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Influence of Automated Façades on Occupants: A Review

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Abstract

Several studies performing building simulations showed that the automated control of façades can provide higher levels of indoor environmental quality and lower energy demand in buildings, in comparison to manually controlled scenarios. However, in several case studies with human volunteers, automated controls were found to be disruptive or unsatisfactory for occupants. For instance, automated façades became a source of dissatisfaction for occupants when they did not fulfil individual environmental requirements, did not provide personal control options, or did not correctly integrate occupant preferences with façade operation in energy-efficient controls. This article reviews current evidence from empirical studies with human volunteers to identify the key factors that affect occupant response to automated façades. Only twenty-six studies were found to empirically investigate occupant response to automated façades from 1998 onwards. Among the reviewed studies, five groups of factors were found to influence occupant interaction with automated façades and namely: (1) personal factors, (2) environmental conditions, (3) type and mode of operation, (4) type of façade technology, and (5) contextual factors.. Overall, occupant response to automated façades is often poorly considered in research studies reviewed because of the following three reasons: (i) the lack of established methods or procedures for assessing occupant response to automated façade controls, (ii) poor understanding of occupant multi-domain comfort preferences in terms of façade operation, (iii) fragmented research landscape, on one hand results are mainly related to similar contextual or climatic conditions, which undermines their applicability to other climates, while on the other hand the lack of replication within the same conditions, which also undermines replicability within the same condition. Lastly, this paper suggests future research directions to achieve a holistic and more comprehensive understanding of occupant response to automated façades, aiming to achieve more user-centric automated façade solutions and advanced control algorithms. In particular, research on the impact of personal factors on occupant satisfaction with automated controls is deemed paramount.

Keywords

Automated control, automated façades, occupant-façade interaction, occupant acceptance, occupant comfort, dynamic façades

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1 INTRODUCTION

In buildings, façades act as a buffer and connector between indoors and outdoors (Knaack et al., 2014) and affect building energy consumption and occupant multi-domain environmental comfort (Luna-Navarro et al., 2022). In particular, façades can affect occupant satisfaction with the thermal environment (Carmody et al., 2004), acoustic (Tang, 2017), air quality (Izadyar et al., 2020), daylight, and view out (Boyce et al., 2003; Heschong et al., 2013).

Dynamic façade technologies, identified as building systems or façades that can move by forces acting on an object, can vary the visual or solar transmittance (e.g. switchable glazings or movable blinds) or the level of airflow through them (e.g. openable vents) (Barozzi et al., 2016) to effectively respond to changes in outdoor or indoor conditions. Dynamic façades can be manually controlled by occupants (Reinhart & Voss, 2003), or react to changes in environmental conditions, either by passively responding to them (e.g. phase change materials (Balocco & Petrone, 2017)), or by automatedally being controlled by actuators and sensors (Bakker et al., 2014). Several automated façades are controlled by a semi-automated logic, which also allow occupants to override the system when they disagree with the control logic (Gunay et al., 2017). Previous work showed that automated controls can assist occupants and overcome the limitations of manual operation by reducing energy consumption (Sullivan et al., 1994; Tzempelikos & Athienitis, 2007) or improving thermal or visual comfort (Hosseini et al., 2019). Contrariwise, the automated control can also negatively impact occupants' satisfaction and behaviour, when the control action does not match individual requirements (Day et al., 2019; Grynning et al., 2017).

In scenarios with automated façades, the type of control logic and the occupant-façade interaction strategy (i.e. the level and mode of interaction) affect occupant behaviour and satisfaction, indoor environmental quality, and energy consumption (Luna-Navarro et al., 2020). Several studies showed that occupant requirements are subjective and individual, affecting occupant response to the control system (Cheng et al., 2016; Gunay et al., 2017). These variances in occupant responses may be explained by a different personal significance of environmental comfort domains (Meerbeek et al., 2014; Cheng et al., 2016) or differences in the level of knowledge of users with automated control (Lee et al., 2012). Therefore, the adaptation of the control logic to individual occupant requirements can be important to achieve occupant environmental comfort and satisfaction, acceptance of automated control strategies, and energy performance of office buildings (Kim et al., 2009).

Four previous studies have performed a literature review on automated controls for automated façades. Konstantoglou & Tsangrassoulis (2016) reviewed automated control strategies of dynamic shading systems and their effects on building energy performance and indoor environmental comfort. This literature review concluded that, even though automated control strategies can enhance energy performance and occupants' comfort, their high level of complexity makes them prone to failure and therefore they often do not achieve the predicted performance. Jain & Garg (2018) analysed the feasibility of various daylight prediction methods and their application in controlling dynamic shading and lighting systems, coming to the conclusion that modified and improved closed loop systems, which include and adapt to user feedback, are better than open loop control strategies based on sensor measurements. However, Luna-Navarro et al. (2020) examined interaction strategies and requirements for satisfactory occupant-façade interaction, pointing out that achieving effective closed-loop operations by satisfactorily engaging the occupant, is challenging since several factors play a role. Tabadkani et al. (2021) reviewed the state-of-the-art regarding occupant-centric control strategies, showing that current interaction strategies are ineffective in improving both user satisfaction and energy efficiency. Ultimately, there is a need to comprehensively review existing studies on occupant-automated façade interaction and highlight the current evidence of the factors that influence individual occupant response to automated façade controls. This will facilitate the design and operation of automated façades in an occupant-centred manner. *To achieve this*, the aim of this work is to review previous experimental work that evaluates human volunteers' responses to automated façades, either in lab experiments or field studies, and to evaluate current evidence to indicate the directions of future research.

Section 2 explains the review methodology, including selection criteria and the classification scheme that structures this article. Section 3 describes the results of the review, including the discussion of the evidence collected. Finally, Section 4 draws the conclusions, and highlights potential future challenges and investigations based on the review conducted.

2 METHODS

In order to review previous work on the factors that influence occupant preferences regarding automated façade operation, a systematic review was conducted. This section provides a detailed explanation of the inclusion and exclusion criteria and keywords. Advanced queries in all databases based on terms definition were conducted. Therefore, a searching protocol through defined keywords has been used, as shown in Table 1. As a result, all the papers must meet the following requirements: only papers on automated dynamic façade control strategies and that monitor actual occupant response through experiments and monitoring with human volunteers were considered. Occupant response was considered by including the following keywords: user interaction, comfort, satisfaction and acceptance.

The following studies were excluded from this literature review:

- Studies that only considered manually controlled systems that do not incorporate any automated feature;
- studies that only considered façades that passively respond to changes in environmental conditions but do not have active control strategies;
- studies without human volunteers.

Keywords were divided into four groups (Table 1): (1) façade operation, (2) façade technology, (3) experiment placement, and (4) façade control. Consequently, references were searched (WoS (2.328), Scopus (2.795)). Only 127 studies were selected by title and abstract, reduced to 106 after removing duplicates. Full-text revisions assessed the eligibility of articles, applying the inclusion and exclusion criteria described previously. Finally, we ended up with 26 studies that met the requirements for being examined for this literature review, published between 1998 and 2022.

