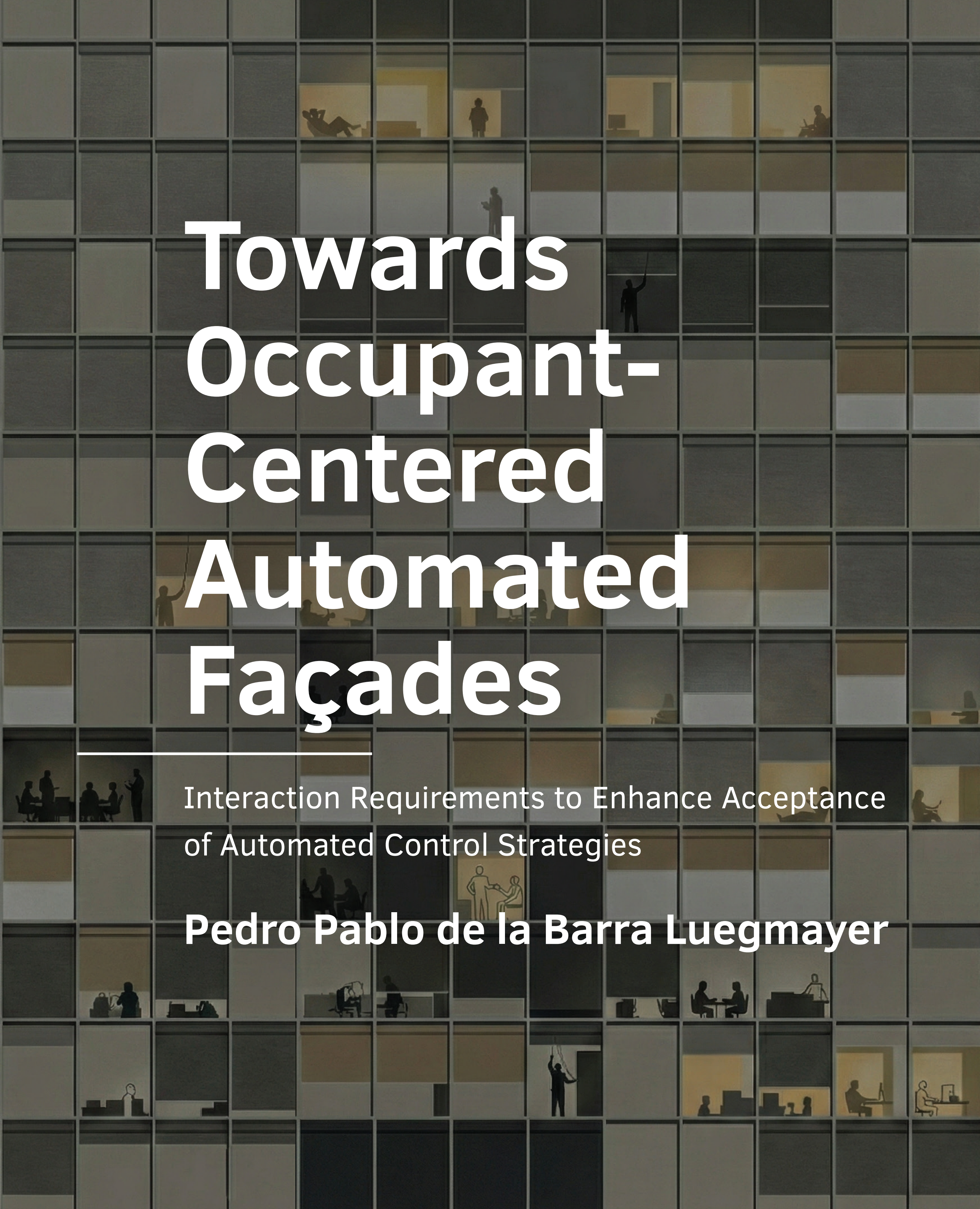

Towards Occupant-Centered Automated Façades

Interaction Requirements to Enhance Acceptance of Automated Control Strategies

Pedro Pablo de la Barra Luegmayer

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Dissertation

for the purpose of obtaining the degree of doctor
at Delft University of Technology
by the authority of the Rector Magnificus,
Prof.dr.ir. H. Bijl,
chair of the Board for Doctorates
to be defended publicly on
Thursday, 4 June 2026 at 17:30

by

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This dissertation has received funding from the European Union’s Horizon Europe Research and Innovation Programme under Grant Agreement No. 101103956 (SMARTeeSTORY). This work was also supported by the Agencia Nacional de Investigación y Desarrollo (ANID), Chile, under the Doctoral Scholarship Programme (Scholarship ID 72200582).

