay et al. [19] found that the mean sunniness during the previous three hours was a better predictor of shade movement than current conditions. A few studies [19, 24] concluded that shade control was gradual and resulted in long-term (in the range of days to months) trends in conditions. This suggests that a weekly sampling rate may be acceptable for the photographic and walkthrough techniques, where there is a certain cost associated with each time the shade positions are sampled. About half of the studies reported that the time of day has a significant role in shade movement [17, 23]. Thus, to be conservative, a sampling frequency of no less than twice daily is necessary.

A diverse array of monitoring periods was used throughout the studies: two days [18] to six years [17]. Rea's [18] finding that the MSO from a picture taken 10 years prior to his study where within 2 percentage points of current ones, suggests that multi-year studies might be unnecessary. In addition, the low shade operation frequency found by most studies suggests that studies should extend over a few days to preferably a few months.

3.4 Experimental invasiveness

With regards to invasiveness, the subjects should be unaware that their behavior is being monitored [30], assuming it is collected without compromising their privacy or regulations. While it has been acknowledged that the more invasive methods could introduce bias [31], none of the researchers speculated as to how their presence may have affected occupant behavior. Several studies [24, 25] opted to interfere with natural shade movement in order to i) compile a list of significant factors that will affect manual shade movement and ii) increase confidence that shade movement is intentional and not random. After discovering that natural shade movement was exceptionally low, Rubin et al. [24] had the unique approach of attempting to incite blind movement by moving them to extreme positions and observing the occupants' response over time. The researchers hypothesized that by positioning the shades to some extreme position, the occupants were more likely to return them to their preferred position than leave them as is.

Four of the studies conducted occupant surveys to complement the quantitative shade data. Typical questions involved the motivation to open or close shades and importance of daylight and views. While this data cannot be directly applied to occupant behavior models, it is very useful in preliminary work for identifying the environmental characteristics that should be measured and the site characteristics that should be recorded.

3.5 Number of discrete shade positions

For the observation technique of photography, all of the studies used between 3 and 10 discrete shade positions for recording purposes. The number of discrete positions was typically balanced by the need for precision and the technical difficulty (e.g., low image resolution) or tediousness of interpretation. Care must be taken to use a camera with sufficient resolution and the size of the façade may have to be limited to achieve the desired level of precision [19]. In general, a smaller sample size allowed greater detail to be obtained from individual photographs. While most studies did not mention the error of interpretation, Rubin et al. [24] clearly acknowledged human error due to manual interpretation of the photographs.

For application to building performance simulation, the error in predicted heat transfer and solar gains from over-discretization of shades is approximately linearly proportional to the difference in shade position. However, this may propagate to be more significant, particularly for visual comfort and daylighting, which can be sensitive to exact solar and window geometry. At the façade and building-level (i.e., large groups of windows), the error from discretization should approximately cancel out. Thus, recording shade positions using four to five discrete positions is adequate. However, the resolution should be fine enough that any deliberate shade movement is recorded. Furthermore, Venetian blind slat angles should be recorded at a maximum of 30-degree increments, and preferably in 10-degree increments, including whether they are tilted up or down. However, the thermal and optical properties are sensitive to slat geometry and reflectance [32, 33]. Thus, a sensitivity analysis should be performed for each study to establish the appropriate angular resolution to properly record the proper shading system properties.

3.6 Collected data

While shade position data collection was the focal point of the experiments, other data were collected to provide a context for the experimental conditions. All the reviewed studies acknowledged the potential impact of weather conditions on shade controls. Means for collecting weather data ranged from a qualitative description of sunniness [12] to weather data from a weather station mounted on the building of interest [24]. Localized conditions (e.g., temporary cloud shading) is unlikely to significantly impact shade positions, since occupants tend to control their shades accordingly to longer term conditions [19], as discussed later. Therefore, use of a local weather station is adequate for the purposes of collecting data for an occupant behavior model.

Multiple studies [16, 26, 28, 34] monitored the office illuminance levels, providing an indication of the interior lighting conditions on manual shade operation. Despite the cost of deploying interior illuminance sensors, the collected data is a direct indication of the occupants' visual comfort and necessary for closed-loop control applications, as explained later. As such, future studies should either measure interior lighting conditions or provide sufficient site and building characteristics that interior lighting conditions can be derived from the weather data.

About half of the studies measured indoor air temperature and/or relative humidity in at least one location in the building. As with shade position sensors, if they are not already installed, there is considerable cost in measuring and recording interior temperature and relative humidity; particularly since these indoor environment variables could vary between offices, thus requiring sensors in each office. However, as discussed later, interior temperature and relative humidity are not significant contributors to occupants' shade operation.

Mahdavi et al. [34] directly measured the presence of occupants. Ultimately, this will affect shade movement rates, but any occupant behavior model based on real building data should incorporate typical occupancy.

Four of the studies conducted occupant surveys to complement the quantitative shade data. Typical questions involved the motivation to open or close shades and importance of daylight and views. While this data cannot be directly applied to occupant behavior models, it is very useful in preliminary work for identifying the environmental characteristics that should be measured and the site characteristics that should be recorded. Future studies can lessen the reliance on detailed surveys as have been done in the past, unless an unexplained behavior is observed.

3.7 Office and site characteristics

Most studies provided a brief description of the building site(s), with several also providing a map. Because of the potential impact of obstructions to views to the outdoors, solar radiation and potential privacy concerns, detailed data is preferable. For example, knowledge about the tree species may have a significant impact in temperate and cold climates where the foliage levels vary seasonally. All shading information can be directly applied to BPS where solar and visual obstructions can be quantified for the individual office level. Aside from the energy and comfort implications of obstructions, the presence of a proximate building could influence occupants' control of shades to allow for privacy. For the same reason, it is recommended that future published studies state whether a building is near pedestrians and other traffic.

Most studies described the type of shading device and other major specifications, but did not describe their thermal or optical properties. Venetian (horizontal) blinds were the predominant shading device type of the studied buildings, while top-down roller shades and vertical blinds followed, as shown in Figure 2. Three studies [16, 17, 34] had two shades per window (one located at the upper part of the window and one on the bottom part or one interior and one exterior), which further complicates matters and limits universality of results, as they acknowledged. The building studied by Haldi et al. [17] also had anidolic system - a curved reflector posited outside of the top window whose purpose is to reflect direct incident solar radiation deep into the space on the ceiling without sensitivity to solar altitude. Such a system significantly increases daylight penetration regardless of the shade occlusion of the viewing section (mid-height) shades.

Only a small fraction of the studies characterized the interiors of the offices (e.g., furniture locations, surface reflectances, and office depth). However, orientation of desks and of Visual Display Units (VDUs) is known to significantly affect visual comfort [35]. Furthermore, the nominal number of occupants per office or room should be noted, since it has been shown to affect manual shade operation tendencies, as discussed later.

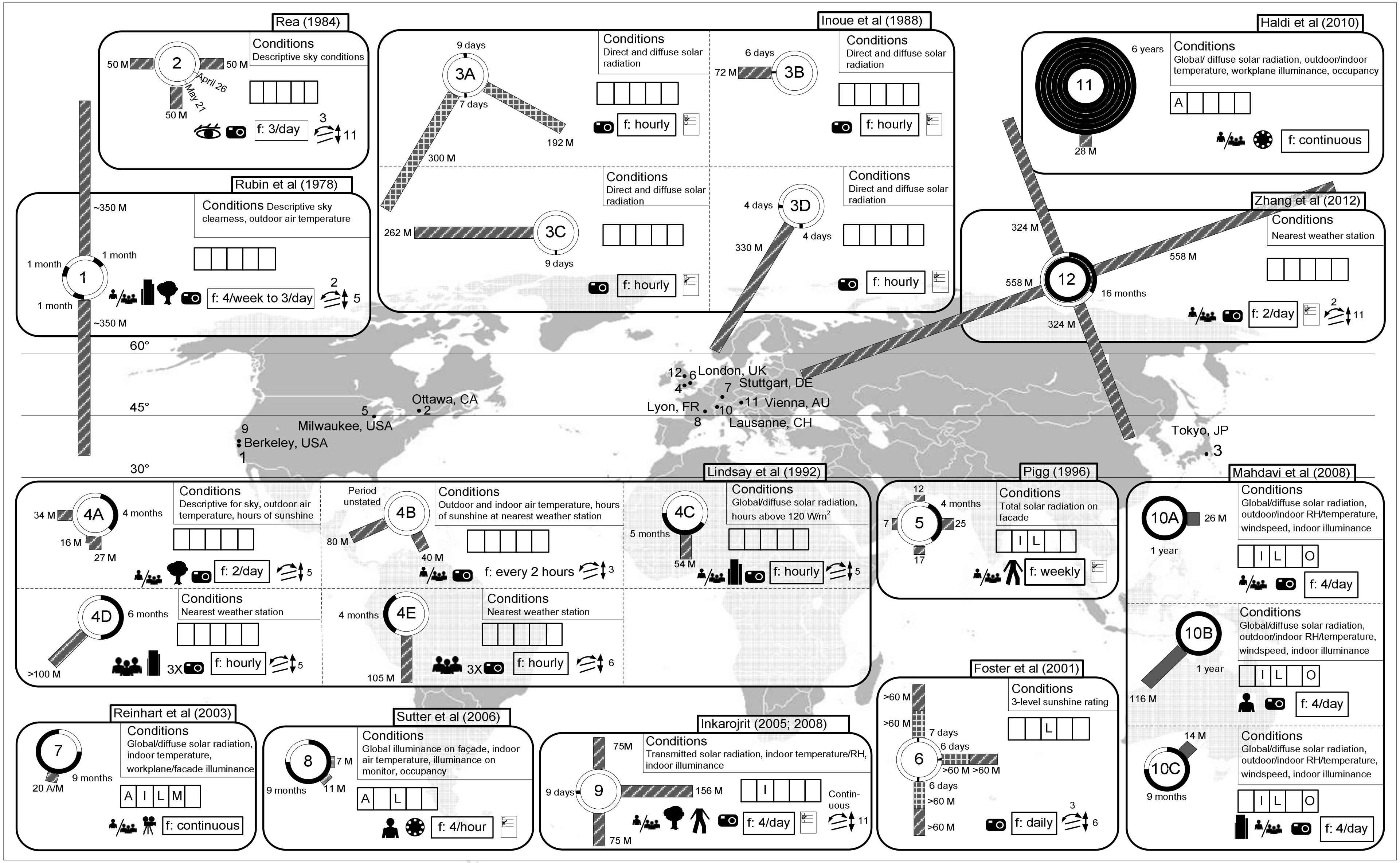
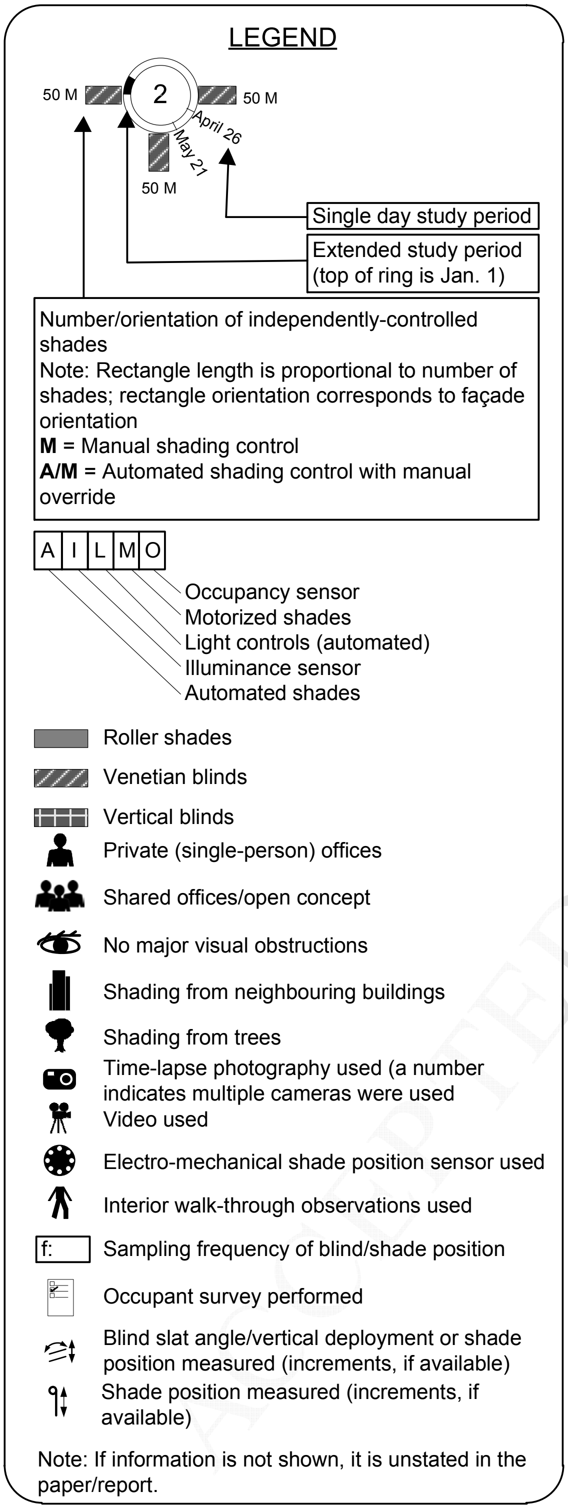


