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Abstract

In recent years, research has emerged to quantitatively and qualitatively understand occupants' interactions with buildings. However, there has been surprisingly little research on building interfaces and how their design, context (e.g., location), and underlying logic impact their usability and occupants' perceived control, as well as the resulting comfort and energy performance. Research is needed to better understand how occupants interact with building interfaces in both commercial and residential applications; both applications are important to address as there are many differences in interface types, level of control and understanding, and even expectations of engagement. This paper provides a cursory review and discussion of select common building interfaces: windows, window shades/blinds, thermostats, and lighting controls. The goal of this paper is to review literature related to these human-building interfaces to explore interface characteristics, current design and use challenges, and relationships between building interfaces and occupants. Human-building interface interactions are complex, more research is needed to understand design, use, and characteristics. Common themes emerged throughout the literature review to explain occupant interactions (or lack of interactions) with building interfaces, which included thermal and visual comfort, ease and access of control, interface/control placement, poor interface/control design, lack of understanding, and social-behavioral dynamics.

1 Introduction

In the past, it was common for occupants to have a direct connection to (and control of) the sources for building control, for example, heating (e.g., fireplace) and ventilation (e.g., operable window). However, as buildings become more complex, these basic building functions now oftentimes take place outside of the room, or even the building (e.g., district heating). In these cases, direct control of building services may be remote or intentionally removed to prevent occupant control, e.g., [1], [2]. This widening gap between building systems and occupants can remove real or perceived control over building systems, often at the detriment of occupant satisfaction, productivity, and comfort [3]–[6]. Behavioral interventions are commonly used to encourage energy-efficient interactions, but these will only work to the extent the building interface allows [4]. Furthermore, if occupants are given control, it is paramount they understand how to operate or control the given building interface to prevent unintended comfort or energy outcomes (e.g., [3], [7]). In contrast to specialized equipment (e.g., in hospitals and labs), building users typically do not receive any training or education on how to use or interact with interfaces, and instructions or signage is rare [3], [8].

Much research within the domain of the built environment has largely focused on building systems (such as heating, ventilation, and air conditioning (HVAC) and lighting), building envelopes, occupant comfort, and behavior, e.g., [9]–[12]. However, there has been surprisingly little research on building interfaces and how their design, context (e.g., location), and underlying logic impact their usability and occupants' perceived control, as well as the resulting comfort and energy performance. To optimize both building (e.g., energy use) and occupant outcomes (e.g., comfort and health), a more holistic understanding of building interface characteristics and associated occupant behavior is critical [4].

While interface design is a mature topic in the fields of human factors and human-computer interaction [13]–[16] from which research strategies and best practices can be exploited, many characteristics make building interfaces fundamentally different than other designed interfaces and systems such as websites and vehicle dashboards . For example, buildings are typically designed as "one-of-a-kind" and, therefore, the context of building interfaces changes with each application and user group, and they are not (or seldomly) considered in user testing or expert involvement during the design of interface products. In addition, the building design process is fast paced. Seemingly minor decisions, such as interface selection, may receive little attention as designers and builders work to maintain aggressive budgets and project schedules. Often, technicians or contractors make decisions about interfaces on-site with little in-depth thought about users (i.e. occupants) [17], [18]. This is slowly changing with modular construction innovations and fast paced construction prefabrication and delivery [19], [20]; however, this delivery method of buildings is still new and does not address the existing building stock or new one-of-a-kind buildings.

Thus, future research is needed to understand how occupants interact with building interfaces, how interfaces provide feedback to occupants, and the impact transparency of operations and interfaces on occupants' satisfaction and perceived control. A limited amount of research is available surrounding specific interfaces and their quantifiable impacts. Further complicating these issues, many differences in commercial and residential interface types exist; in addition, national/cultural/regional differences in expectations and operation of interfaces may vary considerably from place to place and at home vs. work [21]. There is a lack of literature surrounding how occupants use different interfaces types; more work is needed in this area. This paper is a first step toward more holistically understanding the complicated relationship between humans and building interfaces.

Understanding building interface use is critical to both human and building outcomes. The goal of this literature review is to better understand building interfaces, design and use challenges, and the relationship between building interfaces and occupant behavior, building energy use, and indoor environmental quality (IEQ) related comfort factors. Both commercial and residential applications are explored throughout the paper, as both applications are important to address, and there are many differences between interface types, level of control, understanding, and expectations of engagement in residential and commercial applications.

This paper provides a review for key issues surrounding select building interfaces: windows, window shades/blinds, thermostats, and lighting controls. Authors acknowledge there are many more building interfaces beyond this list. However, these specific categories were selected to (1) cover those which are most common and have a significant energy and comfort impact, (2) are integral to building functionality (e.g., thermostats, in contrast to entertainment systems and appliances), and (3) based on the availability of relevant literature and research. As this line of inquiry develops beyond this paper, a robust review and analysis of key building interfaces, associated characteristics and corresponding occupant behaviors is critical. To provide a foundation in which to review building interfaces, the next section presents a conceptual model of occupant-interface interactions and the resulting impact on building outcomes. A brief explanation of the methodological approach implemented for this study to explain occupant motivations, behaviors, control and feedback concerning interfaces is also presented.

2 Conceptual Model and Select Interface Definitions

To adequately discuss building interfaces, it is necessary to articulate how the interface categories and human behavior were conceptualized. In the context of this review, the authors defined a *building interface*, as anything the occupant can interact with within a building that may affect: (a) building services, (b) energy use, (c) interior environmental conditions. The interfaces discussed in this review vary from simple switches to complex dashboards.

For this review, the authors followed the work of Polinder and colleagues (2013), defining human behavior as "*observable actions or reactions of a person in response to external or internal stimuli, or respectively actions or reactions of a person to adapt to ambient environmental conditions such as temperature, indoor air quality and sunlight* [22] p.7."

Occupant interactions with building interfaces, as well as their experience of the associated outcomes of those interactions, are illustrated by the conceptual model in **Error! Reference source not found.Error! Reference source not found.**. A variety of factors drive individual occupants to interact with an interface [23]. Those drivers, in combination with the context, and the extent to which an interface provides the occupant with feedback on and control over different building systems, influence how they use the interface. The interface-related behavior then results in a change in the end-use and its related service, such as thermal and visual comfort, and energy consumption. The occupant experiences this change in service through feedback from the space and/or the interface. This review primarily focuses on understanding the interactions between the occupant and the interface, represented by the shaded blue box in Figure 1. The next sections detail research on components of this sub-region, namely occupant motivations for interacting with building interfaces and feedback and control mechanisms that moderate these interactions.