TABLE 1 **Search keywords**

Database	Date of search	Inclusion searching criteria in Title, Abstract and Keywords					Number of Articles
		1) Façade operation		(2) Façade technology		(3) Experimental testing	
Web of Science	24-2-2022	(adaptive OR responsive OR dynamic OR kinetic OR intelligent OR advance OR smart OR interactive OR active OR automated OR switchable OR climate OR control)	W/3	(façade OR envelope OR skin OR shading OR glazing OR glazed OR window OR venetian OR roller OR blind)	AND	(laboratory OR on-site OR field OR experimental OR post-occupancy OR testbed OR test room OR campaign OR monitoring)	2.328
Scopus	22-2-2022						2.795

Studies were not restricted in terms of geographical location since the scope of the review is also to contextualise the research results and evaluate whether any geographical location is missing in the research landscape to inform future research directions accordingly.

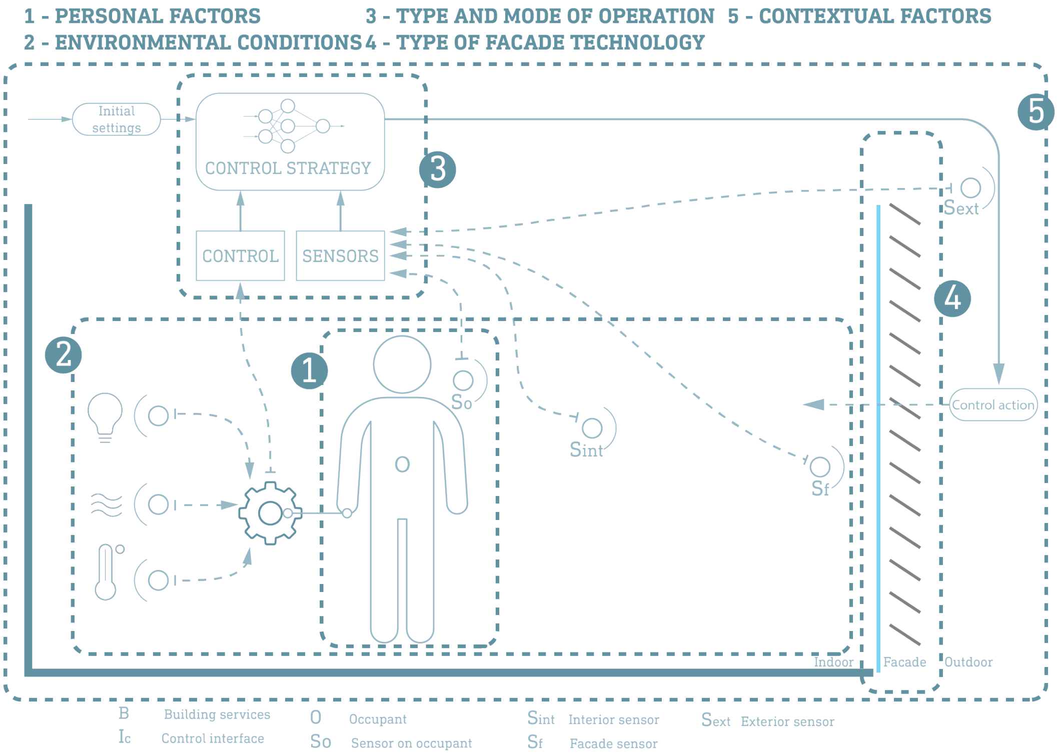

FIG. 1 The classification scheme used in this review to group the factors influencing occupant response that were identified through the literature review (after (Luna-Navarro et al., 2020)

2.1 FACTORS THAT INFLUENCE OCCUPANT RESPONSE

The classification scheme from Luna-Navarro et al. (2020) was used in this review to group the factors that affect users as follows (shown in Fig. 1): 1. personal factors, 2. environmental conditions, 3. type and mode of operation, 4. type of façade technology, and 5. contextual factors (e.g. type of building etc.).

3 RESULTS AND DISCUSSION

3.1 TYPE OF OCCUPANT RESPONSE TO AF STUDIED THROUGH PREVIOUS WORK

Before going to the evidence on factors affecting occupant response, the review results are analysed to identify what type of user response has been considered by previous work.

Occupant response was evaluated in terms of behaviour (13 studies), environmental comfort (20 studies), environmental satisfaction (18 studies), environmental sensation (6), acceptance of the control system or of the indoor environmental conditions (5 studies), and overall satisfaction with the automated control (4 studies). Table 2 shows the type of occupant response considered by each study. These different types of occupant response were studied by previous authors thorugh questionnaires, surveys, and interviews. In addition, occupant behaviour was monitored by tracking occupant override actions (Bakker et al., 2014; Cheng et al., 2016; Goovaerts et al., 2017; Gunay et al., 2017; Lee et al., 2012; Luna-Navarro et al., 2022; Motamed et al., 2019; Sadeghi et al., 2016), or occupant actions to deactivate the control logic (Meerbeek et al., 2014), and set-points (Clear et al., 2006; Guillemin & Morel, 2001, 2002; Vine et al., 1998).

Some studies used the term “comfort” and “satisfaction” interchangeably (Cheng et al., 2013, 2016; Lee et al., 1998; Sadeghi et al., 2016), while other studies used these terms to describe different states of mind. For instance, comfort was intended as the threshold or set-point that defines comfortable environmental conditions, which was often contrasted by surveys of the occupant perception to the environmental quality (Bakker et al., 2014; Cheng et al., 2013, 2016; Clear et al., 2006; Guillemin & Morel, 2001, 2002; Kim et al., 2009; Lee et al., 2012; Meerbeek et al., 2014; Motamed et al., 2017; Sadeghi et al., 2016; Taniguchi et al., 2012; Vine et al., 1998). Satisfaction was used to indicate occupant contentment with the visual environment (Cheng et al., 2013, 2016; Choi et al., 2019; Clear et al., 2006; Day et al., 2019; Guillemin & Morel, 2002; Karlsen et al., 2015; Kim et al., 2009; Lolli et al., 2019, 2020; Luna-Navarro et al., 2022; Meerbeek et al., 2014; Sadeghi et al., 2016; Vine et al., 1998), thermal environment (Choi et al., 2019; Clear et al., 2006; Day et al., 2019; Lolli et al., 2020; Luna-Navarro et al., 2022; Meerbeek et al., 2014; Sadeghi et al., 2016; Wu et al., 2020), acoustic environment (Clear et al., 2006; Lolli et al., 2019; Luna-Navarro et al., 2022), air quality (Luna-Navarro et al., 2022), or overall satisfaction with the automated façade (Cheng et al., 2013, 2016; Clear et al., 2006; Day et al., 2019; Goovaerts et al., 2017; Gunay et al., 2017; Karlsen et al., 2015; Lolli et al., 2020; Luna-Navarro et al., 2022; Meerbeek et al., 2014; Painter et al., 2016). Three studies incorporated acceptance as a descriptor of the level of agreement with the control system implemented. Acceptance was studied in terms of the different modes of operation applied to venetian blinds (Vine et al., 1998) by registering occupant override actions that were intended as a lack of acceptance of the control logic operating the façade (Goovaerts et al., 2017; Gunay et al., 2017). Only one study considered occupant acceptance of the indoor environment (acceptance of the overall indoor environment (Lolli et al., 2019)).