Keywords: Automated Façades, Building Automation, Human-Building Interaction, Indoor Environmental Quality (IEQ), Control Interfaces, Human Factors, Occupant Satisfaction, Energy Efficiency, Office Buildings

Printed by: CB
Design by: Sirene Ontwerpers, Véro Crickx
Cover by: Pedro Pablo de la Barra Luegmayer

Series: A+BE | Architecture and the Built Environment
ISBN: 978-94-6518-345-9
ISSN: 2212-3202

An electronic version of this dissertation is available at: http://repository.tudelft.nl

A+BE | Architecture and the Built Environment | TU Delft BK | **26#11**

This dissertation is open access at https://doi.org/10.71690/abe.2026.11

To my parents, Elizabeth and Pablo,
my sisters, Camila and Daniela,
my nephews and niece, Martín, Mateo, and Amanda,
my children, Antonia and Borja,
and my wife, Carolina,
with love.

Acknowledgments

This doctoral research, although having my name on the cover, is the outcome of a shared journey. It has been shaped by the presence, generosity, and encouragement of many people along the way.

I would like to begin by expressing my sincere appreciation to my supervisors. **Prof. Dr.-Ing. Ulrich Knaack**, thank you for the opportunity to pursue this PhD. It has been an experience that has contributed not only to my professional development but also had a meaningful impact on my family. **Dr.-Ing. Alessandra Luna Navarro**, I greatly value your trust, steady support, and the opportunity to work on projects that were both challenging and rewarding. Your patience and commitment created the space to grow, improve, and remain motivated throughout the process. **Dr. Eleonora Brembilla**, thank you for your feedback and encouragement, which consistently helped strengthen the work and maintain direction.

I would also like to express my appreciation to the independent members of the doctoral committee: **Prof. dr. ir. Atze Boerstra**, **Prof. dr. ir. Yvonne de Kort**, **Prof. Dr. Burcin Becerik-Gerber**, **Prof. dr. ing. Runa Hellwig**, and **Prof. dr. ir. Martin Tenpierik**. I am grateful for the time dedicated to evaluating this dissertation.

A special mention goes to **Pablo Martínez Alcaraz**, whose support never weakened. Our collaboration, your clarity of thought, and your attention to detail brought structure to both the work and everyday life.

I owe much to those who guided my first steps into research. **Claudio Vásquez** played a key role in opening this path and encouraging me to pursue it. **Renato d'Alençon** offered perspective and optimism during challenging moments, alongside a way of working I deeply admire. **Gracian Figueroa** shared his knowledge of electronics and programming, skills that became essential to my research interests. **Alejandro Prieto** provided valuable guidance during the PhD application process, helping me take the first step in this journey.

My appreciation extends to the department and its support staff. **Daniël Pantophlet**, **Carla van der Krogt**, **Barbara van Vliet-van der Haas**, **Sasha Kasturiarachchi**, and **Annelies Friesser** offered support across a wide range of matters, from administrative processes to personal guidance, making a crucial difference and allowing me to feel part of the department and at home. **Mauro Overend**, **Kim Scheffelaar**, **Thaleia Konstantinou**, **Olga Ioannou**, and **Marcel Bilow** contributed to creating an academic environment that is both collaborative and supportive.

I am grateful to the team at **The Green Village**, especially **Tim Jonathan**, **Marijn Leeuwenberg**, **Jean-Paul de Garde**, and **Nando Versteeg**, for their support during the experimental work. At the **Science Centre Delft**, **Simon Aerts** made dissemination efforts both possible and enjoyable.

To my research group (**Adam Pajonk**, **Alvaro Balderrama**, **Victoria Davalos**, **Amin Jalilzadeh**, **Amira Elnouty**, **Diletta Ricci**, **Kyujin Kim**, and **Magdalena Zabek**), our discussions, shared seminars, and visits enriched both the research and the experience.

To my colleagues in the PhD room and the AET department (far too many to name individually), your companionship, shared lunches, and moments beyond work created a sense of community that carried me through these years. I would still like to acknowledge **Justin Schembri**, **Aga Kuś**, **Yan Zhou**, **Anna Maria Koniari**, **Komal Potdar**, **Sasja van Andel**, **Lara Neuhaus**, **Wilfried Damen**, **Jack O'Hagan**, **Bodil Eiterstraum**, **Carla Chacón**, **Juan Carlos Prazmowski**, **Brenda Loeser**, **Feras Alsaggaf**, **Husam Murad**, **Shivani Dolas**, **Meg Ou**, **Nan Bai**, **Ziao Wang**, **Meng Zhang**, **Michiel Fremouw**, **Menandros Ioannidis**, **Erica Ding**, and **Amneh Hamida**.

To **Ruben van der Plas**, thank you for your steady friendship and support. **Nima Forouzandeh**, **Prateek Bustali**, **Prateek Wahi**, and **Ziead Metwally**, thank you for the conversations, coffees, and moments that made everyday life lighter. **Hamza Hamida**, thank you for always knowing how things worked and making sure the rest of us did too.

Nick Ten Caat, thank you for welcoming me (you were the first person I met in the PhD room) and for helping me on countless occasions, not only me but also Caro and my children. **Cynthia Souaid**, thank you for your charisma and joy, which still feel like a privilege every time we meet.

Tatiana Armijos and **Robert Jan Vos**, thank you for your friendship and for welcoming my family and me, and for always being available.