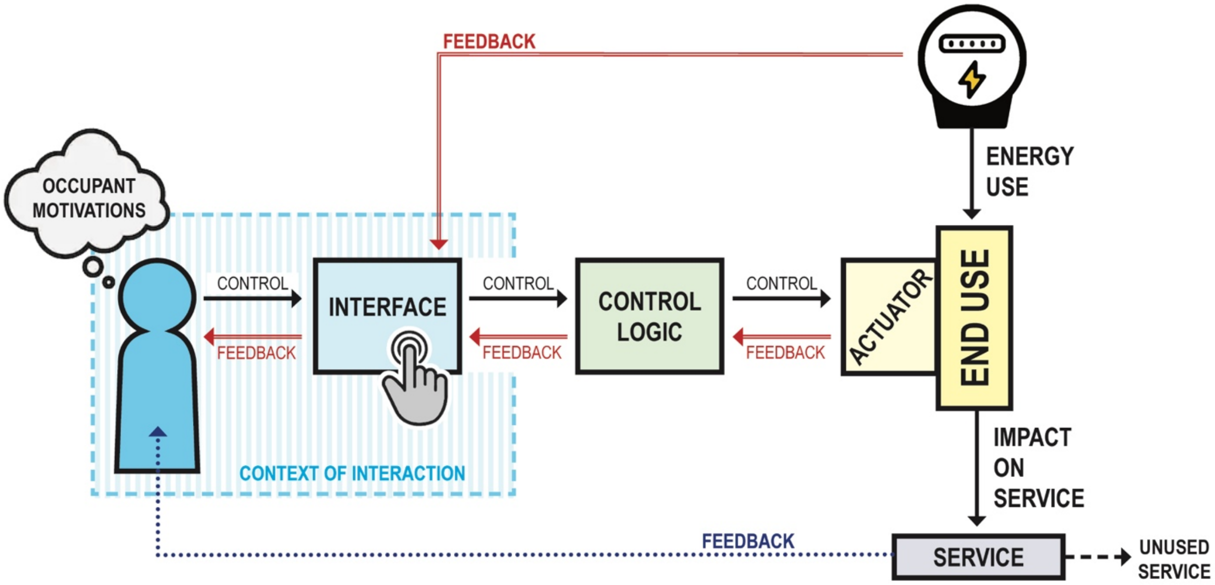

Figure 1: Conceptual model for understanding the occupant engagement with building interfaces.

2.1 Occupant motivation and context of interaction

Many factors drive occupants to interact with the built environment. At a high level, these factors generally fall into the categories of internal and external drivers of behavior [23] [24]. Internal drivers stem from within the occupant and include biological and socio-psychological factors [24]. Biological factors refer to occupant characteristics like age or body composition, in addition to their physiological response to their environment, such as how they react to feeling too warm. Socio-psychological factors include personal attributes such as preferences and habits in addition to broader social factors such as social norms [25]. These socio-psychological factors could include social norms around what temperature or level of clothing is appropriate for office buildings [26] or values surrounding energy conservation [27].

Alternatively, external drivers act upon the occupant [24] and involve the physical environment or wider economic or technical context. These factors include building characteristics, such as equipment or appliances, the time of day [22], and building type, such as residential versus commercial [28]. They also include broader influences such as technological innovation, policy contexts, or cultural or social practices [21], [25]. Examples of external factors include the cost of electricity, the diffusion or availability of smart technologies, and building design principles that may vary with culture or climate. While many attempts have been made to categorize or isolate different factors and their impact on occupants, ultimately, overlap exists between these factors and their influence on behavior [22]. Interfaces often affect many people (e.g. light switches in open plan offices or thermostats at home), which imposes unspoken or spoken social constraints on the degree to which an occupant can adjust an interface for their own benefit; these social science factors are complex and not always well understood in the design and engineering disciplines [3], [17], [18].

2.2 Interface mechanisms: control and feedback

Once occupants are driven to interact with the building, interfaces provide them with a variety of opportunities to adjust their interior environment to meet their needs. The extent to which interfaces provide information and control to the occupant varies greatly; this depends on system type, control logic and actuator capacity. Ultimately, the design and implementation of interfaces impact how occupants use these interfaces and perceive control of their space and broader everyday activities.

2.2.1 Control

Control represents a multifaceted concept with a variety of implications for interface designs. While it is possible to conceptualize control as related to the level of automation or technical control systems in a building, it can also take on a broader meaning with regard to the behavior, beliefs, or perceptions of occupants in the system. [29]. Building interfaces can offer occupants a variety of opportunities to directly or indirectly control the indoor environment with varying levels of automation. Karjalainen [30] discussed various levels of manual and automated controls. On the extreme ends of the spectrum, systems can include either fully manual or completely automated controls. Manual controls require the human to initiate all actions, such as opening a window, whereas full automation uses technology exclusively to automate the activation of building systems, with no possibility for occupant overrides. As technology evolves, an increasing level of automation has emerged in building systems [31]. While digital building automation systems have been used in commercial buildings for several decades, their use in the residential sector is more recent. As these systems become more sophisticated, uncertainty remains regarding the optimal level of automation to achieve building performance goals and occupant satisfaction. The question is not only about whether manual or automated systems yield a more desirable indoor environment, but whether they provide occupants with perceived control over the indoor environment, which is also critically important.

From a technical perspective, the increased presence of automated control in buildings theoretically offers numerous benefits. Modern sensors can collect more granular and useful data. Low-cost microcomputers and inexpensive cloud-computing can translate large volumes of data into optimal control decisions [32]. However, in practice, these benefits are not always realized, and as buildings incorporate increased levels of automation, concerns have risen about the impacts on occupants' experience [33]–[35]. The complexity of these systems runs contrary to empirical evidence, which highlights the importance of keeping interfaces and their related controls simple while ensuring the user understands the design intent how it supports intended building function [3], [5]. In particular, concerns have emerged that increased complexity of automated or intelligent systems may lead to negative impacts on occupant comfort or satisfaction [5], [36].

Qualitative research efforts have revealed occupants prefer to maintain some level of manual control over building systems [30] and automation, especially when initiated by a third party, which may lead to concerns over autonomy and perceived control [37]. Specifically, research has shown that occupants have a preference for direct control over their indoor environment, [5], [38] and the level of perceived control over the indoor environment has an impact on building outcomes such as thermal comfort [28], [39]. Such effects are part of the adaptive comfort theory, which suggests people have a wider comfort band if they have effective means of control [3], [31], [1].

2.3 Feedback

In addition to technical control opportunities, the provision of information to occupants through feedback mechanisms can significantly impact key building outcomes. Occupants receive feedback through interactions with building interfaces and through experiencing the outcomes of actions in the space (for example, feeling warm air from the diffusers or hearing systems turn on or off). Feedback can enable the occupants to learn, understand, interpret, motivate, and/or interact in and with buildings and information can be disseminated visually, auditorily, and/or hepatically, depending on contextual need and available technology. Feedback plays a crucial role in occupants' perception, interaction, and engagement in buildings for sustainable adaptive strategies – particularly for slow responding (e.g., thermal) systems.

Various disciplines, including human-computer interactions, environmental psychology, and ubiquitous computing (ubicomp), have contributed in-depth research on how feedback influences occupant engagement and interactions with buildings. For example, multidisciplinary work by Sanguinetti and colleagues [40] proposes a framework to guide the design of feedback, highlighting the importance of the information provided to occupants, the timing of when this information is presented, and how the information is displayed to the user, components critical to consider during the design of building interfaces.