TABLE 2 **Summary of type of occupant response reported by studies: overall response to the Control strategy & Façade technology (CS); Occupant response to the Indoor Environmental Quality (IEQ); None (N).**

	Occupant response to the indoor environment					
	Behaviour / Interaction Behaviour	Comfort	Satisfaction	Acceptance	Perception	Sensation
(Vine et al., 1998)	CS	IEQ	CS / IEQ	CS	N	N
(Guillemin & Morel, 2001)	CS	IEQ	N	N	N	N
(Guillemin & Morel, 2002)	CS	IEQ	IEQ / CS	N	N	N
(Clear et al., 2006)	CS	N	IEQ / CS	N	N	N
(Kim et al., 2009)	N	IEQ	N	N	N	N
(Lee et al., 2012)	CS	IEQ	CS	N	N	N
(Taniguchi et al., 2012)	N	IEQ	N	N	N	IEQ
(Cheng et al., 2013)	N	IEQ	CS	N	N	N
(Bakker et al., 2014)	CS	IEQ	IEQ / CS	N	CS	N
(Meerbeek et al., 2014)	CS	IEQ	IEQ / CS	N	N	N
(Karlsen et al., 2015)	N	IEQ	IEQ / CS	N	N	N
(Cheng et al., 2016)	CS	IEQ	IEQ	CS	N	N
(Painter et al., 2016)	N	IEQ	CS	N	N	N
(Sadeghi et al., 2016)	CS	IEQ	IEQ	N	CS	N
(Goovaerts et al., 2017)	CS	IEQ	CS	N	IEQ	N
(Gunay et al., 2017)	CS	IEQ	CS	CS	N	N
(Motamed et al., 2017)	N	IEQ	N	N	N	IEQ
(Choi et al., 2019)	N	N	IEQ	N	IEQ	N
(Day et al., 2019)	N	IEQ	IEQ / CS	N	N	N
(Lolli et al., 2019)	N	IEQ	CS	IEQ	N	IEQ
(Motamed et al., 2019)	CS	IEQ	N	N	N	N
(Wu et al., 2020)	N	IEQ	CS	N	N	IEQ
(Bian et al., 2020)	N	IEQ	N	N	N	IEQ
(Lolli et al., 2020)	N	IEQ	IEQ	N	N	IEQ
(Korsavi et al., 2021)	N	IEQ	CS	N	N	N
(Luna-Navarro et al., 2022)	CS	IEQ	IEQ / CS	N	N	N

A few studies also assessed perceived health (Choi et al., 2019) and productivity (Choi et al., 2019; Sadeghi et al., 2016). The least studied aspect of occupant response was sensation. Regarding the visual environment, Glare Sensation Vote (GSV) and Illuminance Rating (IR) were used to capture visual sensation. Thermal Sensation Vote was the subjective rating scale to capture occupant thermal sensation (TSV), which was assessed by using a 5-point Likert scale (from cold to hot) (Lolli et al., 2019, 2020).

3.2 CONTEXTUAL FACTORS AFFECTING OCCUPANT RESPONSE TO AF

All of the studies provide information about the context in which the experiments or the field measurements took place. Table 3 describes the contextual factors summarised from articles, classifying them into location, climate, orientation, testing facility, and floor layout. Regarding location, the studies were conducted in five European countries (14 studies), two North-American countries (7 studies), and three Asian countries (5 studies). Despite the variety of locations, the climates were limited to temperate and continental conditions (Fig. 2).

TABLE 3 **Summary of contextual factors described by previous works to assess the influence of façades on occupant response.**

	Climate	Orientation							Layout		
	Location	North	West	Southwest	South	Southeast	East	Non-declared	Open plan	2-3 persons office	Single office
(Vine et al., 1998)	Oakland, California - US					√					√
(Guillemin & Morel, 2001)	Lausanne - Switzerland				√						√
(Guillemin & Morel, 2002)	Lausanne - Switzerland				√						√
(Clear et al., 2006)	Berkeley, California - US				√						√
(Kim et al., 2009)	Seoul - South Korea		√		√		√		√		
(Lee et al., 2012)	Berkeley, California - US		√							√	
(Taniguchi et al., 2012)	Hiratsuka - Japan							√			√
(Cheng et al., 2013)	Beijing - China						√			√	
(Bakker et al., 2014)	Eindhoven - The Netherlands		√								√
(Meerbeek et al., 2014)	Eindhoven - The Netherlands				√					√	
(Karlsen et al., 2015)	Aalborg - Denmark				√						√
(Cheng et al., 2016)	Beijing - China						√				√
(Painter et al., 2016)	Leicester - U							√		√	
(Sadeghi et al., 2016)	West Lafayette, Indiana -US				√						√
(Goovaerts et al., 2017)	Brussels - Belgium					√					√
(Gunay et al., 2017)	Ottawa - Canada			√							√
(Motamed et al., 2017)	Lausanne - Switzerland		√		√						√
(Choi et al., 2019)	Toronto - Canada							√	√		
(Day et al., 2019)	Charlotte/Richmond/Virginia - US			√					√		
(Lolli et al., 2019)	Trondheim - Norway				√						√
(Motamed et al., 2019)	Lausanne - Switzerland				√						√
(Wu et al., 2020)	Lausanne - Switzerland				√					√	
(Bian et al., 2020)	Guangzhou - China					√					√
(Lolli et al., 2020)	Trondheim - Norway				√						√
(Korsavi et al., 2021)	Plymouth - UK	√			√				√		
(Luna-Navarro et al., 2022)	Cambridge - UK				√					√	

In terms of the relevance of the weather conditions, Clear et al. (2006) pointed out that two parameters were strongly correlated to occupant behaviour, such as the variation of the sky conditions and the outdoor vertical illuminance. Korsavi et al. (2021) have also reported that occupant behaviour can be impacted by building-related features such as orientation and floor level on automated window operation. Lolli et al. (2019) and Luna-Navarro et al. (2020) showed that orientation and sky condition affect blind occlusion. Moreover, depending on the hemisphere, some orientations can be more challenging. For example, the west and east orientation in the northern hemisphere is challenging due to the low-angle sun situations during the late winter and early spring (Day et al., 2019), while south orientation can be more challenging for overheating. In most cases, the studies were conducted with south-oriented façades (14 studies).