I also remember with affection those who were part of this journey for shorter periods: **Phillipo Molaioni**, **Agnese Chiucchiù**, **Federica Romagnoli**, **Pooyan Kazemi**, **Adriana Ciardiello**, **Lourdes Beneito**, **Pio Lorenzo Cocco**, **Raquel Marijuan**, **Michele Matteoni**, and **Cem Ataman**.

To my friends beyond the academic environment and to all who feel part of that circle. You created a sense of belonging far from home. Shared meals, gatherings, and celebrations became a welcome pause from research, bringing joy and making distance feel lighter. Your friendship has meant more than words can express, especially **Javier Pavez**, **Nicole Pereira**, **Nicol Díaz**, **Francisco Garrido**, **Constanza Gutiérrez**, **Jaime Soza**, **Carolina Contreras**, **Heather Andrews**, **Ignacio Urria**, **Luis**

Burgos, **Paulina Toledo**, **Tomás Burgos**, **Felipe López**, **Soledad Temporín**, **David Monge**, **Felipe Bucci**, **Anna Batelle**, **Coti Maass (and Samba)**, **Tamara Eger**, and **Fabian Elgueta**.

I am also grateful to the master's students I had the pleasure of supervising, particularly **Thaleia Kalfa**, **Serhan Yuksel**, **Eleni Mousteri**, **Eleni Chatzi**, **Mohammed Ibrahim**, and **Jan Zawadzki**.

To my parents, **Elizabeth Ximena Luegmayer Rosenberg** and **Pablo Andrés de la Barra Ahumada**. Your constant support, trust, and presence, even across distance, have been a steady foundation. Knowing you are always there has given me a sense of certainty. I am grateful for the opportunities, the experiences, and for all the lives you have allowed me to live. I love you deeply.

To my sisters, **Camila Andrea** and **Daniela Belén**. With you, my life began, and in many ways, so did the person I am today. We have shared paths, laughter, learning, and moments that have left a deep mark on me. Your constant support has been a source of strength. And to my wonderful nephews, **Martín**, **Mateo**, and **Amanda**.

Antonia and Borja, my children. I hope that one day you will read this and understand how deeply I love you. You are the energy that keeps me going. Everything I have done, everything I do, and everything I will do is for you. Forgive me for the times work pulled me away or asked you to wait; none of it was ever more important than you. It was always part of trying to build something that would carry you further, open more doors, and give you choices I never had. And even when I wasn't there, you were always at the center of every decision I made.

And to **Carolina Andrea Díaz Lagos**. Life feels lighter and fuller with you. Thank you for your love, your care, and for listening even when I struggled to find the words. For being there, steadily and without question. For helping me find my footing, for bringing order to my daily life, and for being such a wonderful mother. For sharing this journey in all its complexity and making it better. You are my partner in everything that matters. This is not an end, but the beginning of a new chapter—one I'm truly happy to share with you.

This work carries you all within it.

Pedro Pablo de la Barra Luegmayer
Delft, June 2026.

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Summary

Modern office buildings face the dual challenge of meeting strict decarbonization targets while ensuring the comfort and satisfaction of their occupants. Automated façades, dynamic systems like switchable glazing and automated shading, offer a promising solution by regulating solar gain and daylight to reduce energy demand and improve indoor environmental quality (IEQ). However, in practice, these systems often fail to perform in real buildings as predicted in simulations. This "performance gap" frequently comes from a misalignment between automated control logic and occupant needs. When automation is perceived as disruptive, opaque, or restrictive, occupants often reject or override the system, leading to energy inefficiency and dissatisfaction.

The success of automated façades depends on moving beyond purely technical optimization to strategies that explicitly integrate human factors. Current control strategies often treat occupants as passive recipients or sources of disturbance, rather than active participants with diverse and changing needs. Consequently, there is a critical need to understand the interaction requirements of occupants and to translate these into control strategies that are acceptable, trustworthy, and effective.

To address these challenges, this research aims to develop empirical evidence and scalable measurement approaches that translate occupant requirements into actionable interaction strategies for automated façade control. It addresses the main research question:

How do interaction strategies influence occupant responses to automated façades?

To comprehensively answer this central question, the following sub-questions were formulated:

- **What is the impact of automated façades on energy savings, IEQ, and occupant response?**
- **What factors influence occupant response with automated façades, and how do these factors impact satisfaction and acceptance?**
- **How do speed and direction of change in automated façades influence occupant satisfaction, acceptance, and response?**

- **How do information, position, and type of control interface influence occupant satisfaction, acceptance, and response with automated façades?**
- **Do occupants have different requirements for interaction with automation depending on personal factors, type of service, and context?**

Research Methodology

This study employed a mixed-methods approach structured in three complementary parts to investigate occupant interaction with automated façades, combining literature analysis, controlled experiments, and large-scale data collection.

The **first part** established the research landscape through two systematic literature reviews. The first review synthesized evidence on the performance of automated façades in terms of energy, IEQ, and occupant response, highlighting the gap between simulated and real-world outcomes and the limited integration of occupant behavior in performance assessments. The second review focused on the human dimension, classifying the personal, environmental, and contextual factors influencing occupant acceptance and satisfaction, as well as the role of control logic and façade technology.