After the occupant has interacted with the interface, they then experience the change in service associated with the outcome of their interaction (see **Error! Reference source not found.**). Occupants can be frustrated when they do not experience an improvement in comfort in their room or space after interacting with the controls. For example, the thermostat is a frequently used control, and occupants may find it challenging to understand because of the delayed effect in the space. The reasons for this frustration include, but are not limited to the following: functioning of the thermostat, cause-effect, and time delay [4], [41]. If the building is overheated, or if the occupants feel very warm and may leave windows open during winter rather than lowering the thermostat [42], leading to energy waste. Interface design and usability improvements could help alleviate these negative outcomes through thoughtful provision of information.

Building from the conceptual model, Table 1: Interfaces in the context of the conceptual model presents a summary of the main interface categories that are reviewed in this paper in the context of the above conceptual model.

Table 1: Interfaces in the context of the conceptual model

Building interface	Occupant motivation	Control	Key interface feedback
Operable window interfaces	Open to admit fresh air and increase air movement for IAQ and thermal comfort; close to reduce outdoor air flow and noise	Manual: cranks, latch with handle, slider, etc. Motorized: remote interface with buttons, etc. (and possibly automated with manual override)	Tactile: feel the handle, crank, etc., and corresponding window movement Visual: see window position Thermal: feel airflow Acoustic: hear outdoor noise
Window shade/blind interfaces	Open to admit daylight and improve views; close to reduce daylight/glare and improve privacy	Manual: chain, rod, direct contact to spring-loaded roller shade, etc. Motorized: remote interface with buttons, etc. (and possibly automated with manual override)	Tactile: feel the handle, cord, rod, button, etc., and corresponding window shade/blind movement Visual: see window shade/blind position and impact on indoor illuminance Thermal: feel impact of changed solar radiation Acoustic: hear motor or mechanism
Thermostats	Adjust to improve thermal comfort or reduce energy use of HVAC	Direct input on unit (or remote input using app) to adjust setpoints and possible schedules; may be digital or mechanical (e.g. knob or slider) interface	Tactile: button, knob, or haptic feedback from smartphone app, etc. Visual: see thermostat state and feedback, if applicable Thermal: feel changing indoor temperature and/or airflow Acoustic: hear fan or expanding radiators
Lighting interfaces	Turn on/brighten to improve visual comfort; turn off/dim to improve	Input via switch, dimmer slider, buttons, etc.; interface may either be hard-wired into electrical	Tactile: feel the switch, slider, etc. Visual: see change in illuminance on surfaces and luminance of luminaires

	visual comfort and/or reduce energy use	circuit or connected via a digital signal; regardless, lighting may be semi-automated with occupancy- and daylight-based controls	Acoustic: hear outdoor noise

3 Methodology

This literature review was crafted by an international and interdisciplinary group of authors. The blending of these diverse disciplinary and cultural perspectives provided a richer understanding of the human-building interface interactions. Initially, the team compiled a literature repository of high-quality journal papers related to human-building interfaces. Papers were gathered over two-months from Science Direct, Scopus, and Google Scholar. The main keywords included human-building interface, occupant behavior, occupant commissioning, building interfaces, window operation, window shade/blind operation, lighting control, and thermostat interactions. After papers were collected, they were initially binned into (1) behavior and occupant interaction papers, and (2) the four selected building interfaces: windows, window shades/blinds, thermostats, and lighting controls. The papers were reviewed with energy use, IEQ, comfort and interface design/usability in mind. In total, 118 papers were collected and reviewed systematically. Additional papers (~40), beyond the 118, were reviewed as well, but were found to either not add valuable information or were not particularly relevant to interfaces. Guiding questions were used to categorize and organize papers and to find common themes, as well as gaps. The following research questions emerged.

1. RQ1: What influences behavior?
2. RQ2: What are the consequences of occupants' behavior (or lack thereof)?
3. RQ3: How can interface design and usability be improved to "optimize" behavior?
    a. *In other words: how can interface design promote and support behavior that maximizes occupant comfort, satisfaction, and productivity, as well as building energy use outcomes?*

The following section presents a literature review of the four selected building interfaces: windows, window shades/blinds, thermostats, and lighting controls. The authors are aware that many other interfaces that exist in buildings, such as door handles, garage door openers, security system interfaces, etc. However, many of these interface types are not as prevalent within the literature – nor are they as fundamental to both comfort and energy outcomes.

4 Human-building interface review and discussion

The following section includes a review of literature related to the primary four selected interfaces. The literature is presented and organized by the three guiding research questions.

4.1 Operable windows

Window opening/closing behavior controls the highest rate of air exchange between the indoor and the outdoor environment among systems controlled by occupants [42]. Operable windows (e.g., **Error! Reference source not found.**) are one of the most widely studied occupant-building interfaces due to their immediate impact on building energy consumption, thermal comfort, and IAQ. In fact, variation in natural ventilation strategies associated with occupants' operation of windows has a significant role in both whole building thermal energy balance and indoor air quality (IAQ). In contrast to the other reviewed interfaces, the interface (e.g., latch, crank, handle) directly integrates with the actuator, and the corresponding simplicity yields a high degree of perceived control. This characteristic is one of the reasons why operable windows play a central role in the adaptive thermal comfort model [38], [39]. Informed and intentional window operation can contribute to energy savings; however, the introduction of outdoor air into a building during extreme outdoor temperatures (too hot or too cold) can greatly reduce building energy-efficiency and pose risks, such as frozen pipes. Operable windows also present the risk of theft and precipitation [43].

Literature focused on human-window interaction mainly targets thermal and air quality comfort and implications on energy consumption. The acceptability of an open window is determined by the conditions outside, despite window opening behavior being triggered by indoor discomfort and non-physical variables [44]. In this view, smart window control systems, based on both the analysis of outdoor environmental conditions and the perspective of occupants, could achieve true building energy and comfort efficiency [45]. However, it should be noted that no significant literature was found about motorized windows surrounding human-building interactions. As evidenced in the following sections, the majority of existing studies were focused on office buildings and few studies were found about the identification of key variables influencing window control behavior in residential [46]–[49] educational [50], and healthcare [51] buildings.

Figure 2: Different examples of operable windows: Single wing window with handle (left); Dual-tilt window in bottom-hung configuration (center); Top-hung window (right).

4.1.1 RQ1: What influences behavior?

Personal control of windows differs significantly between different building typologies [51] and climate type [52], according to function, usability and living habits. Patterns of interaction between the occupants and windows vary according to building end-use and, in particular, between office and residential buildings. For example, with regards to occupancy profiles in each building type, occupants can only change the state of their windows when they are present and awake [53]. Among physical parameters, outdoor and indoor air temperature were generally the most influential factors in window interaction [46], [50], [54], [55]. Additionally, the indoor CO_2 concentration level was identified as a key environmental variable [47], [56]. Through an experimental campaign in educational buildings, Belafi et al. [57] found that classrooms in the same boundary conditions had different window-related behaviors and thermal comfort, illustrating that motivations of occupant interaction with windows are not limited to the achievement of thermal comfort [45], [58] or related to purely non-physical, (i.e. daily schedule and habits) or physical drivers (e.g., season, type of HVAC system, etc.) [48], [59], [60].

The influence of season on window use occurs independently from the end-use. For example, in office buildings, Kim et al. [61] showed people were more likely to open windows in the warm season than the cold season. Sun et al. [62] found the mode of window-opening by office occupants changed throughout seasons: day and night with no closing during summer and all-closed in winter. Yao and Zhao [46] obtained similar results in residential buildings where intervals of open window states were much longer in the summer than winter months.