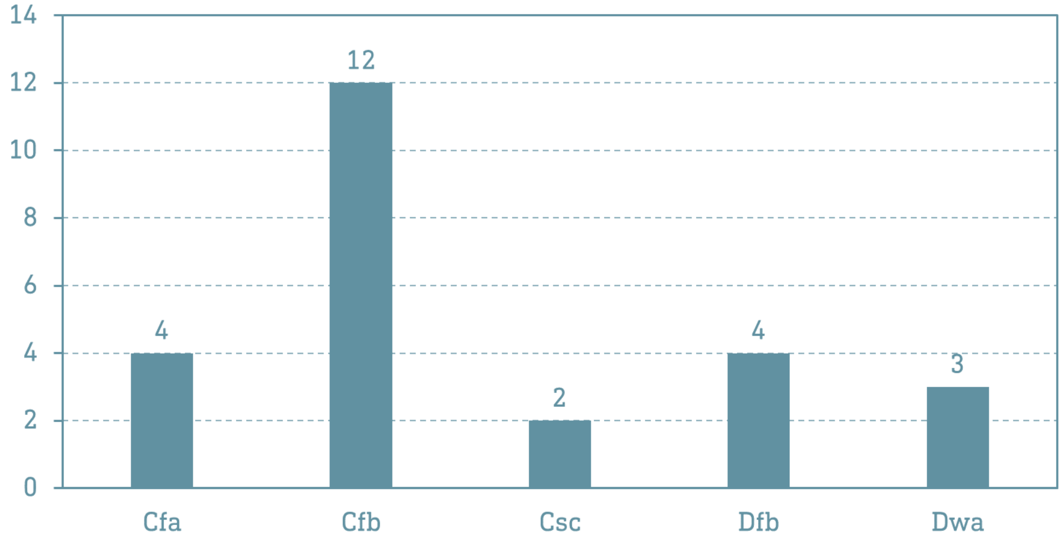

FIG. 2 Climate where the reviewed studies were performed (classification according to the Koppen Climate). The climates are: humid sub-tropical climate (Cfa); temperate oceanic climate (Cfb), cold-summer Mediterranean climate (Csc), warm-summer humid continental climate (Dfb), Monsoon-influenced hot-summer humid continental climate (Dwa).

Concerning where the study took place, two main locations were found: laboratory and real office building (Fig. 3). Laboratory refers to a room fully equipped with sensors and other instruments and that can be adjusted to create the desired experimental conditions and collect relevant data from the indoor environment and occupants. In addition, laboratories are occupied by users only for the purpose of conducting an experiment. In contrast, real office building includes real-world occupied buildings. The studies were split almost eqally between field and lab environments.

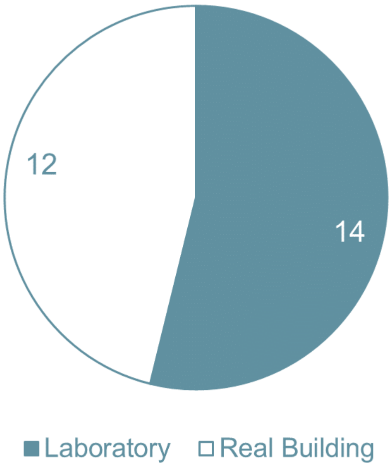

FIG. 3 Pie chart diagram with the number of studies performed on laboratory and real buildings.

Some studies showed that the number of occupants and room characteristics may impact occupant response. Clear et al. (2006) mentioned that visual dissatisfaction reported by occupants was not only produced by the level of sun exposure of the windows but also by the interior walls and object reflection. Additionally, occupants indicated that the room's colour was a source of dissatisfaction.

The weather conditions impact occupant response, and the magnitude of its impact depends on other factors such as orientation, building characteristics, obstructions, window size, and indoor features (Karlsen et al., 2016). Also, indoor room characteristics, such as type of layout, wall colour, amenities, and office features have been proven to affect comfort perception, satisfaction, and occupant response (Bakker et al., 2014; Clear et al., 2006).
Regarding the number of occupants in the same room, Cheng et al. (2016) and Bian et al. (2020) stated that the situation of multiple persons in the general space, performing different tasks should affect the occupant's response to the automated control, even changing throughout the day. However, only a few studies have studied occupant response in shared office spaces.

3.3 PERSONAL FACTORS AFFECTING OCCUPANT RESPONSE TO AF

Personal factors might affect occupants' behaviour and perception, varying from person to person and depending on specific occupants' attributes (Clear et al., 2006). Based on the articles reviewed, personal factors that might affect occupant response are shown in Fig. 4 and are grouped into: "General characteristics", "Personal attitudes", and "Personal significance of the environmental quality". General characteristics refer to the group of features that describe each individual, such as age, gender, profession or work performed, use of glasses, visual disability, handedness, eye colour, and ethnicity (Karlsen et al., 2015). Attitudes refer to the predisposed state of mind of occupants, including habituation to the laboratory or test room, enjoyment of task, pleasantness of the indoor space, rest, and mood (Clear et al., 2006). Finally, personal significance of the environmental quality defines the level of importance that an occupant attributes to a specific environmental domain, such as visual aspects, thermal aspects, air quality, acoustic aspects, privacy, personal control, and room quality, e.g. amenities or services in the room (Sadeghi et al., 2016).

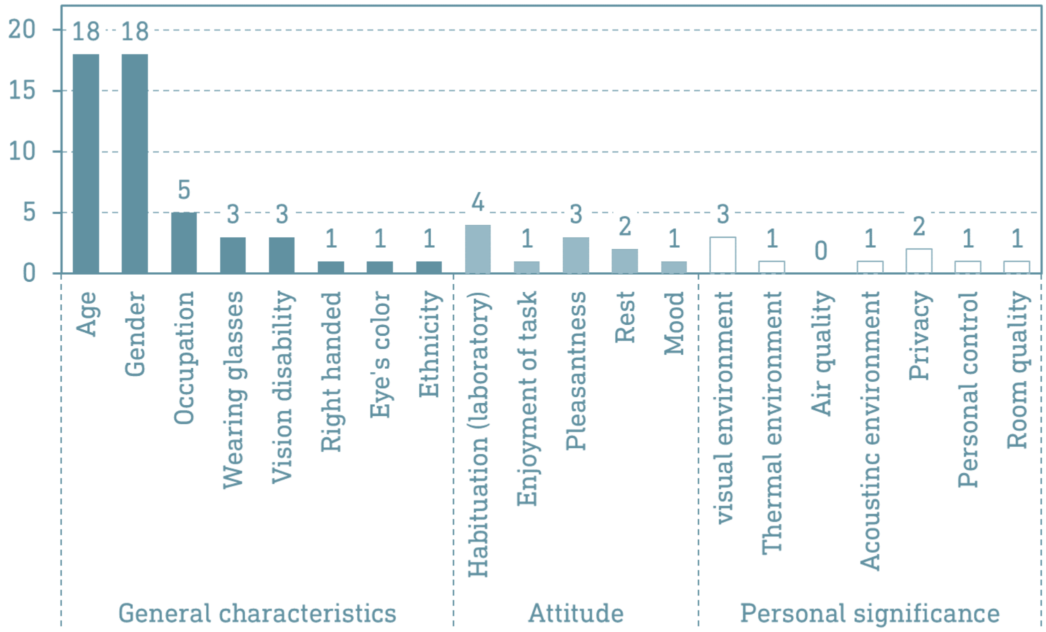

FIG. 4 The number of studies that investigated personal factors in previous works as affecting occupant response to automated façades are shown per type of personal factor studied: general characteristics, attitude, and personal significance of the indoor environmental condition.