Figure 2: A graphical representation of the experimental approaches and building characteristics of 12 major studies



4 EXPERIMENTAL RESULTS

This section presents a cross-sectional analysis of the 12 major studies' findings in an attempt to identify where consensus has been reached and where further research is required. A summary of all common and opposing findings is provided in Table 1, at the end of this section.

Since there was no standard way of reporting results among the papers, there are many instances where they cannot be directly compared to each other. Often, this inconsistency is due to the different shading device hardware. For instance Venetian blinds have two degrees of freedom (blind position and slat angle), whereas roller shades only have one. The strongest conclusions drawn are for the situations where two situations are directly compared with only one apparent factor that is different (e.g., façade orientation, weather conditions, or time of day).

Many of the studies stated that there was at least one experimental peculiarity that could put the universality of the results at question. Furthermore, the studies are scattered across North America, Europe, and Asia, introducing a wide variety of climates and cultural differences (e.g., certain professional or ethnic cultures may have different attitudes on the formality of attire, and therefore affect the ability of occupants to adapt to thermal conditions [36]). It should be noted that all of the studies were performed in the Northern hemisphere (between latitudes of 37° and 55° N); thus south-facing means equator-facing. The results presented below are within the context of particular building or group of buildings being studied.

4.1 Solar intensity and geometry

Nearly all of the studies recognized solar radiation could have a significant impact on shade use, since after all, one of the primary purposes of shades is to prevent glare and control solar gains. The measured solar-related metrics varied widely and included incident solar radiation on the façade, global horizontal radiation, workplane illuminance, window luminance, depth of solar penetration, daily hours of sunshine, and several qualitative metrics, such as “sunshine index” and “sunny” or “cloudy”. It is preferable for studies to examine the nature of transmitted solar radiation rather than exterior solar conditions because it is the interior conditions, not the exterior ones, which motivate occupants to control their shades. Despite this, more than half of the studies used external conditions only; likely because there are fewer points of measurement and thus, this is easier to instrument. It is important to note that studies that used interior illuminance (e.g.[17]) and other interior conditions include the complication that the metric itself is affected shade positions.

In general, both MSO and SMR increase with sunnier conditions. Zhang et al. [37] found that the SMR increased by two to three times at peak horizontal radiation relative to low radiation levels. Mahdavi et al. [30] found a strong correlation between MSO and global horizontal solar radiation on two of the facades in their study – one east-facing and one north-west facing – with MSO increasing about 20 percentage points between the lowest and highest encountered global horizontal solar radiation. However, the MSO was found nearly constant (within about 3 percentage points) for the north and south-west façade. Thus indicating that the effects of global solar radiation must be taken in the context of façade orientation. This is probably a consequence of the fact that global horizontal solar radiation is not necessarily indicative of the amount of solar radiation transmitted through windows.

As a counterexample, Foster et al. [12] reported that the shade use patterns are independent of the solar conditions. In order to quantify the intensity of solar radiation, they invented a simple “sunshine index”. The sunshine index is a function of the horizontal global radiation and the time of the day. Its major limitation is its maximum value (sunny conditions) tends to be in the middle of the day. Moreover, Foster et al. [12] limited the shade observation and analysis on the midday only . This is the likely explanation for Foster et al. [12] drawing conclusions that directly contradict the majority of studies that considered solar radiation as a factor.

The studies that merely described the solar conditions (e.g., sunny and cloudy) generally support the studies that used more quantitative measures. For instance, Inkarojrit [24] found that 67% of shades were fully open on the cloudy day, compared to 43% on the sunny day. Furthermore, 50% of occupants moved blinds once or more per day on sunny days versus 25% on cloudy days. Lindsay and Littlefair [18], who studied five different buildings and used incident solar radiation on each façade as a metric, found that MSO approximately doubled for sunny days versus cloudy days and that this metric was the leading cause of shade position changes. More significantly, they were among the first to indicate that occupants did not control their shades because of sudden events but rather the sunniness of the previous 1.5 to 3 hour period.

Reinhart et al. [16] and Inoue et al. [23] found solar penetration depth (D_{solar}) - defined as the normal distance from the façade that the beam solar radiation reaches the workplane (see Figure 3) - to be a very good predictor of shade position. Furthermore, their models are in good agreement with Inoue et al. [23], as shown in Figure 4. As previously noted, Inoue et al. [23] eliminated inactively used shades from their study. Thus, the ability of the correlation to predict the position of shades with SMR = 0 is nullified. Inoue et al. [23] found the solar penetration depth to be a far better predictor than merely the incident solar radiation on the façade. A major advantage to the solar penetration depth (D_{solar}) metric is that it is independent of many other characteristics such as glazing type and can therefore be readily calculated using the following geometrical relationship:

$$D_{solar} = \left[(1-p)H_{win} + H_{sp} - H_{wp}\right]/\tan d \qquad (4)$$

where p is the fraction of the window that is shaded by a shade (assuming a top-down roller shade), H_{win} is the height of the window, H_{sp} is the height of the window spandrel (if any), H_{wp} is the height of the workplane (normally 0.70 m) and d is the solar profile angle [38], as shown in Figure 3.

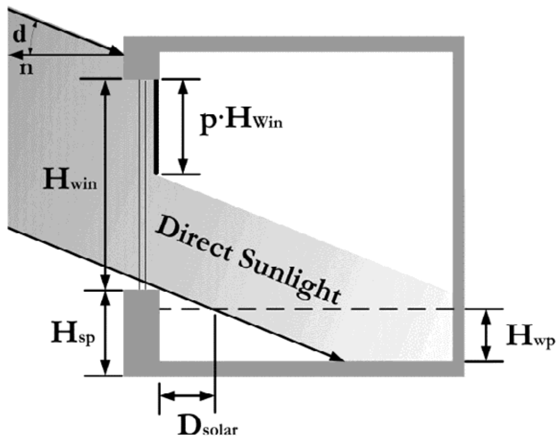


Figure 3: Section view of a perimeter office, showing key geometry, including solar penetration depth

However, the concept is less applicable for north-facing facades (in the northern hemisphere) because even when there is incident direct solar on the north façade, the surface-solar azimuth angle is very high [16].

Zhang et al. [37] found that MSO increases modestly (about 5 percentage points) with decreasing solar altitude over the range of all values. They found that occupants were as likely to raise their shades as they were to lower them at different solar altitudes, but that the SMR increases linearly with increasing solar altitude. As suggested by Haldi et al. [17] and Inkarojrit [26], it may not be adequate to consider shade use to be independently related to solar geometry or intensity; but rather a function of both.