Window opening behavior in buildings is also strongly related to daily activities of occupants, such as sleeping, cooking, cleaning, or arriving in a space [63]. Occupant activities vary during a day and can play an important role in determining window opening and closing behavior. As a result, a key issue relates to identifying the relationship between daily activities and window control [63]. Moreover, essential internal and social differences could be identified as the reason for different behavioral patterns observed in similar spaces [57]. A window opening model based on habits could be more realistic compared to models based on only weather-variables [53]. In office buildings, window opening is often driven by the schedule of arrival and departure (i.e. open on arrival; close before departure) [54]. Similarly, in educational buildings, one study [50] found daily routine-dependent occupant-window interactions, and window openings mostly occurred during breaks, especially in the morning. On the contrary, in residential buildings, window interaction habits were not time dependent, but rather activity dependent [54]. While considering all the aforementioned drivers, Jeong et al. [63] confirmed that occupants open windows when doing activities or when they desire fresh air. In some cases, occupant behavior in offices is more constrained than in the residential environment [64]. There are a few notable studies about open offices where window operating behaviors are influenced by social norms and interrelationships between coworkers. This suggests behavioral patterns in these offices are complex and need further investigation [60].

For many office buildings studied, researchers are mainly interested in finding suitable predictors of window-opening behavior to be used in modelling. Zhou et al. [60] found there are differences between subjective and objective feedback. The outdoor temperature, daily work schedule, and on-off state of air-conditioners are the three main factors affecting the final window operating behavior. Other investigations add more complexity to the problem by including further variables like differences in the window opening and closing behavior during the seasons [65], and indoor environmental conditions like “too hot,” “background noise,” and “air circulation” [61]. Other physical factors, such as wind speed, relative humidity, outdoor PM2.5 concentrations, solar radiation, daylight hours showed significant impact on window-opening probability. In addition to these factors, different people demonstrated various personal preferences on using windows. They may prefer different window states, even at similar indoor or outdoor air temperature conditions [54].

There is no general agreement about the reasons why people interact with these interfaces or the driving factors that trigger their decisions. Accordingly, the determination of typical patterns of window opening presents high complexity [66], [67] and further efforts in the estimation of window-opening behavior are needed.

4.1.2 RQ2: What are the consequences of occupants’ behavior (or lack thereof)?

A key variable influencing the potential effect of human-window interaction on overall indoor comfort and building energy need is represented by the type and operation of the HVAC system. To improve indoor comfort and save energy, occupants are generally encouraged to keep windows closed while air-conditioning is running [51]. Accordingly, Rijal [64] showed the frequency of the window opening in free-running periods was significantly higher than in cooling or heating modes with associated reduction of thermal discomfort. However, users can modify window states both to improve room thermal comfort and/or air quality, which are often not compatible with each other or with building energy-efficiency.

Although the control of the environment through window opening is welcomed by occupants, (compared to mechanically ventilated buildings, where occupants must passively accept the system operation [66]), it could have a negative impact on building energy performance, especially during the heating season [68]. Fabi et al. [56] stressed that, in cold boundary conditions, much more energy would be required to heat a building when all the windows are open compared to the same building with all windows closed. Among other factors, natural ventilation, operated by users, was confirmed as a primary driver for variation in heating energy consumption, especially in residential buildings [69]. Instead, during the cooling season, the proper use of natural ventilation when the outdoor environment is within the comfort range can generate energy savings through free-cooling [70]. Nevertheless, occupants' direct control of natural ventilation can provide large variations of indoor thermal comfort in hot environments without proper interaction [71]. In fact, the resulting indoor air temperature is directly influenced by human interaction with this interface [67]. In buildings characterized by specific end-uses, such as hospitals, it could create even higher risks, such as the airborne infection risk [51].

4.1.3 RQ3: How can interface design and usability be improved to "optimize" behavior?

Many of these challenges surrounding window usability differs based on the typology of a given building (especially between commercial and residential buildings). Despite the fact most studies only consider environmental variables as key influential factors of occupants interaction with windows [46], [48], [50], [51], [60], [61], [65], different parameters can influence the control on natural ventilation [42], [63]. For example, a variety of window features and design variables such as window size, shape and location within the facade, window opening type and opening angles/percentages, and shading devices could influence the occupants interaction [42], [70], or how windows usability affects IAQ [52].Some blinds/curtains configurations may prevent the proper operation of the window. On the other hand, optimizing window design based on only building energy-efficiency can affect occupants' quality of the view to outside and the received daylight [72]. Moreover, when designed focusing on limited aspects, windows may be then difficult to use. Examples include windows positioned high up on the wall to promote thermally driven airflow, but difficult to reach and interact with, windows that swing open inwards, often obstructed and with reduced usability, or windows that require too high strength to be adjusted by weaker people. Window type also influences human interaction. Different types of operable windows offer with different levels of flexibility, i.e. some can only be open or closed, but usually they have in between positions, such as sliding and dual-tilt windows. For instance, some types have the option to be controlled to open a crack for allowing ventilation, while preventing theft and rain, quality valued by occupants.

4.2 Window shade/blind interfaces

When properly designed, window shades protect the indoor environment from solar radiation. These systems can help avoid glare, admit more natural light, and mitigate overheating and solar heat gains to reduce mechanical cooling loads and improve comfort. Additionally, shading systems relate to lighting energy usage, particularly in commercial buildings. Therefore, research in window shading operation is often coupled with lighting control. Research in this area focuses on the preference of occupants with manual (through an interface; e.g., **Error! Reference source not found.**) compared to automated implementations of shading systems. Blinds and other shading devices can be controlled manually, motorized and controlled through control interfaces, or automated and controlled by one or more inputs (e.g., illuminance, temperature, wind, schedule) and possibly manually overridden. In many countries, manual operation is common in residential buildings, while motorized blinds are becoming common in office buildings [2], [73], [74]. Motorized control of window shades and blinds is of particular interest to researchers as it allows for automation and much easier monitoring of the operation of these devices.

Figure 3:Different examples of window shades/blinds: Automated perforated Venetian blinds in office with automated control (and manual override)(left); Residential blinds with manual control (center); Internal curtain and external roller shades in dwelling.

In recent years, different types of shading devices have been proposed, dependent of building orientation, location, window characteristics, etc. Consequently, different geometrical configurations of shading devices have been evaluated in terms of both their energy-efficiency and occupant comfort perception. In this review, varied shading systems, characterized by different configurations and possibilities of operation, are considered, namely venetian blinds, louvers, internal shades, roller shades, and dynamic shading systems. The corresponding interfaces must reflect the number of degrees of freedom (e.g., blind tilt angle and retraction level) and accessibility of the system (e.g., clerestories are out of reach). In general, manually controlled systems are either controlled directly (e.g., move the louvers of California blinds, pull on a spring-loaded roller shade) or indirectly (e.g., pull a cord or chain, rotate a rod). While indirect systems may add to complexity and reduce durability, they are more suitable for between-glass or exterior shading systems and may exploit mechanical advantage.