The most reported personal characteristics were age and gender, while the level of rest was rarely considered. Five studies included occupants' attitudes (Clear et al., 2006; Karlsen et al., 2015; Luna-Navarro et al., 2022; Motamed et al., 2017; Sadeghi et al., 2016), with Luna-Navarro et al. (2022) being the study that took into account the most attitude descriptors. A few studies considered the personal significance of environmental characteristics, such as visual environment, thermal environment, air quality privacy, personal control and room quality (Clear et al., 2006; Karlsen et al., 2015; Sadeghi et al., 2016). Clear *et al.* (2006) gave a detailed summary about all of them.

Even though most of the studies gathered personal information, the data was often not used to differentiate the results and provide evidence about the importance of occupants' characteristics, attributes, and personal significance in response to automated façades. Overall, three out of twenty-six studies differentiated the data on one or more personal factors to evaluate their impact on occupant response. Clear et al. (2006) reported that age, gender, and other characteristics affected occupants' responses to the electrochromic window operation. This was determined by finding correlations between characteristics of the subjects and appraisals of the different test modes. The main findings were a significant correlation (explained by the level of fitness R^2) between the importance of quiet and sensitivity to environmental noise ($R^2 = 0.48$), the importance of access to outdoor view and the importance of windows ($R^2 = 0.25$), the importance of good lighting and the importance of light and window control ($R^2 = 0.22$), and the importance of good temperature control and the sensitivity to both heat and cold ($R^2 = 0.26$). Karlsen et al. (2015) analysed the percentage of males and females who selected one of the two control strategies (simple and detailed) or the option 'No preference'. Using a Fisher test, the analysis showed no significant dependence between gender and preferred control strategy. Painter et al. (2016) examined the data for studying user interaction, considering that one out of the four participants had a visual condition that affected her vision at times and increased her sensitivity to light. However, no evidence was reported about the effect of the visual conditions in the responses provided by the occupant.

Some authors pointed out that personal factors may determine whether the selected control threshold would lead to a satisfactory indoor environment (Lee et al., 2012; Painter et al., 2016). For instance, personal significance to specific surroundings impacts occupant tolerance to indoor environmental conditions. Karlsen et al. (2015) suggested that the participants might tolerate some glare disturbance depending on the relative importance of access to the outside view. Even the occupants' knowledge (regarding habituation) about the system functionality may impact their ability to interact with the automated façade (Bakker et al., 2014; Lee et al., 2012; Sadeghi et al., 2016). Additionally, specific users' characteristics, such as wearing glasses (Lee et al., 2012) and visual conditions (Painter et al., 2016), could explain why some occupants are more likely to prefer different lighting conditions.

Several studies did not report information on personal factors, both in the laboratory and in field studies. This includes a lack of clear information about general characteristics (e.g. wearing glasses, vision disability, handedness, eye colour), attitude (e.g. habituation, enjoyment, pleasantness, rest, mood), and personal significance (regarding the visual, thermal, air quality, personal control, room, and acoustic environment).

3.4 IMPACT OF OCCUPANT RESPONSE TO INDOOR ENVIRONMENTAL CONDITIONS ON OCCUPANT OVERALL SATISFACTION WITH AF

Occupant response to indoor environmental condition was taken into account in 26 studies when evaluating the performance of AF. The indoor environmental conditions were evaluated by capturing a wide range of comfort domains, particularly in the visual and thermal domains (see Table 4).

TABLE 4 **Summary of environmental domains measured by sensors and occupant responses captured by questionnaires investigated in previous works.**

	Visual environment											
	Outside view	Daylight	Glare	Thermal Environment	Acoustic Environment	Indoor air quality	Behaviour and Interaction	Comfort	Satisfaction	Acceptance	Perception	Sensation
(Vine et al., 1998)		√		√	√		√	√	√	√		
(Guillemin & Morel, 2001)	√	√		√			√	√				
(Guillemin & Morel, 2002)		√					√	√	√			
(Clear et al., 2006)		√					√		√			
(Kim et al., 2009)		√		√				√				
(Lee et al., 2012)		√		√			√	√	√			
(Taniguchi et al., 2012)		√						√				√
(Cheng et al., 2013)		√						√	√			
(Bakker et al., 2014)	√	√		√			√	√	√		√	
(Meerbeek et al., 2014)	√			√			√	√			√	
(Karlsen et al., 2015)		√	√					√				√
(Cheng et al., 2016)		√					√	√	√	√		
(Painter et al., 2016)		√	√					√	√			
(Sadeghi et al., 2016)	√	√	√	√			√	√	√		√	
(Goovaerts et al., 2017)		√	√	√			√	√	√	√		
(Gunay et al., 2017)		√					√		√	√		
(Motamed et al., 2017)		√	√					√				√
(Choi et al., 2019)		√							√		√	
(Day et al., 2019)		√	√	√				√	√			
(Lolli et al., 2019)		√	√						√	√		√
(Motamed et al., 2019)		√	√				√	√				
(Wu et al., 2020)		√	√					√	√			
(Bian et al., 2020)		√	√					√				√
(Lolli et al., 2020)		√	√						√			√
(Korsavi et al., 2021)				√	√				√			
(Luna-Navarro et al., 2022)		√	√	√	√	√	√	√	√			
Total	4	24	12	11	3	1	13	20	18	4	4	6

The visual environment was evaluated by measuring daylight levels (24 studies), glare probability (12 studies), and access to outside view (4 studies). Daylight was very often measured on the work plane in terms of horizontal illuminance (18 studies) and vertical illuminance (10 studies). Glare probability was calculated by measuring vertical illuminance at eye level (6 studies) and luminance distribution from the occupant's point of view by HDR imaging (6 studies). Access to outside view was monitored by estimating the visible unobstructed window area (1 study). The thermal environment was captured by measuring indoor air temperature (9 studies), window surface temperature (2 studies) and vertical irradiance at the window plane (3 studies). The acoustic environment (1 study) and indoor air quality (1 study) were not extensively described since the articles reviewed are talking about dynamic shading devices.