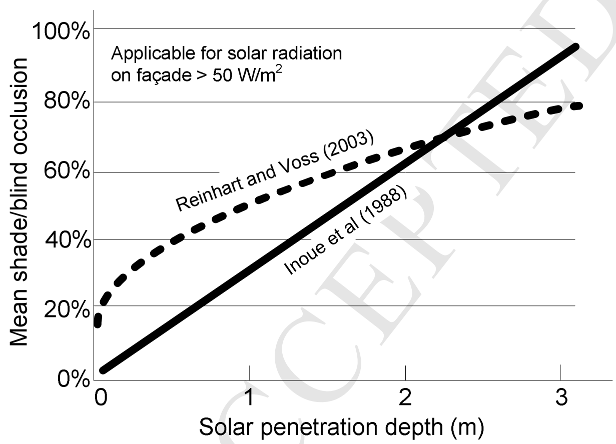


Figure 4: Regression relationship between mean shade/blind occlusion and solar penetration depth (reproduced from [16])

Several researchers attempted to find correlations between illuminance and shade operation. Haldi et al. [17] found that the greatest number of shade openings and closings occurred when the workplane illuminance was 200 lux and 1200 lux, respectively. Inkarojrit [26] found luminance – both window and background – to be among the best predictors of blind closing events. Reinhart [16] found that the mean thresholds of exterior vertical illuminance when occupants overrode the blinds for closing and opening were 50 klux and 25 klux, respectively.

With only a few exceptions, the studies indicate that both MSO and SMR increase with higher levels of solar radiation,, which supports the notion that universally-accurate shade use models can be created.

4.2 Time of day

Given that occupants tend to occupy offices only during the daytime and that solar geometry varies cyclically with a period of 24 hours, one would expect some daily patterns in shade use. Many of the studies found that the peak periods of SMR were immediately after arrival and/or immediately before departure. Haldi et al. [17] found actions immediately upon arrival of occupants to be about five times more frequent than during any other 5-minute period during the day; this is likely because of the rapid change in environments between before and after they enter their offices and also due to the fact that people tend to set-up their office environment at the beginning of the work period. Furthermore, the specific action was highly-dependent on solar related phenomena, such as the workplane illuminance [17] and the façade orientation [23]. Inoue et al. [23] reported that shades on east façades are usually closed by occupants upon entry but gradually opened during the course of a day and that the opposite occurs for the shades of the west façade. Rea [18] contradicted these findings, reporting that time of day had minimal effect on shade position and that occupants make little effort to change it during the day, despite a change in solar penetration depth – especially on the east and west facades. While generalized occupant behavior models can implicitly capture the diurnal variation in solar intensity and geometry, there is sufficient evidence that SMR increases at certain times of the day.

4.3 Time of year

There is some evidence to suggest that occupants are relatively slow in moving their shades to reflect short-term (e.g., hour- or day-long) external conditions, but that they do react to longer term trends [19]. Furthermore, one might expect occupants to have a greater tolerance for transmitted solar radiation in the winter because sunlight is less abundant - both in intensity and duration and because solar gains could potentially help heat spaces in the winter.

About half of the studies extended across multiple seasons in order to specifically study seasonal effects. Despite the above hypothesis that the time of year could impact shade use patterns, none of the studies demonstrated that it independently affected shade operation. Haldi et al. [17] found that the seasonal effect on shade use was statistically insignificant. Rubin et al. [24] support this notion, with the exception that there were about 50% more blinds in the down (slats fully declined) and open position (slats horizontal) in February relative to in October and July – possibly a result of the lack of shading from foliage and low solar altitudes. Zhang et al. [37] found the non-north blinds to vary seasonally by as much as 15 percentage points. In general, the studies suggest that any seasonal effects can be captured by other variables without having to directly introduce the time of year as a variable in the models.

4.4 Outdoor air temperature

While the observational studies represent a somewhat diverse range of seasonal patterns of outdoor air temperature, none of the studies found outdoor air temperature to be a significant factor in shade operation.

4.5 Motorized and automated shades

The three distinct levels of shade control include manual (e.g., operated by turning a rod, pulling a chain or cord), motorized (i.e., controllable with a single button-push or holding a button until the shading device reaches its desired position), and automated with manual override (e.g., automatically controlled based on external conditions or time of day).

In general, the ease with which occupants can control their shades increases the SMR since it reduces the effort required to improve the indoor environment. Zhang et al. [37] reported that nearly 70% of occupants found blinds difficult to control. Sutter et al. [27] found that on average, occupants with motorized shades moved their shades three times more often than those without motorized shades. Motorized shades have two major control options, including: 1) a single button push to fully open or fully close them, or 2) hold a button to finely control their position. Thus, there is less effort to change a shade position to its extreme positions than somewhere in between. This phenomenon was observed by Haldi et al. [17] and Sutter et al. [27], who reported that the shades were in extreme positions for 72% and 93% of the time, respectively.

Many of the studies (e.g., [16], [23], [17]) had one or more forms of motorized and/or automated shades with manual override. This yields important information, provided that the statistical results are taken within the context of the specific shade control. Reinhart et al. [16] reported a daily average of 3.7 blind position changes per office – significantly higher than most studies with non-motorized shades; 53% of these were manual adjustments and the rest automatic. Interestingly, 45% of the automatic blind position changes were corrected by the users within 15 minutes of the automated position adjustment. Of these overrides, 88% were to open them more than the automatic system had, a finding supported by Sutter et al. [27].

In general, it is evident that providing occupants with easy-to-use shade controls tends to make them more likely to control them to improve their comfort, thus potentially reducing energy use by minimizing the use of energy-intensive measures (electric lighting, heating and cooling). However, results from Reinhart et al. [16] indicate that further research is needed to automatically control shades to match occupant preferences. Automated shades do have the advantage that predictive controls through a building automation system can be implemented to reduce cooling and heating energy consumption even when the offices are unoccupied such as on weekends when it is known that there are no occupants. That is, in the cooling season they would be kept closed, while in the heating season they would be kept open during the daytime.

4.6 Adjustment of Venetian slat angles

Despite the prevalence of Venetian blinds and their ability to block direct solar radiation while admitting ample diffuse daylight and maintaining a view to the outside, few of the studies performed in-depth analysis of slat angles; either because they were difficult to record or because they simply did not report it. Inkarorit [25] found that 65% of blind slat angles were adjusted less than once per day and 35% more than once per day. Sutter et al. [27] found that 93% of Venetian blinds where raised or lowered to their extreme values and that most control was achieved by changing slat angles only. Furthermore, they had them tilted downwards 95% of the time – presumably to prevent direct solar radiation penetration while allowing some views.

4.7 Façade orientation

Façade orientation plays a major role in the temporal patterns and the magnitudes of solar gains. For instance, north facades receive minimal solar gains. South facades are best oriented for capturing potentially useful wintertime solar gains. One would expect the east and west facades to have the greatest SMR since they experience the greatest variation in incident solar radiation (magnitude and direction) over the course of a typical workday. Furthermore, these facades experience the greatest depth of penetration of beam solar radiation (D_{solar}) around the time of sunrise and sunset.

All of the studies identified the façade orientations of their subject building(s) and many of them studied at least two façade orientations. Although the studies were relatively well distributed among all major directions, there was some emphasis on south-facing facades with the reason that the researchers hypothesized the south-facing shades would be more actively controlled because of the higher solar exposure.

The strongest conclusion is that the MSO on near north-facing facades is among the lowest of all façade orientations [12, 24, 26, 28, 34]. The same set of studies found that the near south-facing facades were most likely to have the highest MSO. The ratio of south to north MSO ranged between about 1.5 [26] and 5.0 [34]. One of the buildings [18] did not even have shading devices on the north façade, reflecting the minimal duration of direct solar gains. Pigg [28] reinforces this by reporting that shades on the north façade were fully closed less than 1% of the time and fully open 83% of the time.

Except for Rea [18], who found that there was minimal correlation between MSO and façade orientation, the studies with at least one east or west façade (e.g., [28, 37]) found their MSO to be somewhere between that of the south and north façades; though more often closer to that of the south façade's.

The only study with a façade orientation that deviates significantly (more than 30 degrees) from the cardinal directions is Mahdavi et al. [34], with a NW façade. They reported a MSO similar to that of the north façade (~13%) under cloudy conditions but that the MSO nearly triples to about 35% when the horizontal irradiance exceeds 500 W/m^2. In contrast, the MSO on the north-facing façade remained nearly constant under the same range of conditions, which confirms the fact that on north-facing windows the main factor affecting shade position is privacy and view.

There were few conclusions drawn with regards to SMR with respect to façade orientation. Inoue et al. [23] reported significant diurnal patterns in the east and west facades. It was found that occupants in the east-facing offices close shades, upon arrival, and gradually open them up during the day, whereas, those in west facing offices opened their shades (which would have tended to be closed at the end of the previous day) and then close them over the course of the day. Other studies were less conclusive about the effect of façade orientation on SMR. Pigg [28] found that the south-facing offices tended to have the most active users but not at a high level of statistical significance.

While the majority of researchers have found façade orientation to have a major impact on both MSO and SMR; this is almost certainly related to solar intensity and geometry patterns and not merely the orientation. Thus, if possible, future behavioral models can likely eliminate façade orientation as an independent variable as long as solar radiation and/or geometry are incorporated.

4.8 Type of office

Shared and open concept offices present further complexities to occupant shade control, compared to private ones. Occupants tend to be more reluctant to control their environments if others are present because of social constraints. Boyce's [30] study about manual light control in large offices reported that switching actions are usually consistently performed by the same people (i.e., leaders) and that such actions occurred either when there was ample daylight or when the action was deemed to not impact anyone because most people had left.

Not only could preferences vary by person under identical conditions, but the position of a shade could result in different conditions for two different people (e.g., one person is further from the façade than the other) [5].

The studied offices were predominantly single occupancy/private offices. However, about half of the buildings contain one or more shared offices or small open plan offices with up to nine occupants. Haldi et al. [17] found that the shades of single-occupancy offices were more adaptive of changing indoor illuminance levels than the double-occupancy offices. Reinhart et al. [16] stated that the applicability of their study is ideally used for open plan settings because people "loosen the perception of ownership over their immediate environment" under such conditions. Rubin et al. [24] hypothesized that the social factors associated with offices with more than one occupant could impact shade movement, but were unable to test it. Zhang et al. [37] provided conclusive evidence that shade usage is affected by space use. They found that the MSO in their building was about 20 percentage points higher for offices than non-offices (i.e., hallways and waiting areas); likely attributed to the fact that people spend less time in non-offices, and are thus less sensitive to potential visual and thermal discomfort.