4.2.1 RQ1: What influences behavior?

One of the primary challenges is understanding *how* and *why* occupants interact with window shading systems and how the interface design affects this interaction. An existing literature review studied the shading devices control through three different levels of operation systems: manual, motorized and automatic control. The manual operation of blinds is preferred by occupants because their status influences both thermal and visual comfort and other comfort-related factors [75]. However, motorized blinds have limitations in their effectiveness because occupants tend to move the blinds only when the direct solar radiation makes conditions uncomfortable. Automatic shading control systems represent a promising solution for improving indoor thermal conditions and saving energy for cooling [76]. Conversely, some studies with shading automation systems found that occupants frequently override these systems about three times more than they use manual shades (especially after closure events), either indicating discomfort or implying their desire for customized indoor climate and control (e.g., [77]).

Within the literature, few examples of digital control interfaces used to manage blinds exist. In the examples that do exist, studies focus on office buildings. In the case of mixed systems (both manual and automatic), the key issue was related to understanding users' preference in choosing one of these control options. Meerbeek et al. [74] performed a field study to investigate how office workers respond to automated blinds. The interface allowed the automatic features to either be overridden by manually adjusting the blind position or completely turned off. The blinds were automated based on light level and closed when the expected office level was too bright. In this study, it was noted that a large majority of the office workers deactivated the automated features, however those who did not remove it still felt satisfied with the conditions, as they felt they had control through the ability to override the automatic features. The authors noted that it is likely the feeling of control that lead to satisfaction, over the automated features themselves.

Similar results were found by Sadeghi et al. [78] who conducted a comparison of environmental controls. These ranged from fully automated to fully manual, as well as interfaces with a low or high level of accessibility (wall switch, remote controller, and web interface). A significantly higher number of interactions were observed in instances where ease of control accessibility was high (manual control with web interface). In addition, in the residential sector, researchers found that the interactions with roller shades changed depending on the room of the house, especially among the seasons [45]. The motivations of occupant's interaction with shades are not only attributable to environmental parameters and optimization of energy use.

Some researchers (e.g., [79], [80]) found that occupants are totally or partially inactive in the interaction with window shading systems, and when active, interactions occurred on a weekly or monthly basis. O'Brien et al. [80] reported that office workers tend to be less active in interaction with window blinds because of perceived or realistic social constraints (i.e., concerns of annoying office mates). In addition to inactivity from the occupants, one justification found is the inaccessibility of shades [18], [79], [80]. This problem is particularly relevant in work environments where those without access to window shades are the least satisfied because they can neither choose their light level preferences or manage glare, neither satisfying their personal needs of outdoor views [18].

4.2.2 RQ2: What are the consequences of occupants' behavior (or lack thereof)?

Occupants' interactions with window shades have a significant impact on visual and thermal comfort, building energy use, and peak load. Despite this, research in this field is not widespread, presents a high degree of uncertainty, and primarily focuses on commercial office buildings [73], [80]. Van Den Wymelenberg [73] presented a review on patterns of occupant's manual interaction with blinds, recognizing a significant lack of literature in this field. This analysis of state-of-the-art interfaces highlighted that most of the available studies use small sample sizes and alternative research methods, making the direct comparison of results a complex task. In addition, many of these studies are based on time-lapse photographic data collection which is a complex and time-consuming technique.

Variables outside of the configuration of shading devices could potentially affect the energy consumption of a building. User interaction with shading devices also plays a significant role. One research study [81] revealed that the occlusion level and frequency of adjustment of window blinds can affect the daylight condition and energy consumption of a building. The survey shows that most of the occupants preferred to keep their blinds at half-closed or almost fully closed positions, but a majority of participants were satisfied with the amount of daylight. However, this result was achieved because the electric lights were turned on during the daytime. Many of the participants claimed that they experienced computer screen glare and too much or too bright electric lighting [81]. Furthermore, a critical review was performed to study occupants' use of window shades in many offices. The researchers concluded that discomfort often triggered blind closure, but when the shades remain closed, and electric lighting was used instead of daylight, the overall energy use was significantly impacted [80].

One study carried out research in different latitudes to evaluate the effect of louver shading devices on space heating and cooling requirements as well as thermal comfort of occupants. In certain latitudes, the total annual energy demand was higher without shading, due to the lower solar gains in the heating season [82]. In another study, three types of internal shades (diagonal, vertical and egg-crate) were evaluated to study their effect on the illuminance levels, thermal analysis and perceived human interactions. They found that each type could affect differently solar gain protection and visual connection to the outside [83]. External shades aim to retain visual comfort and internal thermal levels, while still maintaining views to the outside. Both vertical and horizontal shading were found sufficient in controlling the correct level of illuminance and minimize solar heat gains. Comparatively, horizontal shades with various degrees of rotation were more inhibitive of natural views to the exterior than the vertical shading [84].

Although occupant manual control of these interfaces has a profound effect on energy use, few examples exist in the literature where control interfaces were used to control blinds. Commonly are electric blinds and control interfaces allow for automation, with the intent to improve either visual comfort or energy use. In a research study, three different control setups were deployed in private offices of a high performance building to control motorized roller shades and electric lights: wall switch in setup 1, graphical interface in setup 2 and 3. For this study, data collected from all three setups were used to develop occupant-shading interactions models [85]. The study demonstrates the impact of control interfaces on human interactions and consequently the energy use. In particular, higher daylight utilization in offices with easy-to-access controls was observed, which implies less frequent use of electric lights and less energy consumption accordingly [78].

4.2.3 RQ3: How can interface design and usability be improved to "optimize" behavior?

Architects' and designers' awareness of realistic window blind use is critical to design, as indicated by the above literature review that indicates their relatively inactive use and diverse motivators for movement (e.g., glare, daylight availability, privacy, space overheating, consideration of impact on others, etc.). However, the above literature suggested that the operation of window shades and blinds is inconsistent, and often unpredictable. In addition, building designers commonly assume that window blinds will remain open during dark or overcast periods and are closed during sunny periods [82]; thus potential for daylight and views to the outside are often greatly diminished. The literature indicates automating blind control to reduce the need for manual control has not necessarily solve the problem; occupants' preferences for daylight levels and value of views is difficult to predict.

Another phenomenon that suppressed interaction with window blinds is the spoken or unspoken constrained by co-occupants (e.g., fear of annoying others). This problem is multiplied in environments where multiple occupants in a space are engaged in a variety of activities and their location/orientation means that they experience daylight and views differently. In such cases, occupants without access to window shading controls are often the least satisfied because they cannot easily control shades. In the case of both manual and automatic control shading systems, the primary issue is understanding users' preference in choosing one of these two options.

Even for private spaces, interior design and space layout is critical; Day et al. [18] found that poorly conceived space design and furniture layout may also present a barrier to blind control and use. In their study, the researchers found that more than 50% of total respondents (*n*=35) reported that the manual blind interface was difficult or impossible to reach because of furniture layout. This further led to increased electric lighting use in some offices. Ill-conceived designs and furniture layout can either facilitate or hinder building energy use outcomes and occupant comfort [86].