The **second part** explored occupant response through controlled laboratory experiments. One experiment examined the impact of system control logic (specifically the speed and direction of transitions in switchable glazing) on perception and override behavior, incorporating both self-reported and behavioral measures. A second experiment investigated control interfaces, assessing how usability, reachability, and information feedback (system cues) influence satisfaction and perceived control in a simulated office environment.

The **third part** captured occupant preferences at scale through a large online questionnaire administered to office workers in the Netherlands and Spain. The survey validated and extended the experimental findings by quantifying preferences for automation levels across building services and workday phases, and by identifying preferred interface characteristics. Statistical analysis enabled the identification of patterns and user profiles, supporting the development of scalable, occupant-centered interaction strategies.

Results

What is the impact of automated façades on energy savings, IEQ, and occupant response?

The systematic review revealed that while automated façades consistently reduce lighting energy demand (31–86% savings reported), their impact on cooling and heating is variable and highly dependent on context. Crucially, studies that do not account for occupant overrides often overestimate energy savings. In terms of IEQ, automation can improve visual and thermal comfort but often involves trade-offs, such as sacrificing view to prevent glare. The review highlighted a critical gap: occupant behavior is acknowledged as influential but is rarely integrated into performance evaluations, leading to unrealistic predictions of system effectiveness.

What factors influence occupant response with automated façades, and how do these factors impact satisfaction and acceptance?

Occupant response is driven by five interacting factors: personal characteristics (e.g., preference for view vs. glare protection), environmental conditions (e.g., solar angle), contextual factors (e.g., task type), façade technology (e.g., noise of operation), and the type/mode of operation (e.g., logic and feedback). Satisfaction is highest when systems are transparent, predictable, and offer easy manual override. Conversely, opaque or disruptive automation triggers "sabotage" behaviors that undermine system performance.

How do speed and direction of change in automated façades influence occupant satisfaction, acceptance, and response?

Experimental results showed that the direction of a façade transition (e.g., clear-to-dark vs. dark-to-clear) significantly impacts occupant behavior. Transitions toward a darker state were more likely to trigger manual overrides, as they were perceived as a loss of view and daylight. While transition speed had a smaller effect on overall satisfaction, faster transitions were noticed more readily and could trigger quicker interventions. This suggests that transition dynamics are not just technical parameters but interaction design choices that influence acceptance.

How do information, position, and type of control interface influence occupant satisfaction, acceptance, and response with automated façades?

Usability testing demonstrated that interface design is a primary driver of perceived control. Participants strongly preferred interfaces that were easy to reach (e.g., desk-mounted) and provided clear feedback (system cues) about status and intent. Digital interfaces were favored when they offered rich information, whereas analogue switches were preferred for simplicity when located at the entrance. The study confirmed that opaque interfaces increase frustration and disengagement, while informative interfaces build trust and support the acceptance of automation.

Do occupants have different requirements for interaction with automation depending on personal factors, type of service, and context?

The large-scale survey revealed that automation preferences are not fixed but vary by context. Acceptance of automation increases throughout the workday, being lowest at arrival and highest when leaving. Preferences are also service-specific: occupants are willing to automate "background" services like ventilation and heating but strongly prefer manual control for "personal" services like windows and task lighting. Most occupants fit a "mixed-control" profile rather than being strictly pro-manual or pro-automation, reinforcing the need for flexible, differentiated control strategies.

Conclusions

The main research question — **How do interaction strategies influence occupant responses to automated façades?** — is addressed by demonstrating that interaction strategies are the link between control logic and operational performance. The dissertation reframes the performance gap as an "interaction gap," showing that energy and IEQ goals can only be met if automation is designed as a collaborative system.

Evidence from the reviews, experiments, and surveys confirms that successful interaction strategies must be **understandable**(transparent about actions), **negotiable** (easy to override), and **context-dependent**. Specifically, the research shows that transition dynamics (speed/direction) and interface quality (reachability/feedback) directly influence the likelihood of manual overrides. Furthermore, the finding that preferences vary by building service and time of day challenges the "one-size-fits-all" approach to automation.

To close the performance gap, automated façade strategies must prioritize **occupant-centered design**: prioritizing automated modes for background services while preserving manual agency for personal ones, using informative interfaces to build trust, and designing transitions that minimize disruption. By aligning technical operation with human requirements, these strategies can resolve the conflict between energy efficiency and occupant satisfaction.

Samenvatting

Moderne kantoorgebouwen staan voor de dubbele uitdaging om te voldoen aan strenge decarbonisatiedoelstellingen en tegelijkertijd het comfort en de tevredenheid van hun gebruikers te waarborgen. Geautomatiseerde gevels, dynamische systemen zoals schakelbaar glas en geautomatiseerde zonwering, bieden een veelbelovende oplossing door zoninstraling en daglicht te reguleren, waardoor de energievraag afneemt en de kwaliteit van het binnenmilieu verbetert. In de praktijk blijken deze systemen echter vaak niet te presteren zoals in simulaties wordt voorspeld. Deze "prestatiekloof" ontstaat vaak door onvoldoende afstemming tussen de automatische regelstrategie en de behoeften van gebruikers. Wanneer automatisering als storend, ondoorzichtig of beperkend wordt ervaren, hebben gebruikers de neiging het systeem te weigeren of handmatig in te grijpen, wat leidt tot energie-inefficiëntie en ontevredenheid.