4.9 Occupancy

A fundamental factor to shade operation patterns is occupancy. For manually controlled shades, a vacant office means no movement, thus reducing the SMR. Inoue et al. [23] discovered that 60% of shades were not moved on a daily based and they deemed those offices unoccupied. One study even completely curtailed monitoring of one building due to lack of response [17]. Several others applied a filter or set up the experiment to provoke exaggerated shade movement. However, many of the studies [26, 28] found minimal shade movement even in fully-occupied offices. Since Inoue et al. [23] only used photographs to track shade movement, they had no direct information about occupancy. In contrast, Mahdavi et al. [34], who did monitor occupancy through sensors, reported a peak daily occupancy rate of only 70% in the institutional buildings that they studied.

The importance of capturing the effect of the occupancy depends on motivation of understanding shade use. If the objective is to understand human tendencies, then filtering out the unoccupied offices could be beneficial, as they dilute the results. However, if the motivation is whole-building energy use, then shade position could affect heating and cooling loads regardless of occupancy. It would be worthwhile to control shades to the optimal position for conditioning loads alone during absences since constraints on visual comfort are nullified.

4.10 View to the outside

One might expect that an occupant's view to the outdoors, which has been cited as a reason for large glazing areas [17, 23, 25, 37], would influence their tendency to keep their windows unobstructed by shades. For instance, sources of visual discomfort may become more tolerable if closing shades also leads to poorer views [23-25]. However, only two studies [19, 24] drew conclusions about quality of view, mainly because it is difficult to quantify. Rubin et al. [24] assessed the level of obstruction of view from trees and found that there was a negligible correlation with shade use. Lindsay et al. [19] reported that the building they studied had unusually high sills, at 1.1 m, and that the results reinforced their hypothesis that the occupants would have little motivation to open shades for the sake of improving views. Haldi et al. [17] found that the lower façade shades in their study were in a closed position four times less frequently than the upper façade ones and suggested that this may be in an effort to maintain views to the outside. Rubin et al. [24] distinguished between "open" and "restricted" views; however, as they noted, the obstructions to the views in their buildings are primarily from other buildings, and thus, also impose privacy concerns (discussed in the next section). Their results show that there are relatively similar frequencies of fully open shades, regardless of the quality of the view. They acknowledged that the quality of view is a fuzzy variable and that their analysis is simplified by using only two categories. One might be able to find correlations between shade use and office height from the ground (since higher offices tend to have better views), but few of the studies distinguished office heights – and those that did not draw any strong conclusions. Ultimately, further research is required to determine the significance of views on shade movement; but initial results suggest that views play only a minor role.

4.11 Privacy

Few of the observational studies considered privacy as a motivation for shade use in offices. Inkarojrit [25] found that only 12% of the 25 surveyed occupants cited visual privacy as a reason for closing blinds. Foster et al. [12] speculated that the unexpectedly high MSO on the north façade of one of the studied buildings could be a result of the proximity of a neighboring building. Reinhart et al. [16] drew an interesting conclusion that if the automated shades in his study were overridden to be closed during periods of low ambient horizontal illuminance (<1000 lux) that this must be for the purpose of privacy. Using this definition, they reported that only nine out of the ten occupants closed shades for the purpose of privacy for less than 4% of the time. All studies that investigated privacy as a factor for shade control found it to be relatively insignificant.

4.12 Lighting control

Of the four studies that had automated lighting control, Pigg's [28] results were the strongest in drawing conclusions about the effect of automated lighting control on shade use. Though the sample size was small, he found that occupants without automated lighting control were much more likely to leave their shades closed while those with automated lighting control were much more active shade users. Reinhart [16] found occupants to be somewhat energy conscious, in that if the lights were switched on, they usually (80% of the time) also ensured that the shades were fully open in order to maximize daylight.

4.13 HVAC system and operable windows

If mechanical systems are able to maintain thermal comfort conditions, occupants are less likely to further manipulate their environment. Inkarojrit [25] explored the HVAC system as a potential factor of shade use patterns. His study involved both offices which had air conditioning and some which were limited to natural ventilation as the only means for cooling the space. He hypothesized that the MSO would be higher for the offices without air conditioning, since they have fewer options to maintain comfortable temperatures in the Berkeley, California climate. As he anticipated, the MSO for the offices with air conditioning was 30% compared to 49% for those without. The increasing popularity of hybrid ventilation [39] and other passive means to maintain thermal comfort means that there is increasing importance in providing personalized and localized control over thermal conditions, such as shading devices.

4.14 Visual and Thermal Comfort

Visual and thermal comfort indices represent higher-level metrics that indicate the degree of comfort with regard to visual and thermal sensations. Many of the current reviewed studies chose, instead, to use lower level metrics that are directly measured by sensors and merely represent a portion of the inputs to these high-level indices. However, several studies included an occupant survey, which allowed them to distinguish between visual and thermal comfort as motivating factors to use shades. The results indicate very strong support for visual comfort being a major motivating factor for occupants when controlling their shades. From the subjects in Pigg's [28] study, 43% said they do so to reduce direct light and 37% stated that they do so to reduce glare on VDU's. On the contrary, occupants value increased illuminance, views, connection with the outside [23-25]; and thus they often open shades to improve these benefits.

Unlike glare and other forms of visual discomfort, indoor air temperature is not a function of instantaneous solar gains, and could therefore be less of a factor, because improvement of conditions via shade control requires foresight of the occupants. There is little evidence to support the notion that occupants control their shades to reduce indoor air temperature. For instance, contrary to their hypothesis, Lindsay et al. [19] reported that no correlation was found between indoor air temperature and blind control. Similarly, Haldi et al. [17] suggested that occupants' lack of movement immediately before leaving their offices is indicative of the fact that they do not control their shades to improve future (i.e., next working day) thermal comfort conditions. They also found that both the indoor temperature at which the greatest number of shade openings and closings were about the same at 24°C; suggesting that temperature alone is not a significant indication of shade position or actions. Despite these observed findings, respondents of several of the surveys [23, 25] cited reduction of solar gains to improve thermal comfort as being among the top two reasons for controlling shades. It is also important to view these results in context of the studies' buildings, which mostly had HVAC equipment to maintain acceptable thermal comfort conditions. Thus, the range of indoor temperatures that occurred in these studies may not have been great enough to allow conclusions to be drawn about the effect of thermal conditions on shade use.

While occupants may not be as conscious of longer-term (i.e., minutes to hours) impact of solar gains, one can be certain of the fact that incident solar radiation increases skin temperature - by about 0.025°C/Wm^{-2} [40] . Inkarojrit [25] found that higher mean radiant temperature (MRT) decreases the mean tolerable threshold of window luminance by a factor of ten, from about 10,000 to 1000 candelas/m^2. Similarly Sutter et al. [27] found that 50% of shades are closed at 10,000 lux external vertical illuminance when indoor air temperatures are lower than 26°C versus just 3000 lux when it is over 26°C, supporting the idea that indoor temperature does affect occupants' tolerance of high illuminance conditions.

The research indicates that occupants control their shades to improve visual comfort more than thermal comfort. While shade positions may result from long-term, multi-day or –month conditions leading up to the present, occupants do not specifically control their shades to improve future anticipated conditions [17]. This finding is very important, as it indicates the value in automated shade controls with a predictive element.

All low-level thermal and visual comfort-related factors that were used can be directly measured with sensors. However, occupant comfort is complex and dependent on multiple measured physical quantities. Thus, aggregated metrics are more suitable for predicting occupant discomfort. For instance, the predicted mean vote (PMV) metric incorporates all major factors (e.g., air temperature, occupant activity level, and clothing level) that affect thermal comfort [41]. Similarly, there are numerous metrics that indicate the potential for visual discomfort such as the Daylight Glare Index [42], the Daylight Glare Probability [43], the Daylight Autonomy [44], and the Useful Daylight Illuminance [45]. However, glare metrics that are highly affected by the angular displacement of the source from the observer's line of sight as well as the size of the source of glare should be used carefully, taking into account their limitations, as occupants tend to reposition themselves when glare occurs [35]. Moreover, Kim et al. [46] reported difference in glare sensation between uniform and non-uniform glare sources and Lee et al. [47] reported different glare perceptivity between Caucasians and Asians.

4.15 Other observed behavior patterns

One of the most widespread conclusions of all studies was that, for the most part, many occupants operate their shades very infrequently or even never [23, 25, 28] possibly because adaptation to short-term changes in conditions is not worth the effort [24]. Sample observed movement rates include 0.7/day for manually operated shades [27] and between 0.05 and 0.41/day depending on the building [19]. Furthermore, many researchers reported that a high fraction of shades were never moved (up to 60%) during the study period [23]. The infrequency of shade operation in many buildings suggests that merely assuming fixed shade positions in BPS models, with a realistic MSO would be a big step towards more accurate results.

While occupants do consciously choose a shade position [24], it is largely based on the long-term integration of environmental conditions rather than short-term phenomena [16]. Rubin et al. [24] demonstrated that occupants do put significant thought into shade positions, since they showed that 80% of occupants returned their shades to their original position within a day of being perturbed by the researchers.

Several studies [16, 23, 27] reported a hysteresis, in which the mean illuminance (or some other indication of solar-related magnitude) at which occupants tend to close shades was significantly higher than that at which they reopen them. In other words, occupants tend to prefer their shades to be extraneously open versus closed [16, 24].

4.16 Summary of experimental results

This section presents a detailed cross-sectional analysis of major observation studies in an attempt to identify the factors that contribute to shade use. The results support the fact that solar phenomena are the leading factors of shade use patterns. This is not necessarily apparent from the individual studies, but as shown in Figure 1, many of the factors that were found to be significant are directly tied to the magnitude and geometry of transmitted solar radiation. While these findings are encouraging towards a universal understanding of how occupants control their shades, it does identify the major issue that researchers need to standardize their reporting units and metrics such that studies can be compared with each other.

While solar phenomena were found to be the major variable affecting shade controls, many of the studies found that all related technologies, including shade controls, lighting controls, HVAC, and operable windows affected shade use. Therefore, from the standpoint of creating a universal model, these parameters need to be incorporated. With the large diversity of office geometries, climates, and lighting- and shading-related technologies, it is imperative that care be taken in applying a set of results or behavior models to other buildings [18, 19, 34]. This is highlighted by the fact that Lindsay et al. [19] found large variations in multiple similar buildings in the same climate and using the same observational methodology.