Although several studies captured occupant response to indoor environment, only a few reported that occupant response to indoor environmental conditions affected occupants' response to AF (Fig. 5), either in terms of the visual environment, thermal environment, privacy and acoustic comfort. Several studies showed that occupant response to automated control strategies was significantly driven by occupant dissatisfaction with indoor illuminance control (21 studies). Regarding visual occupant requirements, office occupants tended to prefer higher indoor illuminance levels when the AF was activated (Bakker et al., 2014; Cheng et al., 2013; Clear et al., 2006; Guillemin & Morel, 2002; Lee et al., 2012; Vine et al., 1998). Sadeghi et al. (2016) and Goovaerts et al. (2017) reported that override actions to open the façade were carried out when increasing daylight was needed, while Motamed et al. (2017) described that the preference for the automated mode was driven by the discomfort produced on excessive daylight indoor conditions. Additionally, it was told that occupants' illuminance requirements differ with tasks and areas (Cheng et al., 2016), changing even throughout the day (Bian et al., 2020). Vine et al. (1998) indicated that occupants were satisfied not only with the ability to control the blinds to adjust the amount of daylight but also to adjust the direction and distribution of the daylight in the indoor space.

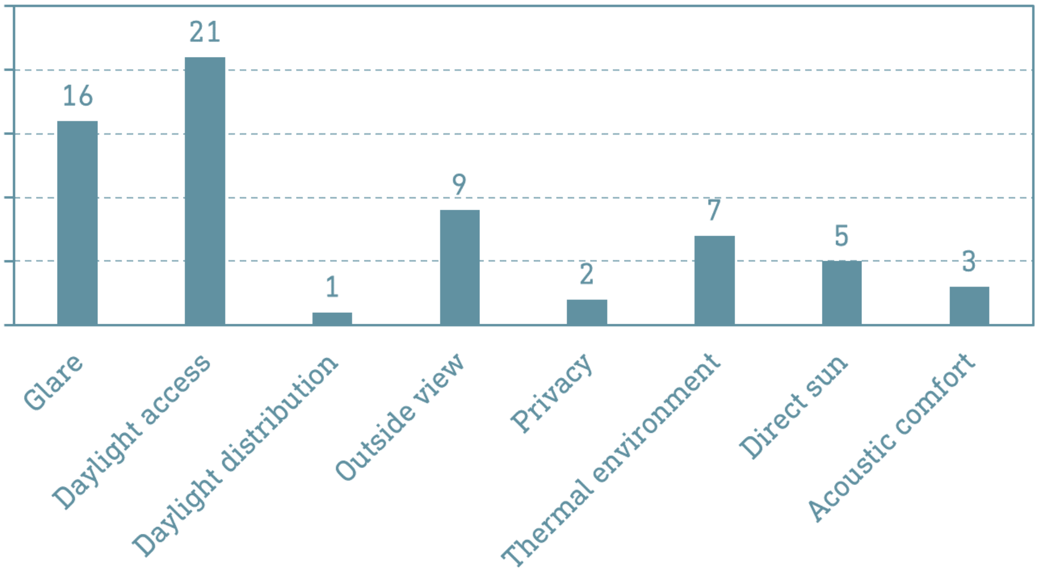

FIG. 5 The number of studies that showed that environmental factors affect occupant response with the AF operation.

Glare discomfort is the most frequent factor affecting occupants' responses to the automated control (16 studies). When the automated control did not effectively protect against glare, occupants overrode (Goovaerts et al., 2017; Gunay et al., 2017; Lolli et al., 2019; Sadeghi et al., 2016) or adjusted the control parameter as allowed (Bian et al., 2020). Glare competes with daylight provision. When the automated control was operated based on glare, occupants intervened to improve daylight quality (Gunay et al., 2017; Meerbeek et al., 2014). When the automated control avoided discomfort from direct sun and or glare, occupants preferred more daylight (Lolli et al., 2019; Meerbeek et al., 2014; Motamed et al., 2017).

Other studies also suggested that the outside view impacts occupants' environmental preferences (9 studies), influencing even the choice of the preferred control strategy (Karlsen et al., 2015; Luna-Navarro et al., 2022). Clear et al. (2006) and Meerbeek et al. (2014) pointed out that the outside view was an important comfort factor for the occupants, who were operating the façade not only to improve the connection with the outside but also to decrease the level of visual stimulus from the exterior. Gunay et al. (2017) described that occupants interfered with the automated control mainly to improve the outside view when the system worked to avoid glare.

A few studies also mentioned that occupant response was impacted by privacy (3 studies). Sadeghi et al. (2016) mentioned privacy as the most important factor affecting lowering blind actions together with glare discomfort. However, privacy depends on contextual characteristics such as the surrounding environment and position in the building. For instance, Meerbeek et al. (2014) explain that the subjects surveyed were not worried about privacy because the office was located on the third floor, far away from the street level.

Dissatisfaction with the thermal environment was mainly related to the ability of the façade to control the incoming solar radiation (Lolli et al., 2019; Sadeghi et al., 2016) or to provide air flow, as suggested by Korsavi et al. (2021) and Lolli et al. (2020). A few studies surveyed occupants to calculate the predicted mean vote (PMV) (Kim et al., 2009).
A few studies also reported acoustic environmental conditions and acoustic satisfaction (4 studies). Luna-Navarro et al. (2022) pointed out that acoustic discomfort was the main driver of occupant dissatisfaction with the façade system.

Studies have also reported that metrics used to capture occupant requirements presented problems when implemented into the automated façade control system. Goovaerts et al. (2017) informed that DGP underestimated the impact of direct sunlight, which generated the set-point lowered by users when direct sunlight was present. A similar problem was reported by Taniguchi et al. (2012) when the algorithm to evaluate indoor luminance overestimated glare sources in the afternoon. Other authors have said people's glare sensation increases gradually from morning until midday but becomes stable or more sensitive to glare in the afternoon (Bian et al., 2020).
The majority of the studies investigated the impact of control strategies on occupant's visual domain. On the thermal domain, articles did not report conclusions on how an automated façade affects the thermal environment.

How distance from the façade affects occupant interaction with the façade is still undetermined. Only Day et al. (2019) mentioned that the window's proximity improves occupants' satisfaction. Moreover, the impact of indoor environmental conditions on the occupant response to the automated façade has not been researched sufficiently, making it difficult to extrapolate results, throughout different façade technologies, control logics, and under different weather conditions, to improve current control strategies.

What the main drivers of occupant satisfaction with automated façades are, remains undetermined, in particular whether or not there is an inherent order of importance among different environmental domains. For example, it has been reported that occupants significantly value daylight access (Lee et al., 2012) and outside view (Choi et al., 2019; Wu et al., 2020) and that these factors are often the main reason for overriding an automated façade control system (Meerbeek et al., 2014). The personal level of control also influences occupant environmental requirements. Thus, occupant preferences may be different depending on the interaction level provided by the façade controller (Luna-Navarro et al., 2020). However, there is no clear evidence on whether or not a hierarchy of comfort domains exists.