Het succes van geautomatiseerde gevels hangt af van een verschuiving van puur technische optimalisatie naar strategieën die expliciet rekening houden met menselijke factoren. Huidige regelstrategieën beschouwen gebruikers vaak als passieve ontvangers of als bron van verstoring, in plaats van als actieve deelnemers met diverse en veranderende behoeften. Daarom is er een duidelijke noodzaak om de interactiebehoeften van gebruikers te begrijpen en deze te vertalen naar regelstrategieën die acceptabel, betrouwbaar en effectief zijn.

Om deze uitdagingen aan te pakken, heeft dit onderzoek als doel om empirisch bewijs en schaalbare meetmethoden te ontwikkelen die gebruikersbehoeften vertalen naar toepasbare interactiestrategieën voor geautomatiseerde gevelregeling. Het richt zich op de volgende hoofdvraag:

Hoe beïnvloeden interactiestrategieën de reacties van gebruikers op geautomatiseerde gevels?

Om deze centrale vraag volledig te beantwoorden, zijn de volgende deelvragen geformuleerd:

- **Wat is de impact van geautomatiseerde gevels op energiebesparing, de kwaliteit van het binnenmilieu en gebruikersrespons?**
- **Welke factoren beïnvloeden de gebruikersrespons bij geautomatiseerde gevels, en hoe beïnvloeden deze factoren de tevredenheid en acceptatie?**

- **Hoe beïnvloeden de snelheid en richting van veranderingen in geautomatiseerde gevels de tevredenheid, acceptatie en respons van gebruikers?**
- **Hoe beïnvloeden de informatievoorziening, positie en het type van de bedieningsinterface de tevredenheid, acceptatie en respons van gebruikers bij geautomatiseerde gevels?**
- **Hebben gebruikers verschillende interactiebehoeften met automatisering, afhankelijk van persoonlijke factoren, het type gebouwinstallatie en de context?**

Onderzoeksmethodologie

Dit onderzoek maakte gebruik van een mixed-methodsbenadering, opgebouwd uit drie delen, om de interactie van gebruikers met geautomatiseerde gevels systematisch te onderzoeken.

Het **eerste deel** bracht het onderzoeksveld in kaart via twee systematische literatuurreviews. De eerste review vatte het bewijs samen over de prestaties van geautomatiseerde gevels op het gebied van energie, de kwaliteit van het binnenmilieu en gebruikersrespons, en identificeerde de kloof tussen gesimuleerd potentieel en werkelijke prestaties. De tweede review richtte zich specifiek op de menselijke dimensie en classificeerde de persoonlijke, omgevings- en contextuele factoren die de acceptatie en tevredenheid beïnvloeden.

Het **tweede deel** onderzocht het gedrag van gebruikers via gecontroleerde laboratoriumexperimenten. Eén experiment analyseerde de impact van de regelstrategie, met name de snelheid en richting van overgangen in schakelbaar glas, op perceptie en de neiging om handmatig in te grijpen. Een tweede experiment richtte zich op de bedieningsinterface en onderzocht hoe bruikbaarheid, bereikbaarheid en informatiefeedback (systeemindicaties) de tevredenheid en het gevoel van controle beïnvloeden in een gesimuleerde kantooromgeving.

Het **derde deel** bracht gebruikersvoorkeuren op grotere schaal in kaart via een uitgebreide online enquête onder kantoormedewerkers in Nederland en Spanje. Deze enquête valideerde de experimentele bevindingen door voorkeuren voor automatiseringsniveaus in verschillende gebouwfuncties en fasen van de werkdag te kwantificeren, en door gewenste interface-eigenschappen te identificeren binnen een diverse populatie.

Resultaten

Wat is de impact van geautomatiseerde gevels op energiebesparing, de kwaliteit van het binnenmilieu en gebruikersrespons?

De systematische review liet zien dat geautomatiseerde gevels consequent het energiegebruik voor verlichting verminderen (gerapporteerde besparingen van 31–86%), terwijl het effect op koeling en verwarming variabel is en sterk afhankelijk van de context. Cruciaal is dat studies die geen rekening houden met handmatige ingrepen van gebruikers, de energiebesparingen vaak overschatten. Op het gebied van de kwaliteit van het binnenmilieu kan automatisering het visuele en thermische comfort verbeteren, maar dit gaat vaak gepaard met afwegingen, zoals het beperken van uitzicht om verblinding te voorkomen. De review benadrukte een belangrijke lacune: gebruikersgedrag wordt erkend als invloedrijk, maar zelden geïntegreerd in prestatie-evaluaties, wat leidt tot onrealistische voorspellingen.

Welke factoren beïnvloeden de gebruikersrespons bij geautomatiseerde gevels, en hoe beïnvloeden deze factoren de tevredenheid en acceptatie?