From a design perspective, it is evident that occupants tend to be more active shade users if the controls are easier to use. On the contrary, they become less active users if other systems (often more energy intensive ones) are in place to conceal the benefits of shades (e.g., if mechanical cooling is available, occupants are less likely to control their shades to reduce solar gains). Thus, short of removing the very technologies that improve occupant comfort, automated shade controls can be implemented to simultaneously optimize visual and thermal comfort and building energy use. A common finding among several of the studies [17, 19, 24] is that occupants tend to use reactive control rather than predictive control. That is, they control shades based on current or past conditions rather than on anticipated future conditions. Predictive control that is based on information from building performance simulation and forecasted weather data could potentially reduce energy use by taking proactive actions that optimize comfort and energy use [48]. Generalized façade design guidelines based on observed shade use patterns are proposed in the next sections.

Table 1: Summary of experimental findings.

			Fixed office parameters											**Variables**										
	First Author	**Year**	**Automatic shading device**	**Shading device motorization**	**Automatic lighting control**	**Façade orientation**	**Operable windows**	**HVAC system**	**Height of façade**	**Private vs. shared office**	**View to outside**	**Privacy**	**Self-reported brightness sensitivity**	**Magnitude of external solar radiation**	**Magnitude of transmitted solar radiation**	**Geometry of transmitted solar radiation**	**Shading from vegetation**	**Time of day**	**Time of year**	**Workplane Illuminance**	**Window Luminance**	**Previous shade position**	**Indoor Temperature (air or MRT)**	**Outdoor air temperature**
1	**Rubin**	**1978**				Y					Y			Y			Y		N					
2	**Rea**	**1984**				Y								Y				N						
3	**Inoue**	**1988**				Y								Y	Y	Y		Y						
4	**Lindsay**	**1992**				Y			Y		Y			Y/NA			Y	Y	Y				N	
5	**Pigg**	**1996**			Y	Y/NB			Y															
6	**Foster**	**2001**				Y								N				Y	Y					
7	**Reinhart**	**2003**	Y			Y						N		Y		Y		Y		Y				
8	**Sutter**	**2006**		Y										Y	Y						Y		Y	
9	**Inkarojrit**	**2005/ 2008**				Y	Y	Y					Y		Y	Y				N	Y		Y	
10	**Mahdavi**	**2008**		Y		Y								Y/NA				Y	Y					
11	**Haldi**	**2010**	Y							Y		N				N		Y	N	Y		Y	Y	N
12	**Zhang**	**2012**				Y				Y				Y		Y		N	Y					

Yes	2	2	1	9	1	1	2	2	2		1	6	3	4	2	6	4	2	2	1	3	
No										2		1		1		2	2	1			1	1
Other				1								2										

Notes
Y. The paper concluded that the factor is statistically significant (formally or not)
N. The paper concluded that the factor is not statistically significant
A. Multi-building study; results vary by building
B. Yes for mean occlusion; no for movement frequency
Some of the authors speculated certain factors; however these were excluded from the table. Many of the speculations are discussed in the text.

5 APPLICATION OF RESULTS

Ultimately, the purpose of performing the detailed observational manual shade operation studies is to apply our understanding of occupant behavior and preferences to other buildings. Among the studies, there are four distinct approaches to applying study findings, including: i) qualitative analysis of occupant behavior ii) creation of mathematical or statistical occupant behavior models that relate stimuli and shade movement, and iii) use in development of automated shade control algorithms iv) providing input to façade and movable shading device design of buildings.

5.1 Mathematical relationships and statistical occupant behavior models

It is important to be able to properly predict occupant control of shades so that BPS can employed to accurately predict building performance. The solution to this could be a simple rule-based algorithm or a more complex model, such as agent-based modelling. Five studies [16, 17, 23, 26, 37] transformed the observed data into one or more single variable or multivariate models that relate environmental variables to shade use. This section discusses their results and the success of applying such models, followed by a review of potential future research areas.

5.1.1 Single variable regression

Single variable regression involves finding the relationship between a shade metric – predominantly MSO, here – and a single one of the many factors. Many of the reviewed studies used single variable regression because of its ease of calculation and application. Inoue et al. [23] were the first to establish a single-variable quantitative relationships of shade use. They found that the best predictor of shade position is not solar intensity but rather solar penetration depth (D_{solar}), provided that the direct solar radiation exceeds about 50 W/m^2, as previously reported. Reinhart et al. [16] reported very similar results for their SSW facade (same direction as one of the facades of Inoue et al. [23]) using the same input variable. Several unique experimental conditions reduce the universality of the results: Inoue et al. [23] excluded shades that were not moved at least daily and the building that Reinhart et al. [16] studied has automated blind control. However, most (79%) of the shade movements in the study of Reinhart et al. [16] were either manual or overridden automated controls. None of the other researchers studied solar penetration depth. Mahdavi et al. [34] found that a linear relationship was relatively good for describing the correlation between the normalized probability of closing shades and the vertical solar radiation.

5.1.2 Single variable logistic regression

Four studies [17, 26, 27, 49] that considered single variable models calculated the probability of opening or closing shades based on magnitude of several environmental variables, individually. Specifically, they used logistic regression to find a curve (Figure 5). Probability models are more useful for understanding what prompts shade movement but less useful than MSO models for modeling entire buildings. In fact, Haldi et al. [17] found that logistic regression is much more effective for predicting shade movement actions than absolute shade position. Inkarojrit [25] and Haldi et al. [17] systematically tested different environmental variables to determine the single best predictors for a logistic model. Single-variable logistic regression models take the form shown in Figure 5 and is represented by an equation of general form (5).

$$P(X) = \frac{\exp -(\alpha + \sum[\beta_i Y_i])}{1 + \exp -(\alpha + \sum[\beta_i Y_i])} \quad (5)$$

Where *P(X)* is the probability of the shade being opened (or closed), α and β are regression coefficients, and Y_i is the model input (i.e., the value of the environmental variable).

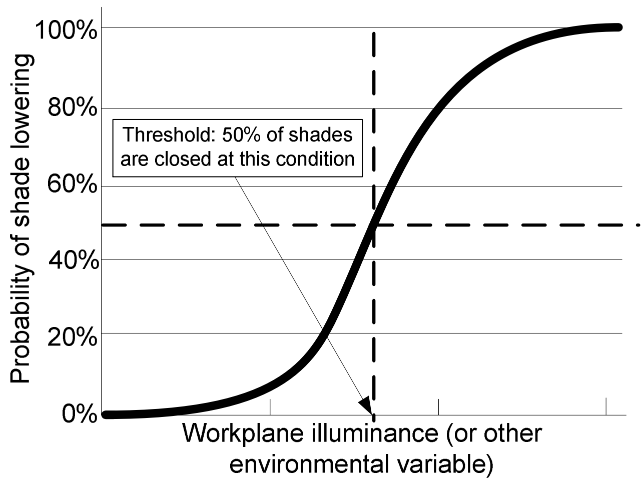


Figure 5: General shape of single-variable logistic regression models. The ordinate could also be: probability of shade raising or mean shade occlusion.

Inkarojrit [25] created models for the probability of closing shades; not opening them. He found that single variable logistic models involving window luminance, background luminance (luminance measured at the eye), or vertical solar radiation on the window were all reasonably good predictors of whether a shade would be closed. These models predicted actual shade movement with accuracy of 72-78%.

Haldi et al. [17] took an approach that was unique to the studies, in that they divided the models into probability of movement upon arrival, before departure, and finally all intermediate times. They found that, on average, on arrival 2.3% of occupants closed their blinds and 1.4% opened them. The best predictor for closing actions (both blinds of upper and lower façade) is the interior horizontal workplane illuminance and for opening actions it is the original (before morning arrival) blind position. They developed a model for the probability of both opening and closing the shades as a function of horizontal illuminance during several different occupant events (e.g., arrival in the morning) with considerable success. For instance, upon the arrival of occupants, the probability of lowering their shades varied approximately linearly from about 0% at 0 lux to 15% at the highest recorded illuminance. Haldi et al. [17] initially explored an additional model to predict shade actions immediately before occupant departure, but found that the daytime model adequately predicted behavior during this time.

5.1.3 Limitations of single-variable models

As discussed in the previous section, many of the environmental factors alone are not good indicators of thermal and visual discomfort, and therefore shade movement or positions. Thus, single-variable models may fail to fully capture occupant operation of shades; particularly if the input variable is low-level (e.g., horizontal solar radiation).

A limitation to logistic regression specifically is that it is most suitable for systems with only two positions or events. In the current case, roller shades and Venetian blinds normally have an infinite number of continuous positions between open or closed. This was partly resolved by having the model predict the direction of movement rather than the absolute magnitude of the movement [37].

The single-variable regression models reviewed were typically for different façade orientations and, in several cases, different ranges of solar radiation. Thus, the models are only quasi-single variable.

5.1.4 Multivariate models

The experimental results described in the previous section suggest that occupants control their shades according to several criteria and that single variables may not be strong enough indicators. Both Haldi et al. [17] and Inkarojrit [25] extended their logistic regressions to multiple variables (up to four). They both found that increasing the number of variables beyond one increased the predictive accuracy of the models, in terms of how well the logistic curve fit to the observed data, but with diminishing returns. Readers are encouraged to read the cited papers for detailed reports of modelling methodology and results.

Haldi et al. [17], who found the horizontal workplane illuminance to be the single best predictor, explored adding a second variable to their model. The best candidate, in terms of model accuracy, was found to be the starting shade position. Haldi et al. [17] found that a third predictor did not significantly contribute to model accuracy. As previously noted, they created different models for different times of the day, and for the upper and lower façade shades present in their building.

Inkarojrit [25] reported that of the 13 different bivariate and multivariate predictive models that he explored, the ones with more variables were almost always more accurate. However, in many cases the gains were marginal and the more complex models are not necessarily the most practical in application, especially when variables such as a self-reported brightness sensitivity is used - which cannot be measured with sensors. The model's sensitivity with respect to brightness sensitivity highlights the high level of variability of preferences and behavior between occupants. Haldi et al. [17] accounted for this variability using Monte-Carlo simulations within their shade movement prediction model. Inkarojrit's [25] model (at 89% probability of correct prediction) included the average luminance from the window, the maximum luminance from the window, the solar radiation on the façade, and the self-reported brightness sensitivity.

Daum et al. [50] examined 25 state variables and found that there was no benefit to including more than three – a very significant result. Current multivariate modelling approaches are relatively complex and would benefit from simplification before widespread application can be expected. The inclusion of higher level comfort metrics, as previously discussed, is proposed as a means of simplifying the mathematical models as to reduce the number of independent inputs.