3.5 THE EFFECT OF CONTROL AND INTERACTION LOGIC ON OCCUPANT RESPONSE TO AF

The control and interaction strategy influences occupant response to the automated façade (Bakker et al., 2014). As a way to improve occupant satisfaction with the automated façade, studies have tested different control strategies. Table 5 summarises the main characteristics of the control logics studied up to now. Additionally, the table gives information on the sensor position (interior/exterior).

TABLE 5 **Summary of environmental domains measured by sensors and occupant responses captured by questionnaires investigated in previous works.**

	Control loop		Source of information			Control algorithm			Control algorithm					Sensor place			
									Visual Environment								
	Closed-loop	Open-loop	Sensor-based	Model-based	Others	Rule-based	Adaptive	Predictive	Outside view	Daylight	Glare	Thermal Environment	Air quality	Exterior	Interior	On occupant	Occupant interaction
(Vine et al., 1998)	√		√		√	√			√	√					√		√
(Guillemin & Morel, 2001)	√		√	√			√	√	√	√		√		√	√		√
(Guillemin & Morel, 2002)	√		√	√			√	√	√	√		√		√	√		√
(Clear et al., 2006)	√		√			√				√	√				√		√
(Kim et al., 2009)		√	√			√				√		√		√			
(Lee et al., 2012)	√		√		√	√				√	√				√		√
(Taniguchi et al., 2012)	√		√	√	√	√				√	√			√			
(Cheng et al., 2013)	√		√	√	√	√	√			√	√			√		√	
(Bakker et al., 2014)	√	√	√		√	√				√					√		√
(Meerbeek et al., 2014)		√	√		√	√				√					√		√
(Karlsen et al., 2015)		√	√		√	√				√	√	√		√	√	√	
(Cheng et al., 2016)	√		√	√			√			√					√	√	√
(Painter et al., 2016)		√	√			√				√	√				√		
(Sadeghi et al., 2016)		√	√		√	√				√					√		√
(Goovaerts et al., 2017)		√	√		√	√				√	√				√	√	√
(Gunay et al., 2017)	√		√		√		√	√		√					√		√
(Motamed et al., 2017)	√		√	√		√				√	√				√	√	
(Choi et al., 2019)		√	√			√				√					√		
(Day et al., 2019)		√	√			√				√					√		
(Lolli et al., 2019)		√	√			√				√					√	√	
(Motamed et al., 2019)	√		√		√	√				√		√			√	√	√
(Wu et al., 2020)		√	√	√	√	√				√	√			√		√	
(Bian et al., 2020)					√											√	
(Lolli et al., 2020)	√		√		√					√		√			√	√	
(Korsavi et al., 2021)	√		√			√						√			√		
(Luna-Navarro et al., 2022)		√	√			√						√		√			√

Sadeghi et al. (2016) reported a dependency between façade configuration (shade position or window transmittance) and occupant satisfaction with the indoor environment. Clear et al. (2006) and Day et al. (2019) pointed out a similar situation for the switchable glazing operation. When electrochromic glazing became opaque, occupants felt more dissatisfied with that configuration, leading to override actions to improve daylight and outside view.

Regarding control loops, studies have described two types: open-loop (12 studies) and closed-loop (14 studies). The control logics used three different sources of information: sensor-based (25 studies), model-based (7 studies), and others (e.g. time, sun profile, weather file, and schedule). The low number of model-based control cases is explained by the fact that this method is computationally intense, lacking in algorithms to develop occupant models inside building controllers (Gunay et al., 2017). The control algorithm implemented in the façade control system was classified into three categories: rule-based (20 studies), adaptive (5 studies), and predictive (3 studies). Most studies implemented rule-based algorithms to control automated façade systems. The adaptive algorithms found were Q-Learning (Cheng et al., 2016) and recursive learning (Gunay et al., 2017). Only three studies implemented a predictive algorithm to analyse and integrate outdoor weather and indoor lighting conditions into a model-based system (Guillemin & Morel, 2001; 2002) to anticipate occupant interaction with the automated façade system (Gunay et al., 2017).

Automated façade control can improve indoor environmental quality (Clear et al., 2006; Kim et al., 2009; Lolli et al., 2019; Motamed et al., 2019), although the effect on occupant satisfaction varies from case to case. For instance, Lolli et al. (2020) reported that automated control improved the desired indoor environmental quality. Similarly, Luna-Navarro et al. (2022) showed that, when the control strategy is properly designed, automated control can provide greater satisfaction than a manually controlled environment. However, if the automated control is disruptive to users, manual controls outperform automated ones. On the contrary, Motamed et al. (2017) showed that the subjects' visual performance was not improved by automated control strategies. Therefore, the type of control strategy is an important factor for occupant satisfaction. The impact of façade control operation affects the indoor space zones differently. Day et al. (2019) reported that occupants placed in the interior, far away from the window did not receive enough daylight when the switchable glazing became dark, and occupants were ultimately displeased with their workspaces.

In regards to determining what aspects of the control strategy most affect occupants, current evidence is fragmented. In terms of control thresholds, Goovaerts et al. (2017) showed that different controls could achieve equal indoor illuminance levels on a desk in the same context but still affect satisfaction among occupants differently. Therefore, personalising the control threshold may not be sufficient to meet individual occupant requirements. In this context, it seems well-established that occupants have individual comfort preference (Cheng et al., 2013) and behavioural responses under different control algorithms (Korsavi et al., 2021). However, to what extent personalisation of control strategies is required is less clear. The automated control's capability to predict occupant preferences is deemed important to improve occupant satisfaction with automated controls (Meerbeek et al., 2014).. A predictive lighting and blinds control algorithm can significantly reduce electric lighting consumption in perimeter office spaces whilst mantaining user comfort (Gunay et al., 2017). The predictive control strategy should incorporate as many profiles as there are occupants in the indoor space (Korsavi et al., 2021). Painter et al. (2016) mentioned that a solution might be to develop tools that allow the system to evaluate comfortable and uncomfortable conditions based on physical measurements and occupant control actions. However, capturing more than one user profile and integrating all that information is one of the challenges that adaptive and predictive control strategies currently face.

Few studies advocated for controlling and designing the façade by taking into account the multi-domain influence of façades on users (Luna-Navarro et al., 2022), however, there is still discussion on whether one environmental domain should be prioritised by the control (visual over thermal) or visual aspect (glare over daylight) . This is particularly challenging since adjusting one comfort domain can affect the others. For example, Goovaerts et al. (2017) showed that occupants overrode the automated control to increase daylight when it was configured to avoid discomfort glare. Karlsen et al. (2015) mentioned that occupants felt more comfortable with the automated control when it considered indoor environmental parameters affecting their satisfaction perception (in this case, thermal aspects). Gunay et al. (2017) pointed out that occupants intervened to improve the view quality when the system operated based on glare mitigation or building energy efficiency.