De gebruikersrespons wordt bepaald door vijf onderling samenhangende factoren: persoonlijke kenmerken (bijv. voorkeur voor uitzicht versus verblindingsreductie), omgevingscondities (bijv. zonnehoek), contextuele factoren (bijv. type taak), geveltechnologie (bijv. geluid), en de wijze van bediening (bijv. regelstrategie en feedback). Tevredenheid is het hoogst wanneer systemen transparant, voorspelbaar en eenvoudig handmatig aan te passen zijn. Omgekeerd leidt ondoorzichtige of storende automatisering tot “sabotagegedrag” dat de systeemprestaties ondermijnt.

Hoe beïnvloeden de snelheid en richting van veranderingen in geautomatiseerde gevels de tevredenheid, acceptatie en respons van gebruikers?

Experimentele resultaten toonden aan dat de richting van een gevelovergang (bijv. helder-naar-donker versus donker-naar-helder) een significante invloed heeft op het gedrag. Overgangen naar een donkerdere toestand leidden vaker tot handmatige interventies, omdat ze werden ervaren als verlies van uitzicht en daglicht. De snelheid bleek een kleiner effect te hebben op de algemene tevredenheid, maar snellere overgangen werden eerder opgemerkt en konden sneller ingrijpen uitlokken. Dit wijst erop dat overgangsdynamiek niet alleen technische parameters zijn, maar ook ontwerpkeuzes in interactie.

Hoe beïnvloeden de informatievoorziening, positie en het type van de bedieningsinterface de tevredenheid, acceptatie en respons van gebruikers bij geautomatiseerde gevels?

Gebruikersonderzoek toonde aan dat interfaceontwerp een bepalende factor is voor ervaren controle. Deelnemers gaven een sterke voorkeur aan interfaces die gemakkelijk bereikbaar waren (bijv. op het bureau) en duidelijke feedback gaven over status en intentie. Digitale interfaces werden gewaardeerd wanneer ze rijke informatie boden, terwijl analoge schakelaars de voorkeur kregen vanwege hun eenvoud, vooral bij de ingang. Ondoorzichtige interfaces vergroten frustratie en afstand, terwijl informatieve interfaces vertrouwen opbouwen en acceptatie bevorderen.

Hebben gebruikers verschillende interactiebehoeften met automatisering, afhankelijk van persoonlijke factoren, het type gebouwinstallatie en de context?

De grootschalige enquête liet zien dat voorkeuren voor automatisering niet vaststaan, maar contextafhankelijk zijn. Acceptatie neemt toe gedurende de werkdag: deze is het laagst bij aankomst en het hoogst bij vertrek. Voorkeuren verschillen ook per type installatie: gebruikers accepteren automatisering eerder voor “achtergrondfuncties” zoals ventilatie en verwarming, maar verkiezen handmatige controle voor “persoonlijke functies” zoals ramen en taakverlichting. De meeste gebruikers vertonen een “gemengd controleprofiel”, wat de noodzaak onderstreept van flexibele strategieën.

Conclusies

De hoofdvraag — **Hoe beïnvloeden interactiestrategieën de reacties van gebruikers op geautomatiseerde gevels?** — wordt beantwoord door aan te tonen dat interactiestrategieën de schakel vormen tussen regelstrategie en operationele prestaties. Dit proefschrift herkadert de prestatiekloof als een “interactiekloof” en laat zien dat energie- en doelstellingen voor de kwaliteit van het binnenmilieu alleen haalbaar zijn wanneer automatisering wordt ontworpen als een samenwerkend systeem.

Bewijs uit de reviews, experimenten en enquête bevestigt dat succesvolle interactiestrategieën **begrijpelijk** (transparant), **onderhandelbaar** (eenvoudig handmatig aan te passen) en **contextafhankelijk** moeten zijn. De resultaten tonen aan dat overgangsdynamiek (snelheid/richting) en interfacekwaliteit (bereikbaarheid/feedback) direct de kans op handmatig ingrijpen beïnvloeden. Bovendien daagt de variatie in voorkeuren per systeem en moment van de dag de “one-size-fits-all”-benadering uit.

Om de prestatiekloof te verkleinen, moeten strategieën voor geautomatiseerde gevels inzetten op een gebruikergericht ontwerp: automatisering prioriteren voor achtergrondfuncties terwijl controle behouden blijft voor persoonlijke functies, gebruikmaken van informatieve interfaces om vertrouwen op te bouwen, en overgangen ontwerpen die verstoring minimaliseren. Door technische werking af te stemmen op menselijke behoeften, kan het spanningsveld tussen energie-efficiëntie en gebruikerscomfort worden opgelost.