There are several design strategies that can be employed to improve usability of blinds and their interfaces. First, the blinds themselves should provide flexibility to customize their state. For instance, venetian blinds provide two degrees of freedom such that direct solar radiation can be blocked, while admitting diffuse radiation and permitting some views [73]. Moreover, the ability to adjust magnitude of deployment is important. Motorized shades and the corresponding logic should allow users to fully or partially deploy shades – ideally without holding a button during lengthy deployment processes. Moreover, personalized control should be prioritized; this means allowing individual blinds/shades to be individually controlled (i.e., in contrast to forcing all blinds to move in unison using automation). For transient spaces (e.g., airports), full automation is sensible; however, the literature indicates a need for more research on automating shades in shared permanent spaces (e.g., offices, homes) considering the diverse needs of occupants and corresponding social constraints. As for all interfaces, other best practices for usability apply, such as natural mapping of interfaces to shades.

4.3 Thermostats

The most common and well-researched examples of control interfaces for heating and cooling systems (e.g., radiators, floor and ceiling panels, ventilation and air-conditioning) are thermostats. According to ASHRAE, "*thermostats are an automatic control device used to maintain temperature at a fixed or adjustable setpoint*" [87]. Thermostats appear in both residential and commercial buildings (e.g., ***Error! Reference source not found.*** and **Error! Reference source not found.**), and they can be either manual, mechanical, or digital. In commercial buildings, they may act as controllers that directly control the heat flux (e.g., mounted on a of a radiator), communicate with the HVAC system components, or integrate into the building automation system (BAS). Therefore, a wide variety of implementations exist, including wall-mounted (e.g., room and zone-thermostats), installed at the building system itself (thermostatic valves at the radiators) or use modern interfaces such as apps, remote control (e.g., for split unit air-conditioners), and control panels.

In residential applications, traditional thermostats integrate both user interfaces and controls logic. The most basic thermostats allow users to establish a setpoint temperature that the HVAC then attempts to achieve (as measured at the thermostat, or possibly other sensors). Programmable thermostats (PTs) offer the ability to set operating schedules and setback temperatures to save energy. Traditionally these PT's have been button based, however more feature rich "smart" or "connected" PT's are increasing in popularity. These thermostats typically have flexible touch screens along with connected web-based interfaces. The literature related to thermostat use and interface design in residential buildings primarily focuses on programmable thermostats because 1) they were once seen as a means to save energy (though this has been since contradicted) and 2) they yield some data collection capabilities.

Figure 4: Examples of residential building thermostat interfaces.

Figure 5: Examples of commercial building thermostat interfaces.

4.3.1 RQ1: What influences behavior?

In commercial buildings, much of the literature focuses on thermostats and thermostatic valves that allow personal control over office spaces. Due to differences in thermal preferences among users, access to adjustable thermostats can have a significant effect on thermal comfort in offices. Wyon [88] found that providing personal control through thermostats of ±2°C is enough to satisfy 90% of office workers; however, the study assumed occupants took adaptive actions, and noted this range would need to increase if strict dress codes were imposed. Similar temperature ranges were found in an in-situ monitoring campaign during the cooling season of an office building, where Peng et al. [89] discovered that occupants tended to adjust room temperatures via control interfaces based on their preferences. According to occupants' temperature adjustments, the experimental results indicated that occupants' thermal preferences differed from each other in both time horizon and temperature levels (a 4.5°C difference) within the case study building.

Even when individual control via room thermostats is available, usability issues related to interacting with a complex system with a slow thermal response, may cause occupants to have low perceived control in their offices [41]. Through surveys, Boerstra et al. [90] demonstrated that if users have access to personal thermostats but they feel their control is ineffective, the number of complaints about their thermal comfort was the same or in some cases higher compared to those without any means of personal control [90]. Similar results were found by Wagner et al. [9] who, through a survey of 16 German office buildings, found that the perceived effect of intervention influenced occupants' thermal comfort in both the cooling and heating seasons. In a large-scale study, Karjalainen [28] surveyed over 3000 people finding that both thermal comfort and perceived control are significantly lower in office buildings, compared to residential or home offices. In offices where occupants share a thermostat, perceived control is significantly reduced [28], [91].

For residential thermostats, since users have full control over their heating and cooling systems, many of the challenges center around promoting energy saving behavior among occupants. [89], [92], [93]. Misuse of thermostats -by not using energy-saving features as intended- may be due to user confusion and low usability. In a review of various thermostat interfaces, Meier et al. [94] categorized numerous barriers to usability. Examples allude to people having a low understanding of how their HVAC system operates, thermostats are too complicated to use or that the buttons are small and hard to understand, and unpredictable time at home makes programable interfaces less effective.

4.3.2 RQ2: What are the consequences of occupants' behavior (or lack thereof)?

In applications where users have full control over their thermal comfort systems, simulations suggest proper use of thermostats can lead to significant reduction in energy consumption [95], [96]. While these savings are dependent on climate and building type, due to occupant behavior, in practice PTs seem to be falling short of expected energy savings [96]–[98]. Typically, expectations of PTs' savings are hinged on two major assumptions: (1) that people are not using their conventional thermostats to apply setbacks during unoccupied periods, and (2) people will take advantage of the programmable features of new thermostats. In a survey with small business' that had recently converted to PTs, 64% of people reported they had been operating their manual thermostats to apply setbacks during unoccupied periods [96]. While automated schedules made possible by PTs could lead to more consistent operation, improper operation can, in some cases, lead to increased energy use.

In 2009, the United States Environmental Protection Agency (EPA) ended its EnergyStar endorsement of PTs, stating that while it recognized their potential benefits, they were not able to confirm any energy savings attributed to the use of programmable thermostats [99]. In an online survey in the U.S., Pritoni et al. [97] found that only 39% of people claimed to take advantage of the programmable functions, and of those who claimed to take advantage, 33% had those features overridden during the time of the survey. While it is not known if that the override was temporary, these results cast doubt on people's PT users' self-reporting regarding the correct use of schedules. This study found that one of the primary barriers to use and energy saving settings is the complexity of feature-rich interfaces (e.g., allowing occupants to set complex daily schedules, and have alternative settings such as holiday modes, etc.). Figure 6: Example of a programable thermostat where the hourly temperatures setpoints are chosen using sliders. shows just one example of a thermostat that may suffer from usability challenges. Some implementations of PT, interfaces. More recently, particularly connected interfaces with thermostats with web-based options for setting schedules, have been demonstrated to lead to more successful completion of schedules [98], [100].

Figure 6: Example of a programable thermostat where the hourly temperatures setpoints are chosen using sliders.

Few studies exist on the energy implications of the interface design of thermostats in the commercial sector. Overall, people may not interact with personal thermostats in office buildings for a variety of reasons including social implications, inaccessibility, lack of understanding, etc. However, if the perceived control of adjustments to commercial thermostats is low, users may resort to space heaters or opening a window, often leading excessive energy use [101]. Interestingly, in a monitoring campaign of an academic building, Gunay et al. [86] found that when occupants interacted with their thermostats, they typically adjusted their temperature in increments of 1°C, and one third of the total interactions were to either decrease the temperature in the heating season, or to increase the temperature in the cooling season. These actions led to an average of 2 to 3°C difference a preference in the cooling season vs the heating season. When offering interfaces for occupants to view and adjust the controlled indoor climate, strategies such as scheduled setbacks or more sophisticated methods (e.g., occupant-centric and demand-driven controls), can be embedded into the building control system to save energy while maintaining or improving occupants' comfort. In experimental case studies, Peng et al. [102], [103] implemented demand-driven algorithms that predict occupancy and control accordingly, leading to energy savings of over 21% during the cooling season. Given the low level of perceived control currently in offices, these techniques should be implemented in a way that does not further reduce the perceived control of occupants.