5.1.5 Validation of models

Given that one of the long-term objectives of studying occupants' shade operation preferences is to create a universally applicable mathematical model of such behavior, these models should be tested with a variety of occupants and other buildings. None of the reviewed studies attempted to test their models outside of the scope of their own subject building or timeframe. However, several researchers successfully compared their models to previous studies and found many similarities. Reinhart et al. [16] found a similar correlation between MSO and workplane illuminance as Inoue et al. [23]. Inkarojrit [25] found this same correlation to apply to one point in his study.

Recent research qualitatively compared findings to the earlier studies with considerable success; thus there is good consensus on the most significant factors affecting shade use and the trends. While some contradictions exist, this is normally explained by an anomaly such as unique building feature, occupancy pattern or measurement type in the disagreeing study/studies.

For quantitative validation, Haldi et al. [17] implemented an algorithm based on their probability models and a Monte-Carlo method to predict shade positions at any given moment. The best of his models predicted MSO to within 4 percentage points. However, they under-predicted lowering actions by about 30% and raising actions by about 20%. Inkarojrit [25] took a simpler approach and assumed that all shades are in equal positions based on the MSO that his model predicts. Premised the fact that the MSO is constant over the course of a day, he calculated the predicted MSO based on the highest incident solar radiation on the façade. The comparison with the mean observed MSO showed that the model was overpredicting. Inkarojrit [25] compared what his model predicted for a single set of conditions to that of Reinhart [16] and Inoue et al. [23] models and found it to be in relatively good agreement.Future studies should test their models on: i) another population or time period, and ii), on other buildings.

5.2 Application of occupant behavior models to BPS

Though none of the 12 main reviewed studies extended their statistical models to BPS, several researchers have applied simplified behavior models to BPS. Tzempelikos et al. [2] incorporated a simple algorithm that closed shades during occupied hours if external solar radiation exceeds 120 W/m^2. Relative to a case with the shades closed, this reduced cooling energy by 50% and total energy use by about 12%. Reinhart [22] implemented a blind and lighting use algorithm in Litghtswitch-2002 that resembles findings from his work [16], as well as the findings of Lindsay et al. [19] and Inoue et al. [23]: blinds are closed if vertical solar radiation on the façade exceeds 50 W/m^2 and slats are adjusted to prevent direct solar radiation on the workplane. Reinhart [22] acknowledges potential limitations and areas for future work including incorporating: the wide variety of different user types, the stochastic nature of shade control, privacy issues, thermal comfort, seating orientation (for calculations of potential glare), and ease of control. Bourgeois et al. [51], who implemented the algorithm into ESP-r simulation engine [52], stated that one of their biggest challenges was to ensure that all the thermal interdependencies between occupants, lights, and blinds were properly addressed.

Many of the most common simulation engines [52-55] have some facilities for incorporating shade controls. One of the more powerful tools for implementing shade control is the building simulation package EnergyPlus [54]. It has about 20 possible control schemes, including illumination, glare, outdoor and indoor air temperatures, solar radiation, and several combinations of those. Further, more advanced controls (e.g., based predicted thermal comfort), can be implemented using energy management system (EMS) features [56].

Many of the reviewed studies recognized that occupants should be treated as having individual preferences and behaviors, to truly appreciate the complexity of shade use. Despite this, modern building performance simulation normally treats occupants as being identical in behavior, heat gains, and schedules. Nicol [29], who studied occupant control of numerous comfort-related building systems, stated that while occupants are clearly influenced by physical parameters (e.g., air temperature), the relationship is not precise, but rather, stochastic. One approach to increase the diversity of modelled occupants that has been proposed is to use agent-based modeling [57]. This associates each building occupant with a probabilistic model based on their job role, tasks, and thermal comfort needs. Agent-based modeling for BPS has not yet gained widespread popularity.

5.3 Automated shade controls

Numerous researchers have encouraged the implementation of shade controls as a means to simultaneously improve the indoor environment and reduce energy use and peak loads [2, 23, 51]. While the results of many of the present studies would suggest a wide variety in observed shade use between occupants, significant evidence suggests that occupant preferences are similar but that they have different propensities to change shade positions to improve comfort. The main studies reviewed here found that providing occupants with easy-to-use controls increases their frequency of use by as much as three times [34]. While some researchers have found some variation in occupant preferences [25], control algorithms could be programmed to incorporate these individualized preferences [58, 59] so long as the same occupants reside in a space for extended periods (months or years).

Despite the clear advantages of automated shading control, occupants have been found to have a low tolerance for undesired changes [16]. Ease of overriding automatic setting [16], delayed reactions to avoid frequent oscillations [60], and quiet operation to avoid distraction [23] are all important features of automated shade controls. Venetian blinds (horizontal type) tend to be the preferred in automated shading device controls applications because they can be controlled to prevent direct solar gains while still allowing views and diffuse light in and their slat angle can be adjusted with minimal energy consumption or noise.

Another major design decision in automated shade control is: open-loop versus closed-loop An open-loop system computes the position of the shade through control algorithms, using a single input (e.g., from a sensor monitoring the exterior solar radiation incident on the façade), without using feedback to determine if the output (e.g., workplane illuminance level) has achieved the desired goal [61]. On the other hand, a closed-loop control system uses a sensor to monitor the output (e.g. workplane illuminance level) and feeds the data to the controller which adjusts the position of the shade appropriately. If the relationship between input (e.g. exterior solar radiation incident on the façade), the position of the shading system and the output (e.g., workplane illuminance level) can be modeled by mathematical correlations, open-loop control can be more effective than a closed-loop one, as it is independent from the interior environment and is more cost effective as with one sensor several shading systems can be controlled. In contrast, a closed-loop control achieves higher response and accuracy at the output if the interior environment is long-standing (e.g. repositioning of the office furniture or change of the office carpet can destabilize a closed-loop controller). However, a sensor is generally required for the control of each shading systems, increasing the initial cost. Closed-loop configurations are particularly useful if the shading control is combined with lighting control [61]. Mukherjee et al. [61] proposed a control system whereby an exterior sensor is used to detect glare conditions, while an interior sensor is used to ensure that the combined illuminance from daylight and electric lighting is adequate.

A number of applications of automated shade controls have been published in the literature [60, 62-65]. Inoue et al. [23] implemented controls based on their findings from the observation of manual control. Among the control schemes they tested was to have the blinds' slat angle vary with time so that no direct solar penetration occurred above a certain threshold. The building in Reinhart's [16] study had blinds whose bottom slats opened and closed when the exterior vertical illuminance was below and above 28 klux. But analysis of the override events strongly suggests that this algorithm could be improved; 45% of the automatic adjustments were overridden. Even more fascinating, 88% of these were to reverse a retraction. Tzempelikos et al. [66] extended the application of controlled shades to a public space in an airport. They performed detailed measurements to determine the illuminance level sensed by a ceiling-mounted illuminance sensors when the sky is clear. Using this information they controlled the roller shades to be lowered to 1 meter – so that no occupants would be exposed to direct solar radiation - when that sensor measures above 800 lux.

6 FAÇADE AND MOVABLE SHADING DEVICE DESIGN RECOMMENDATIONS

Despite the energy and individualized occupant comfort implications of good movable shading device design, they are normally an after-thought to energy-related design decisions (e.g., HVAC type and sizing) [2]; in-part because they are not given credit by most building energy standards, as previously noted.

This section provides a brief review of façade design recommendations, with an emphasis on shading device design and integration. First, numerous shading device lessons can be learned from the studies that were previously reviewed in this paper. Table 2 indicates some interpretations and design implications of different shade operation patterns.

Table 2: Façade design cues inferred from occupant manual shade control

Observed shade patterns	Implied preferences	Design implications
Majority of shades are open all of the time	Glare, solar gains, and privacy are not problematic	Shades may not be necessary for achieving solar controls (e.g., fixed shading is present or the façade is north-facing) and privacy; windows could be smaller than optimal or than preferred by occupants
Majority of shades are closed or mostly closed all of the time or occupants devised a method to permanently block windows (e.g., with paper or furniture)	Glare, solar gains, and privacy are problematic and/or the effort required to adjust them exceeds benefits (views and reduced electric lighting use)	Occupants are generally not exploiting the extent of the fenestration; windows should be smaller and equipped with easily-operated shading devices that encourage more frequent adjustment to adapt to changing conditions
Shade positions are frequently changed	Weather-related or occupancy conditions likely change often, so occupants are using shades to adapt accordingly	Automatically controlled shades or well-designed fixed shading devices (e.g., external fixed louvers) could be implemented. Windows are likely reasonably-sized for the application.
Shade positions consistently vary significantly between sections/stories of the building	The building may have multiple uses (e.g., offices, residential, and theatres)	The shades are serving their purpose by providing flexible visual and thermal conditions. Unless space uses are known prior to construction, there may not be major design-altering conclusions for this situation.
Shade positions vary significantly by orientation	Occupants are likely responsive to solar geometry and intensity	Façade design (including glazing type, window size, fixed shading, and movable shading) should be tailored to orientation.

Incorporating shades design into an integrated building design remains a challenge because of the uncertainty of their positions. That is, optimistically assuming that the shades will be in the optimal position to minimize heating and cooling loads (e.g., all closed in the cooling season when there is incident solar radiation) could result in HVAC under-sizing. However, observed results in this review suggest that in the absence of mechanical cooling, occupants are more responsive to thermal conditions and tend to position shades accordingly [25]. Thus, one design approach would be to slightly undersize HVAC and expect occupants to play a more active and adaptive role for their comfort.

Automated motorized shades can increase, but not completely eliminate, the uncertainty of shade positions and the corresponding thermal loads and electric lighting because of occupant control overrides. However, by studying the occupant shade position preferences (reviewed in this paper) and the underlying thermal and optical indoor conditions that occupants attempt to achieve through shade positions, shade control strategies can be significantly improved so that overrides are mostly reduced to occasions when specific lighting conditions are required (e.g., darkened room for presentations).