Resumen

Los edificios de oficinas modernos enfrentan el doble desafío de cumplir con objetivos de descarbonización y, al mismo tiempo, garantizar el confort y la satisfacción de sus ocupantes. Las fachadas automatizadas, sistemas dinámicos como los vidrios electrocrómico y los dispositivos de sombreado como persianas enrollables y celosias, ofrecen una solución para regular la ganancia solar y la luz natural con el fin de reducir la demanda energética y mejorar la calidad ambiental interior. Sin embargo, en la práctica, estos sistemas a menudo no alcanzan el desempeño esperado en edificios reales en comparación con lo predicho en simulaciones. Esta "brecha de desempeño" suele originarse en una desalineación entre la lógica de control automatizada y las necesidades de los ocupantes. Cuando la automatización se percibe como disruptiva, opaca o restrictiva, los ocupantes tienden a rechazarla o intervenir manualmente, lo que conduce a ineficiencias energéticas y a la insatisfacción.

El éxito de las fachadas automatizadas depende de ir más allá de la optimización puramente técnica hacia estrategias que integren explícitamente los factores humanos. Las estrategias de control actuales suelen tratar a los ocupantes como receptores pasivos o fuentes de perturbación, en lugar de participantes activos con necesidades diversas y dinámicas. En consecuencia, existe una necesidad crítica de comprender los requerimientos de interacción de los ocupantes y traducirlos en estrategias de control que sean aceptables, confiables y efectivas.

Para abordar estos desafíos, esta investigación tiene como objetivo desarrollar evidencia empírica y enfoques de medición escalables que permitan traducir los requerimientos de los ocupantes en estrategias de interacción aplicables para el control de fachadas automatizadas. Para ello, se plantea la siguiente pregunta principal de investigación:

¿Cómo influyen las estrategias de interacción en las respuestas de los ocupantes frente a las fachadas automatizadas?

Para responder a la pregunta principal de investigación, se formularon las siguientes subpreguntas de investigación:

- **¿Cuál es el impacto de las fachadas automatizadas en el ahorro energético, la calidad ambiental interior y la respuesta de los ocupantes?**

- **¿Qué factores influyen en la respuesta de los ocupantes frente a las fachadas automatizadas, y cómo afectan estos factores la satisfacción y la aceptación?**
- **¿Cómo influyen la velocidad y la dirección de los cambios en las fachadas automatizadas en la satisfacción, aceptación y respuesta de los ocupantes?**
- **¿Cómo influyen la información, la posición y el tipo de interfaz de control en la satisfacción, aceptación y respuesta de los ocupantes frente a las fachadas automatizadas?**
- **¿Tienen los ocupantes diferentes requerimientos de interacción con la automatización según factores personales, el tipo de servicio y el contexto?**

Metodología de investigación

Este estudio empleó un enfoque de métodos mixtos estructurado en tres partes complementarias para investigar la interacción de los ocupantes con fachadas automatizadas, combinando análisis de literatura, experimentos controlados y recopilación de datos a gran escala.

La **primera parte** estableció el panorama de investigación mediante dos revisiones sistemáticas de la literatura. La primera sintetizó la evidencia sobre el desempeño de las fachadas automatizadas en términos de energía, calidad del ambiente interior y respuesta de los ocupantes, destacando la brecha entre los resultados simulados y los reales, así como la limitada integración del comportamiento de los ocupantes en las evaluaciones de desempeño. La segunda revisión se centró en la dimensión humana, clasificando los factores personales, ambientales y contextuales que influyen en la aceptación y satisfacción de los ocupantes, así como el papel de la lógica de control y la tecnología de fachada.

La **segunda parte** exploró la respuesta de los ocupantes mediante experimentos controlados en laboratorio. Un experimento examinó el impacto de la lógica de control del sistema (específicamente la velocidad y dirección de las transiciones en acristalamientos conmutables) sobre la percepción y el comportamiento de intervención, incorporando medidas tanto autorreportadas como conductuales. Un segundo experimento investigó las interfaces de control, evaluando cómo la usabilidad, la accesibilidad y la retroalimentación de información (indicadores del sistema) influyen en la satisfacción y la percepción de control en un entorno de oficina simulado.

La **tercera parte** capturó las preferencias de los ocupantes a gran escala mediante un cuestionario en línea aplicado a trabajadores de oficinas en los Países Bajos y España. La encuesta validó y amplió los resultados experimentales al cuantificar las preferencias de niveles de automatización según servicios del edificio y fases de la jornada laboral, así como al identificar las características de interfaz preferidas. El análisis estadístico permitió identificar patrones y perfiles de usuario, apoyando el desarrollo de estrategias de interacción escalables centradas en el ocupante.

Resultados

¿Cuál es el impacto de las fachadas automatizadas en el ahorro energético, la calidad ambiental interior y la respuesta de los ocupantes?

La revisión sistemática mostró que, si bien las fachadas automatizadas reducen de manera consistente la demanda energética para iluminación (con ahorros reportados entre 31–86%), su impacto en calefacción y refrigeración es variable y altamente dependiente del contexto. Es fundamental destacar que los estudios que no consideran las intervenciones de los ocupantes tienden a sobreestimar los ahorros energéticos. En términos de la calidad ambiental interior, la automatización puede mejorar el confort visual y térmico, pero a menudo implica compensaciones, como sacrificar la vista exterior para evitar el deslumbramiento. La revisión evidenció una brecha crítica: el comportamiento de los ocupantes se reconoce como influyente, pero rara vez se integra en las evaluaciones de desempeño, lo que conduce a predicciones poco realistas.