4.3.3 RQ3: How can interface design and usability be improved to "optimize" behavior?

Some implementations of PT interfaces, particularly connected interfaces with web-based options for setting schedules, have demonstrated more successful completion of schedules due to their ability to offer various interfaces that allow users to set schedules to via computer interfaces and apps [92], [98], [100]. These connected thermostats also offer more user friendly and aesthetically appealing digital displays [97], [100], [104]. In addition to allowing for flexibility of interface design, the data generated by these thermostats can be collected by utility companies, policymakers, and researchers [97], [100].

HVAC systems are one of the most complex home comfort systems that users interact with, and with increasing flexibility of thermostat interfaces, there is opportunity for innovative designs of thermostats.

Revell et al. tested a novel interface through a virtual platform. The authors found that interfaces that visually represented actual system components of the physical HVAC system led to a more accurate understanding of how control actions affected the occupants' environment. This understanding of the system improved occupants' control over the system to meet various comfort-related goals [29]

Perry et al. [98] recommended a need for user-based testing to ensure PT's can be operated successfully. Researchers developed several quantifiable metrics including measuring time to complete a task and hesitation time between button presses. When using these metrics to perform user tests on button-based, touch screen, smart thermostats, and web interfaces, web interfaces led to the fastest schedules setting with the fewest errors. This outcome was compared to and agreed with expert evaluations performed by industry experts.

In commercial buildings, while providing a thermostat interfaces for means of personal control is a key factor in satisfying a variety of thermal preferences, occupants must perceive that they have control over the thermal environment before those benefits are realized. Low levels of perceived control can be partially attributed to usability issues with the implementation of commercial thermostats. Through interviews, Karjalainen & Koistinen [41] identified several usability issues with office thermostats and thermostatic valves. Some key examples include; thermostats are hidden behind furniture, users are not aware they are allowed to adjust settings, or they are unsure of how to operate their devices. This study also identified that people were often unaware if their thermostats were active since there was no immediate feedback that would tell users if the thermostat was working. Thus, providing information to users about the HVAC system state (e.g., heating) is a critical feature that should be included in all thermostats.

Another cause for lack of perceived control arises when people do not understand the system they are operating. In a large-scale study of over 3000 Finnish homes and offices, Karjalainen [28] found that an understanding of the heating and cooling system correlated with perceived control, which is typically much lower in offices when compared to residential settings. Based on these types of usability issues, Karjalainen [105] developed a user prototype of a more usable interface, using the following principles: (1) Interfaces should be tested with users in the product development stage, (2) control actions should be intuitive, (3) user inputs should be provided with instant feedback to control action, and (4) the user should be informed on the operation of the system. It is also recommended that users have ±2°C of control with increments of 1°C, and that the system responds quickly to adjustments of the setpoint. Developing interfaces with the user in mind will lead to increased perceived control and thermal comfort in commercial buildings.

4.4 Lighting interfaces

Electric lighting is installed in all types of buildings to ensure safety, visual comfort, and aesthetics. The most common way people interact with their lighting systems is through wall mounted control switches ("hardwired") to turn electrical lighting on/off. Moreover, many user interfaces include multi-zone lighting control, dimming control options, and in some cases, control over light temperature (i.e., color). More advanced systems allow the automation of lighting control, typically based on occupancy and daylight, which operate alongside these manual devices. Lighting interfaces vary significantly by building and range from conventional light switches, buttons, digital control panels, to computer and smart phone apps. Figure 7: Examples of commercial lighting control interfaces. illustrates a few examples of lighting control interfaces.

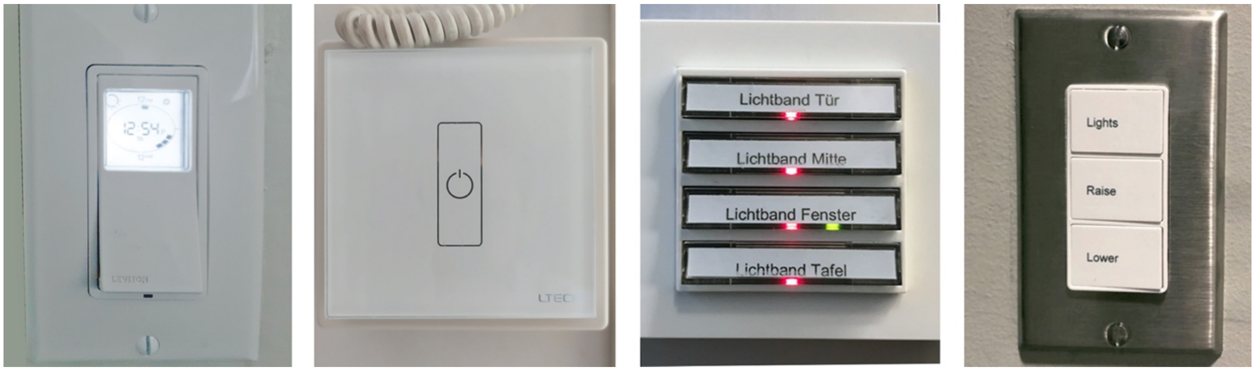

Figure 7: Examples of commercial lighting control interfaces.

4.4.1 RQ1: What influences behavior?

Lighting control interactions are often motivated by visual discomfort (or in some cases safety and security). Typically, the reason that users interact with these lighting interfaces is to adjust the lighting to meet comfort needs and preferences. However, when light switches are difficult to interact with (through location or usability), this also acts as a barrier, causing discomfort and frustration by users. Several studies that apply end-user testing to existing interface design have found that many current products are difficult to understand by users. When light switches are simple and easy to adjust by occupants, users can more easily achieve their preferred light levels [106]–[108]. Interestingly, users are generally very tolerant of their existing lighting configuration, even when they would likely not accept it as a new configuration [107].

Occupant behavior with lighting interfaces can have a large impact on energy consumption of lighting [77], [109], [110], with the exact impact depending on building type, climate, and other factors. Several examples are can be found in the literature where researchers have found similar driving factors when performing field studies with the intent to better understand occupant behavior. Correia da Silva et al. [77] found that 91% of control actions taken by occupants occurred on arrival or departure, finding illuminance being a major driving for predicting both switching on and off behavior. Fabi et al. [110] suggested classifying users as active users, who are likely to change their lighting during occupancy based on factors such as temperature, and illuminance, and passive users who primarily change their lighting settings when they arrive or exit a space. Mahdavi et al. [109] confirmed these results, finding that the probability of light switching on behavior increases significantly when workplace illuminance increases over 200 lux, while light switching off behavior is heavily correlated with leaving a space, and the duration of the absence that follows. While these studies frequently find the same drivers for light switching behavior, they probabilistic models associated with these drivers differ between buildings. This highlights the need to calibrate models between applying it to different buildings.

While relevant, these studies are typically performed with the intent to improve building modelling approaches. As such, they therefore primarily focus on external driving factors, without taking into account the ease of access to lighting controls, interface design and building architectural features. These factors are explored further in Section 4.3.3. [77], [109], [110].