Empirical evidence from the studies reviewed in this paper suggest that ease of manual control of shades (e.g., motorization [16]) causes occupants to move them more frequently . Thus, if the budget allows them, motorized shades are preferable from an energy and comfort perspective and for integrated design (e.g., reduction in HVAC capacity). Manual controls for motorized shades should allow fine adjustment (i.e., hold button to move and release to stop) and extreme (i.e., single button to fully raise and lower). The latter option saves time and occupants appears to be valued [27]. The flexibility to operate some or all shades for an entire office or room (or at least for each façade orientation) is important to maximize utility (e.g., prevent direct solar radiation from entering while obtaining high levels of daylight from diffuse solar). For rooms with multiple occupants (e.g., meeting rooms or classrooms), the control panel for all shades should ideally be located centrally and on a single panel).

Motorized or not, the reviewed studies have indicated that occupants are more likely to move their shades to adapt to changing conditions if controls are more individualized such that they can improve their comfort without concern for possible undesirable effects on others. With the trend towards cubicles and fewer offices, this design consideration becomes more challenging and favors solutions that do not involve manual control (e.g., automation or fixed louvers).

Another approach to solar shading design that eliminates much of the uncertainty is to use fixed shading devices (e.g., overhangs, sidefins, lightshelves, and fixed louvers). Such devices use static geometry and material optical properties alone to reduce direct solar from entering a building, while admitting high levels of diffuse solar radiation; often deeper into the space [67]. These devices can be intentionally biased in varying the amount of solar radiation transmitted through adjacent windows either seasonally or daily. Torcellini et al. [68] demonstrated the strong potential for fixed louvers to block essentially all direct solar transmittance year-round, while reflecting much of it deeply onto the highly-reflective (>80%) ceiling to increase daylighting to a level where the space is 100% daylit during most occupied hours. Since this building – National Renewable Energy Laboratory's (NREL's) Research Support Facility (RSF) - had a very specific and absolute energy target (25 kBtu/ft^2/year; 79 kWh/m^2/year) [68], there was emphasis on increasing the certainty of performance from the beginning of design. Furthermore, fixed louvers are particularly appropriate to the RSF because the space is dominated by cubicles and thus, the adjustment of movable shades would have impacted numerous occupants and would likely have suppressed the frequency of shade adjustment events [17].

A disadvantage to fixed shading devices is their lack of controllability for varying solar shading requirements and the fact that they may be designed to perform relatively well for all seasons but do not normally provide optimal behavior all of the time (e.g., at extreme solar altitudes and azimuths). Furthermore, fixed louvers may not provide significant privacy and they are less effective at reflecting daylight inwards in overcast conditions [69]. Virtually all types of fixed shading devices are less effective at reducing solar gains for non-south facing facades because they would have to be excessively deep to block direct solar radiation at low solar altitudes [11]. For this reason, buildings that are oriented with wider north and south facing facades are preferable where the site permits it [70]. Thus, there is still a strong case for movable shadings devices: to significantly reduce solar gains and glare when the solar altitude is low and solar penetration depth is high (e.g., late afternoon for west facades). Movable shades can also be helpful for reducing glare for the south façade in the winter, north facades in early summer after sunrise and before sunset, and for activities requiring highly controlled illuminance levels.

Integrated façade-related building design extends to inside of the building. For instance, furniture can be oriented to minimize the impact of glare or the chance of incident solar radiation on building occupants. RSF designers set the first row of cubicles several meters back from the façade, such that the workplane almost never receives direct solar radiation. Also key to the success of that design is the low cubical dividers and high-reflectance ceiling – both of which improve daylight penetration into the 18-meter deep office area [68]. Positioning VDUs that face normal to the facade has been shown to minimize glare [70] and should be considered early in design.

The three-section façade, a concept first articulated by Tzempelikos et al. [71], has gained significant popularity. It includes an opaque bottom (spandrel) section, a middle (viewing) section, and a top (daylight) section (see Figure 6). The principle is to select materials and shading devices that are the most suitable for the function of the particular section, rather than having a single continuous window or other façade component from floor to ceiling. The bottom section of the three-section facade, which would contribute little to daylighting [72] is normally opaque and ideally well-insulated. This section could also be used to actively collect solar energy (e.g., with photovoltaics, solar thermal collectors, or a hybrid of the two: photovoltaic/thermal (PV/T)) [73, 74].

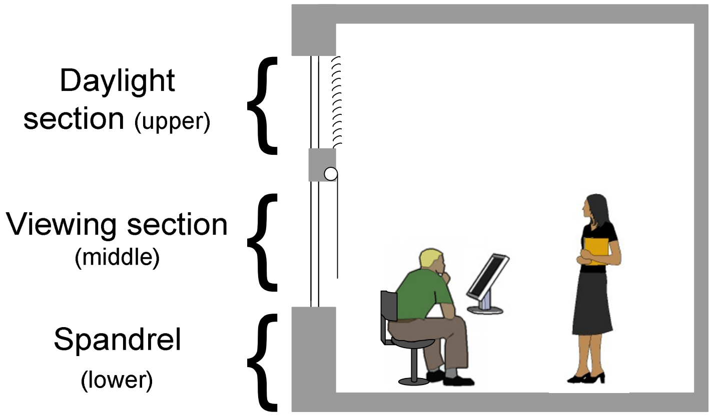


Figure 6: Section view of the three-section facade concept (drawn to scale)

The middle section, which normally extends from the workplane (~0.7 meters above the floor) to about 1.5 to 2 meters above the floor, allows visual exchange between occupants (primarily in a seated position for office workers) and the outdoors. This façade section is moderately useful for daylighting, but has limited daylight penetration depth because floors – the surface that most incoming daylight will first hit – usually have a low reflectance to prevent glare [72]. Therefore, windows with low visible transmittance in the viewing section are adequate and even preferred east and west-facing facades, for which solar gains are hard to control via fixed shading devices. The middle/viewing section of the façade can exploit fixed shading devices to significantly reduce unwanted solar gains – particular for south-facing facades - while providing unobstructed views. In the seated position, occupants may not even be aware of fixed shading – particularly overhangs and lightshelves. The RSF has viewing section windows that are almost always protected from direct solar radiation using deep overhangs and sidefins. Overhangs can also serve the secondary purpose of reflecting visible light through the top façade section, onto the ceiling where it can, in turn, be reflected onto the workplane deep in the zone.

The top/daylight section of the façade has the primary function of admitting high levels of daylight deep into the space while protecting occupants from glare and excessive solar gains. This section should use glazing with a high visible transmittance (unless the windows are excessively large). Depending on the climate, building loads, and orientation, the SHGC should be selected – if possible – to maximize useful solar gains and reflect adverse solar gains. It is not always necessary to have two distinct glazing types with a frame in between the viewing and daylight section of the façade if architectural continuity is prioritized because several coating technologies (e.g., fritting and semi-transparent PV) can be used. Fixed continuous shading devices (e.g., overhangs and sidefins) that reduce direct and diffuse solar radiation on the top section can significantly hinder daylighting performance and should only be used if no fixed or movable shading devices are present to protect occupants in the perimeter zone from direct solar radiation. Furthermore, if excessive solar gains occur, the vastly preferred solution is to merely reduce the glazing area. Fixed louvers have been successfully applied to the daylight section (e.g., RSF) such that daylight penetrates to the back of the 18 meter-deep floorplate.

Among the two glazing sections of the three-section façade, movable shading devices, if present, should be independently operable and possibly have different properties. Numerous buildings (e.g., those studied by Reinhart et al. [16] and Haldi et al. [17]) use independently controlled shades, while another possibility is to use a single shade whose properties vary with height [2].

Generally, a consensus has been reached that modestly-sized windows are preferable for building energy performance, rather than the very large windows that are currently common practice. The benefit to daylighting and views, to some extent, diminish with increasing WWRs beyond a certain point (which is quite dependent on building characteristics and climate). For example, Tzempelikos et al. [2] demonstrated that there was little benefit to the contribution of daylight beyond a window-to-wall area ratio of 30% for a south-facing façade in Montreal. Meanwhile, heat loss and solar gains increase approximately linearly with window area (assuming a well-insulated opaque section). Additionally, the thermal comfort implications of large windows are very critical. The angle factor between a very large window and a nearby occupant approaches 0.5 [11], meaning that glazing temperature can influence mean radiant temperature by as much as 50% and operative temperature by about 25%. This means that air temperature or surface temperatures (for radiant heating and cooling systems) must be controlled to compensate – likely at significant cost. Mean radiant asymmetry – a situation that occurs when an occupant's body experiences significantly different radiant temperatures in opposite directions [75] – is also a concern; both when glazing is warm or cold. The risk of these sources of discomfort can be reduced, but not necessarily eliminated with shades [6]. Thus, the importance of selecting the appropriate glazing area and type – a virtually permanent design decision – cannot be discounted. However, for existing problematic facades, the upgrade to good movable shades may prove to be a cost-effective and relatively non-invasive option (i.e., relative to window upgrades). The importance of good movable shading design and controls increases significantly with higher WWRs. Though 40% is a common WWR limit for prescriptive building energy standards (e.g., ASHRAE 90.1-2010 [13]), it can be exceeded using performance approaches (e.g., compensating with higher HVAC and lighting efficiencies).

In general, ideal glazing properties depend on climate, building type, and façade orientation. Glazing with a low U-value, medium to high visible transmittance, and low SHGC is usually ideal. Though higher SHGCs for south-facing glazing may be advantageous to reduce mechanical heating, many office buildings already have relatively high heat gains from equipment and people. Thus, mechanical cooling may be required for all but the coldest months, even in cold climates. Furthermore, offices often do not have sufficient exposed thermal mass (e.g., structural concrete) to adequately moderate air temperatures resulting from high solar gains.

The two main types of movable shading devices – roller shades and venetian blinds – each offer performance and practical advantages and disadvantages. Roller shades, which are usually deployed from top to bottom, are mechanically-simple, normally allow any level (continuous) of deployment (i.e., occlusion), and allow the top part of the window to be blocked while providing views. This is most suitable if solar altitude is high, but may require complete deployment when the solar altitude is low, thus potentially eliminating views and adequate daylight – depending on shade transmittance. A less common alternative is bottom-up roller shades. This configuration of shades can protect occupants who are sitting adjacent to the facade from bright conditions while still admitting daylight at the top of the window. The disadvantage is the reduced view – especially for occupants in the seated position. However, from an energy and visual comfort perspective, bottom-up shades have been shown to reduce lighting energy use by 21 to 41% relative to a top-down roller shade in one case study [76].