Regarding the mode of operation, several studies indicated that the automated façade might influence occupant response because it affected not only the physical parameter defining indoor environmental quality but also impacted the fulfilment of the occupant requirements for personal control (Meerbeek et al., 2014). For instance, Bakker et al. (2014) reported that less frequent, discrete transitions in façade operation are better appreciated than smooth transitions at a higher frequency. However, this topic is largely unexplored. Personal control is key to restoring comfort when the system is not efficient in controlling environmental parameters (Day et al., 2019). Guillemin & Morel (2002) reported that occupants interacted with the automated control as often as the manual control system, reinforcing that comfortable indoor conditions are insufficient for occupants.Occupant environmental requirements and preferences are influenced by the level of control over the system, being able to accept automated control only if they can control it when they need to. Limited indoor environment control has detrimental effects on occupant comfort (Lolli et al., 2020). Furthermore, interaction strategy could work in the opposite direction, being a source of distraction if occupants are involved in the system's operation too frequently (Bakker et al., 2014).

3.6 THE EFFECT OF FAÇADE TECHNOLOGY ON OCCUPANT RESPONSE TO AF

The type of façade technology affects occupant response to automated control strategies because each façade technology offers a different range of dynamic performances, such as controlling visual transmittance, blocking incoming solar radiation, and redistributing daylight in the indoor space. Additionally, different façade technologies have different performances in terms of their ability to balance conflicting requirements, such as glare versus daylight access, solar transmittance versus surface temperature, and privacy versus outdoor view.

Table 6 summarises the façade systems and the position of the shading system. Regarding façade technologies, the main shading system tested in previous work is that of venetian blinds (16 studies), followed by roller shades (8 studies). Switchable glazing has also been evaluated (5 studies), while window opening was the least implemented (2 studies). The automated control controlled a range of façade characteristics, which depended on the technology implemented. In the case of venetian blinds, the system controlled the slats deployment (hold/release) and slat tilt, for roller shades it controlled up and down positions, switchable glazing allowed the modification of glass visual transmittance, while for window opening the window aperture percentage was controlled.

The type of façade also defines how disruptive a control strategy will be. For instance, Luna-Navarro et al. (Luna-Navarro et al., 2022) reported that placing the blinds within the cavity resulted in more effective control of the solar heat gains and was less disruptive to occupants, especially in terms of their associated noise. Bakker et al. (2014) reported that occupants close to the operation of roller shades were the most disrupted by them. Vine et al. (1998) mentioned that the transition from one position to another, the activation frequency, and the sound generated was considered sources of distraction. Moreover, Wu et al. (2020) also pointed out that the speed of switching also had an impact on occupant satisfaction, who preferred slower and smooth transitions.

TABLE 6 **TABLE 6. Summary of façade technologies included by previous works to assess the influence of façades on occupant response.**

	Façade system				Shading device placement		
	Switch-able Glazing	Roller shade	Venetian blind	Window opening	Interior	In the cavity	Exterior
(Vine et al., 1998)			√		√		
(Guillemin & Morel, 2001)			√				
(Guillemin & Morel, 2002)			√				
(Clear et al., 2006)	√		√		√		
(Kim et al., 2009)			√		√		
(Lee et al., 2012)	√						
(Taniguchi et al., 2012)			√		√		
(Cheng et al., 2013)			√				√
(Bakker et al., 2014)		√			√		
(Meerbeek et al., 2014)			√		√		
(Karlsen et al., 2015)			√		√		
(Cheng et al., 2016)			√				√
(Painter et al., 2016)	√						
(Sadeghi et al., 2016)		√			√		
(Goovaerts et al., 2017)			√		√		
(Gunay et al., 2017)		√			√		
(Motamed et al., 2017)		√					√
(Choi et al., 2019)	√						
(Day et al., 2019)	√	√	√		√		
(Lolli et al., 2019)			√		√		
(Motamed et al., 2019)		√					√
(Wu et al., 2020)			√				√
(Bian et al., 2020)			√		√		
(Lolli et al., 2020)		√		√	√		
(Korsavi et al., 2021)				√			
(Luna-Navarro et al., 2022)		√	√		√	√	

4 CONCLUSIONS

This work reviewed twenty-six previous laboratory experiments and field studies that monitored occupant response to automated façades. These studies were reviewed to gather and analyse current evidence on the influence of the following factors on occupant response to AF: (1) contextual factors, (2) personal factors, (3) environmental conditions, (4) control logic, and (5) façade technology.

Throughout the evidence gathered, this literature review shows how occupant response to the AF is captured in terms of occupant behaviour or interaction with the automated control, satisfaction with the interaction strategy, level of acceptance of the automated control logic, perception of the indoor environmental conditions, and sensation regarding specific environmental domains affected by the AF operation. The focus of existing studies was limited to a few climatic conditions and similar types of buildings. In most studies, the experiments took place in single office layouts, and data on occupant response to AFs in open-plan office spaces is scarce.

Regarding the aspects affecting occupant response to AF operation, studies indicated that personal factors impact occupants' behaviour and perception of the indoor environment, varying from person to person and depending on the specific attributes of occupants. Most of the studies reported personal characteristics, but attitudes and personal significance of indoor environmental quality were missed by most of the articles reviewed.

Concerning the control strategy, occupant interaction with the automated control is an essential determinant of occupant requirements for the AF operation. Occupant requirements and preferences are influenced by the level of control over the system, accepting automated control only if they can control it when they need to. Additionally, occupant interaction with the AF is driven primarily to fulfil personal environmental requirements, such as increasing daylight, privacy, access to views, and avoiding glare discomfort. Although AF can provide "comfortable" indoor environmental conditions, it does not properly ensure the achievement of individual environmental requirements and preferences.

In terms of the impact of façade technology, the type of technology affects how disruptive a façade is and depending on the technology, the overall satisfaction could be higher or lower. In particular, differences in façade effects are noticeable when technologies compromise one environmental domain in favour of another.
Overall, several barriers still exist to automated façades that can enhance occupant response, and further research effort is required to answer the following gaps:

1. relationship between personal factors and occupant response to AF, in particular there is the need to establish common methods for gathering evidence in this domain, since the majority of the studies do not consider personal factors;
2. poor understanding of occupant multi-domain comfort preferences regarding façade operation. Unlocking a holistic and more comprehensive knowledge of occupant response to automated façades should be used to achieve more user-centric automated façade solutions.
3. the lack of research to define to what extent learning and personalised control are possible and, in such a case, how to deal with multiple occupants in the same room operating a unique automated façade.

In addition, extending the test scenario to different climates or contextual conditions would be very beneficial, since studies were mainly concentrated on a few climates and conditions. This also undermines generalisation, since larger replication within the same conditions would be beneficial to extend the results.

Ultimately, there is the need for new studies that can demonstrate the benefits of automated façade control strategies and whether personalised controls are necessary to achieve higher occupant satisfaction whilst reducing the energy demand.

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