4.4.2 RQ2: What are the consequences of the behavior (or the lack thereof)?

As previously stated, occupant behavior can have a significant impact on energy use. A common example occurs when occupants tend to turn their lights on more frequently than off, leading to greater energy use consumption [85]. When light switches are difficult to interact with (through location or usability), this also acts as a barrier, causing discomfort and frustration by users. Similarly, unintuitive lighting interfaces can cause discomfort, leading to confusion and frustration for occupants. Several studies that apply end-user testing to existing interface design have found that many current products are difficult to understand by users [14], [107], [108].

4.4.3 RQ3: How can interface design and usability be improved to "optimize" behavior?

Interface design, control logic, and architectural features can have a role to play in energy using behaviors related to electric lighting. For instance, Maleetipwan-Mattson et al. [111] found that large simple switches, placed in easily accessible locations, promoted switching off behaviors. To further impact occupant behaviors, nudging techniques have been used to encourage switching off lights; for example, these include labeling light switches, or dimming hallway lights [112], [113]. Additionally, Kunduracı et al., demonstrated that architectural features such as room orientation, window size, as well as desk location and orientation all contribute to lighting use behavior [114].

Someren et al. [106] performed interviews with university staff of the lighting of lighting services and identified the lighting of interfaces as one of the largest sources of complaints. The researchers reported multiple usability issues including that light switches are inconsistent between rooms, the majority of light switches fail to meet basic visual impairment and accessibility requirements, the lighting interfaces regularly confused and delayed the building users, and that features such as dimming or zoning were not obvious and where often unknown by users.

Some studies suggest user testing as a solution to poor interface design. Yilmaz et al. [107] performed user testing that compared various switches, as well as computer-based digital interfaces. They concluded that people prefer large, simple, familiar light interfaces. In some interface styles, particularly ones with more features, people are unable to understand all the functions, particularly when dimming control is not obvious. Feedback directly from the interface helps avoid misunderstanding, particularly when the lighting systems are not functioning properly. In a similar user-based study, Amardeep et al. [108] noted that conventional light switches often provided little feedback regarding the dimming functionality, and identified a need for users to be able to quickly identify these functions, and suggested that touch screen interfaces may provide an interactive visual link to the lighting system. This paper suggested a methodology for rating lighting systems, based on categories such as grabability, responsiveness, and learning speed.

In a study of an academic building with automated occupancy-based lighting, Gilani et al. [115] found that lights automatically switched on during occupancy periods, even when users would not have needed them due to adequate daylighting. This led to a significant increase of time the lights were on during occupied periods compared to if the lighting was manual. Significant savings could be made with the implementation of manual on control, highlighting the importance of considering occupant behavior in automation. Automated lights in commercial buildings have increasingly been seen as a solution to this issue, however, when not done properly, it can cause frustration, and in some cases, even greater energy use; this sentiment is shared across multiple types of building interfaces, as evidence by the literature.

5 Discussion and Conclusion

Users are often uneducated or unaware of how to interact with these types of building interfaces, often leading to frustration, discomfort, and in most cases increased energy use [14], [41], [92], [116]. Frequently the person in charge of purchasing building control devices is different than the end-user (even in residential applications) [97], [111]. Therefore, price and ease of installation are valued over usability [41]. There is very little standardization in the field of building controls and as such, interface layouts and symbols vary greatly, even within the same building [97]. Additionally, feedback is not always given through the device, which can cause frustration and confusion, particularly when the buildings are not working as expected [97], [107], [116].

Implications of behavior on energy use are of interest in the literature. Several researchers have tried to model occupant behavior based on field studies for the purposes of building simulation [77], [109], [110]. Those studies note a common limitation: that the behavior varies by a number of factors (e.g., climate, building type) and that the models created may not be applicable to another building. While this represents a major limitation to the current understanding of behavior, the research notes that models based on collected data of real building users is a significant improvement over conventional modeling techniques.

Ultimately, buildings are designed and built for people. However, building systems are engineered to meet codes, standards and guidelines, which does not necessarily correlate to occupant satisfaction or comfort. Common themes emerged throughout the literature review to explain occupant interactions (or lack of interactions) with building interfaces. These included: thermal and visual comfort, ease of control and access of control, interface/control placement, poor interface/control design (not intuitive), education/training needed, and social-behavioral dynamics.

As buildings, and associated codes and standards evolve, there has been a greater focus on energy use than occupant comfort and building usability. Energy use and comfort are often diametrically opposed; however, well-designed and well-understood human-building interfaces can lead to both energy savings and occupant comfort. If an occupant understands how to optimally use a building system via the interface, they are less likely to engage in energy-intensive behaviors in ways that violate the original intent of the building. Future research is needed to refine (and define) both interface design and use.

5.1 Identified research gaps and future work

Interfaces are the primary means for regular interaction between people with buildings. Building interfaces can positively or negatively impact energy use and/or occupant comfort; however, they are poorly understood in terms of occupant behavior and resulting energy and comfort impacts. Future research is needed to explore additional building interfaces, especially those which were not exhaustively addressed in the existing literature, e.g., doors, other mechanical ventilation controls, etc. In addition, there is a lack of literature on motorized blinds and shading systems and especially motorized operable windows; there is great potential for further analysis of these systems.

A greater number of studies are also needed to better understand how occupants interact with (and respond to) specific building interfaces. The literature review revealed many studies, experiments and anecdotal stories, but there were very few observational studies, with sufficiently large populations, to support predictive models of how behavior, and energy usage outcomes, vary with different interface approaches and designs [4]. These studies are needed in both the commercial and residential contexts. Studying occupants' use of interfaces through centrally collected databases (e.g., building automation system archives, residential thermostat databases [117]) shows great promise due to the low cost of data collection, large sample sizes, and avoidance of Hawthorne effect biases. Moreover, the fields of human factors, industrial design, and human-computer action have a wealth of established research methods that could be applied to building interfaces, including hallway testing, think aloud, expert review, and A/B testing.

Future research is also needed to provide more on the richness of cultural diversity and variety, in order to avoid overgeneralization in designing the next generation of building interfaces. Ethnographic aspects might interfere with the extent to which occupants interact with an interface, and thus, with their perception of the interface readability, usability and effectiveness. In addition, national differences and standards of interfaces should be further studied in tandem with cultural expectations of comfort, IEQ, perception, interface designs, etc.

Lastly, as technologies advance, there will be more opportunities for human-building interface design and occupant engagement through new mechanisms, interactions, and possibilities. Current use of digital interfaces includes the use of local command-based (e.g., buttons), touch-based (in-home displays or smartphones) and voice-based gestural interfaces (e.g., smart speakers). This is a subset of the upcoming digital interface concepts and technologies. Promising new directions include tangible, surface, ambient, gestural, exertion and context-aware user interfaces [118]. These novel types of interaction techniques create many new opportunities for designing digital building interfaces. More research is needed surrounding novel digital building interfaces and how occupants will engage with these innovative and new technologies. The building science community has an opportunity to help guide the introduction of these technologies into interface design and use, as opposed to studying the effectiveness from past market introduction.

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[withheld for review]

7 References

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