Venetian blinds generally offer greater flexibility than roller shades because they have two degrees of freedom: slat angle and level of deployment. They can also provide the service that fixed louvers do: blocking direct solar radiation while reflecting mostly diffuse solar radiation into the space. Though there is minimal research on the ease of manually adjusting mechanically driven shading devices, some evidence suggests that occupants find it easier to adjust slat angles than deploy venetian blinds [27].

Unless the venetian blind suspension system (e.g., cords) are concealed within a track, they often have small holes for their mechanism which can allow direct solar radiation through. Furthermore, it is difficult to achieve a perfect light-tight seal between non-rigid slats. Thus, it is generally easier to achieve total blackout (e.g., for presentations and other light-sensitive activities) with roller shades. Vertical blinds do not offer advantageous upward daylight reflection and may be particularly prone to rattling if there are drafts because they are usually only fixed at the top. Venetian blinds are more prone to dust accumulation than other types of shades because of their horizontal surfaces, and thus reduction in reflectance, increased cleaning requirements, and indoor air quality are all important considerations of their use in buildings.

In general, the greatest solar control can be achieved having shades towards the exterior of the glazing (e.g., outside the window or between panes) before solar radiation reaches some or all of the glazing layers [11]. While exterior shades have gained considerable market penetration in Europe, they remain rarer in North America [77]. The effect of high wind loads on exterior shades – especially for high rises - remains a concern but can be mitigated with double facades. In colder climates, exterior shades are exposed to snow and ice, which could interfere with mechanisms [78]. A further advantage to having exterior shades (rather than interior shades) in such climates is that trapping humid air near cold window surfaces (i.e., isolating it from conditioned indoor air) could cause condensation [78]; particularly for cold climates and/or glazing with a high U-value. Exterior shades are less accessible for cleaning and maintenance and can add to the maintenance cost of a building.

Electrochromic windows, which contain a film whose transmittance can be altered by applying a voltage [79], offer similar solar control to interior shades, but still face the design and control challenges and considerations of mechanical shading devices.

Optimal shading device optical properties (reflectance, absorptance, transmittance, and specularity) are dependent on numerous factors including climate, building type, and façade orientation. Several software tools (e.g., Window 6 [80]) and reference manuals (e.g., ASHRAE Handbook - Fundamentals [11]) provide properties for a limited number of effective U-value and SHGC for different shade properties and configurations. Calculations and experiments to determine total fenestration system properties are considerably more complex than the equivalent without shading devices [11], and thus, data on a variety of configurations is somewhat sparse.

Usually, it is advantageous to use highly-reflective shades such that they can significantly alter the total façade optical and thermal properties relative to glazing alone. Such shades are usually white or metallic in color and have low openness factors (ratio of perforations (e.g., holes) to total shade area). Diffuse shade finishes are normally preferred over specular finishes to reduce glare and better distribute daylight. Low shade absorptance – particularly for interior shades – is important if rejection of solar heat gains is desirable because a significant portion of absorbed solar radiation ultimately convects and radiates to the interior air and surfaces. This effect can even cause higher peak cooling loads than having no shade at all because low thermal inertia shades almost immediately transfer heat to the air rather than allowing it to be absorbed by more massive surfaces [81].

Further operational flexibility is offered by either having two layers of shading devices (e.g., low and high transmittance) that can be operated in an *either* or *both* fashion. Bi-color/double-sided (e.g., black and white) venetian blinds also permit greater flexibility since the effective SHGC and visible transmittance of the façade system depend on the outward facing color. Other than shade color and other material optical properties, another variable is openness factor which is controlled by perforating blinds or controlling fiber spacing in woven materials. Shade transmittances of greater than 5% cannot completely eliminate the risk of glare [69], though having a higher average transmittance (e.g., high transmittance at workplane height and lower towards the ceiling) has the potential to offer better energy performance that uniform openness [2].

The decrease in U-value from shading devices is fairly minimal unless a relatively air-tight seal is made between the shade and window frame (e.g., with a track). Plastic and metallic shading devices offer minimal insulating value themselves, though curtains do offer some. While movable louvers can achieve good air-sealing between slats, less rigid venetian blind slats generally cannot. Venetian blinds between glazing layers has been experimentally verified to modestly reduce the U-value – by up to 20% in a fully deployed position with slats closed [82]. However, Gamet et al. [82] found that positioning slat angles at between 30° below and 30° above the horizontal actually increases U-value by up to 10%, relative to having no blinds at all. In general, U-value can be quite sensitive to slat angle because of the complex convective flows that can occur between them. The insulating benefit of movable shading devices is greater – at least in relative terms – for low-performance windows. For the purpose of reducing fenestration system U-value, alone, a higher performance window provides greater certainty. The aforementioned condensation risk and resulting damage can be a major design consideration in cold climates and can be improved with higher performance windows.

In conclusion, modestly-sized windows with fixed shading devices is the preferred configuration to simultaneously optimize energy performance and occupant comfort. However, fixed shading functions best for south facades and does not perform well for non-south facades; nor does it offer privacy or the ability to darken a space. The three-section façade allows fenestration system properties to be tailored to the particular function of the façade at different heights above the floor. Facades are a complex building component and should ideally be designed using dynamic simulation tools so that the numerous trade-offs can be quantified for the specific climate, building use, façade orientation, and design goals. Future research and development is needed to incorporate a greater number of façade technologies into these tools and a larger database of optical properties of shades is also required.

7 CONCLUSIONS

This article reviewed four major topics related to occupant use of manually controlled shades in office buildings: observational study methodologies, empirical results, applications of the results, and finally, façade design principles. In all, twelve main studies were reviewed and they generally drew the same qualitative conclusions, with some minor exceptions. However, the specific and unique nature of each study (e.g., façade design, occupancy patterns, or observational methodology) makes it difficult to quantitatively compare the studies to each other. Some major conclusions are:

- Most occupants are fairly inactive, changing shade position only on the order of weekly or monthly; and some not at all.
- Despite this, shade positions are often quite deliberate and are chosen by occupants to balance views to the outside with visual comfort.
- Many surveyed occupants have cited difficulty of or effort to operated shades as a reason for their lack of activity. Thus, it is important to improve the ease of use of shades to encourage occupants to be less reliant on energy-consuming technologies and more on passive means.
- While worsening visual conditions often lead to prompt shade-closing actions, occupants are slower to respond to improving visual comfort conditions because there is not sudden stimulus.

- Occupants tend to operate shades based on recent and current weather conditions rather than in anticipation of future conditions. For this reason, motorized shades with predictive controls represent a potential for significant energy use reductions.
- The biggest motivation for closing shades is to prevent glare and other forms of visual discomfort. Most researchers found solar intensity and geometry to be leading contributors to occupants taking action.
- Thermal comfort does not appear to be a big motivator, as fewer studies indicated that occupants change their shades in an attempt to control it. However, this is likely due to the fact that HVAC systems maintain reasonable comfort conditions. In the absence of air conditioning, occupants are more inclined to use shades to improve thermal comfort – namely to prevent excessive solar gains.
- If occupants have control over their lighting or if their lights are automated to turn off during periods of adequate daylight, they are more inclined to control shades to achieve desirable lighting conditions.
- Occupants in shared offices tend to be less active shade users and less responsive to changing weather conditions. This is thought to be out of courtesy and in recognition that occupants vary in preference for visual and thermal conditions and that differently positioned occupants are affected by shade position in different ways.
- There is considerable value in talking to building occupants, even if informally, before drawing strong conclusions from shade use studies. There may be a particular reason for a behavior that cannot be explained by environmental conditions alone.
- Lessons relevant to façade design can be learned from occupant shade use patterns. In the extreme conditions, if the shades are always open they may not be necessary (e.g., the façade may rarely encounter glare conditions) and if they are always closed, then the shades should have been designed/selected to be more easily controlled or the windows should probably have been designed to be smaller because occupants clearly do not value views and daylight above the potential for glare and/or overheating.

Future observational studies must attempt to increase the universality of results because such studies are quite resource intensive and not necessarily justified by potential improvements in the subject building alone. Many of the studies considered weather conditions, façade orientation, interior illuminance, and interior air temperature; however, none of them attempted to quantify higher level thermal or visual comfort indices. The current authors propose that future researchers quantify these so that the threshold comfort levels that prompt shade movement can be estimated. If this were done, the peculiarities of different building designs (e.g., upper and lower shades, light shelves, external shading, different glazing technologies) could be removed from the behavior model. As the literature stands now, it is difficult to directly apply behavior models to other buildings; nor have any researchers attempted to do so, in detail.

Study periods should extend well beyond single days to weeks or months. However, there does not appear to be a significant correlation between shade use and season; meaning that whole- or multi-year studies may not be justified. While total shade movement is very slow, a relatively high sampling frequency of at least twice daily (and ideally hourly) is necessary to capture events that cause occupants to move their shades.

Studies should include as big a population sample as possible. While it is too early to conclude how big a sample is required to study a population that represents occupants as a whole, many of the researchers who used samples sizes on the order of 10 to 20 and were able to model them with considerable accuracy, recognized that their models may be limited to that particular set of people.

Future researchers must increase the reported level of building-related details (e.g., window area, window type, major external solar obstructions, etc.) for their studies; particularly if only weather conditions – and not interior conditions - are reported. Furthermore, transparency of data and reporting of all measured data would be extremely useful. This is the only way that future researchers can confidently validate their own results.

Current mathematical behavior shade models are quite complex and unlikely to be applied by building designers or shades controls professionals. Future work is needed to simplify models or to incorporate them into building performance simulation software, just as it has started to be done for occupant lighting controls. In fact, this conclusion can be drawn for most aspects of occupant behavior with regards to BPS.

While most shade use studies are focused on commercial and academic buildings, it should be extended to residential buildings. Residential buildings have numerous characteristics that would lead one to expect significantly different shade use patterns: occupants are often absent during periods of peak solar radiation, occupants are often responsible for energy costs, there are more opportunities for adaptive comfort (e.g., clothing and activity levels and relocation to a more comfortable space within the home), and privacy is a greater concern. Contrary to what the presently reviewed studies indicate for office buildings, residential occupants are likely to consider future weather conditions when deciding to operate shades because of the greater perceived ownership of the space. For instance, consider the fact that many car-owners deploy large shading devices on their windshields to reduce solar gains, for the sake of improving future comfort conditions.

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