¿Qué factores influyen en la respuesta de los ocupantes frente a las fachadas automatizadas, y cómo afectan la satisfacción y la aceptación?

La respuesta de los ocupantes está determinada por cinco factores interrelacionados: características personales (por ejemplo, preferencia por vista vs. control del deslumbramiento), condiciones ambientales (por ejemplo, ángulo solar), factores contextuales (por ejemplo, tipo de tarea), tecnología de fachada (por ejemplo, ruido de operación) y el modo de operación (por ejemplo, lógica de control y retroalimentación). La satisfacción es mayor cuando los sistemas son transparentes, predecibles y permiten una intervención manual sencilla. Por el contrario, una automatización opaca o disruptiva genera comportamientos de "sabotaje" que perjudican el desempeño del sistema.

¿Cómo influyen la velocidad y la dirección de los cambios en las fachadas automatizadas?

Los resultados experimentales mostraron que la dirección de la transición (por ejemplo, de claro a oscuro) influye significativamente en el comportamiento de los ocupantes. Las transiciones hacia estados más oscuros tendieron a generar más intervenciones manuales al percibirse como una pérdida de luz natural y de vista exterior. Aunque la velocidad tuvo un efecto menor en la satisfacción general, las transiciones más rápidas fueron más perceptibles y provocaron intervenciones más rápidas. Esto indica que la dinámica de transición no es solo un parámetro técnico, sino una decisión de diseño de interacción.

¿Cómo influyen las interfaces de control?

Las pruebas de usabilidad demostraron que el diseño de la interfaz es un factor clave en la percepción de control. Los participantes prefirieron interfaces accesibles (por ejemplo, ubicadas en el escritorio) y con retroalimentación clara sobre el estado y funcionamiento del sistema. Las interfaces digitales fueron valoradas cuando ofrecían información sobre el sistema y su estado actual, mientras que los interruptores analógicos fueron preferidos por su simplicidad en ciertas ubicaciones. Las interfaces opacas aumentan la frustración, mientras que las informativas fomentan la confianza.

¿Existen diferencias según contexto y usuario?

La encuesta reveló que las preferencias no son fijas, sino dependientes del contexto. La aceptación de la automatización aumenta a lo largo de la jornada laboral. Además, las preferencias varían según el servicio: los ocupantes aceptan automatización en servicios que afectan o trabajan a nivel de la habitación, pero prefieren control manual en servicios personales (como lámparas de escritorio o calefactores personales). La mayoría presenta perfiles de control mixto, lo que refuerza la necesidad de estrategias flexibles.

Conclusiones

La pregunta principal — **¿Cómo influyen las estrategias de interacción en la respuesta de los ocupantes?** — se responde demostrando que las estrategias de interacción constituyen el vínculo entre la lógica de control y el desempeño operativo. Esta investigación redefine la brecha de desempeño como una "brecha de interacción".

La evidencia muestra que las estrategias efectivas deben ser **comprensibles**, **negociables** y **dependientes del contexto**. Además, factores como la dinámica de transición y la calidad de la interfaz influyen directamente en la probabilidad de intervención manual.

Para cerrar la brecha de desempeño, las estrategias deben centrarse en el ocupante: automatizar servicios que trabajen a nivel de la habitación, mantener control manual en servicios personales, proporcionar interfaces informativas y diseñar transiciones no disruptivas. Alinear la operación técnica con las necesidades de los ocupantes permite reconciliar eficiencia energética y satisfacción.

1 Introduction

Modern office buildings must reconcile two competing requirements: the global requirement for decarbonization and the local need to support occupants in their daily activities [1, 2]. While mechanical systems have become increasingly efficient, a building's ability to meet net-zero targets without compromising indoor environmental quality (IEQ) is ultimately determined by how it responds to external conditions to deliver the indoor environments occupants require [1, 3, 4]. Rather than functioning as a sealed bunker, a building must act as a selective filter, mediating variable weather and changing occupant demands [5, 6]. In this context, façades play a pivotal role because they provide the adaptability and flexibility needed to protect the indoor environment from external loads or harness available environmental resources [5–7].

Over the past decades, façades have evolved from largely static building components to dynamic façade technologies, such as operable shading, switchable glazing, and controllable openings, that can adapt their properties over time [6, 8, 9]. When coupled with sensors, actuators, and control algorithms, these systems become automated façades that promise to reduce energy demand while maintaining acceptable comfort conditions [6, 10]. Yet, the performance of automated façades remains inconsistent in real building operation [11–13]. Control actions that appear optimal in simulation may be experienced as disruptive, opaque, or misaligned with occupants' requirements, leading to dissatisfaction, manual overrides, and reduced effectiveness [11, 12, 14].

This challenge is relevant not only scientifically, but also in policy and practice [15]. European energy policy has moved beyond efficiency targets alone toward an explicit expectation that buildings should be able to adapt to occupants' needs, supported by the Smart Readiness Indicator (SRI) framework and the broader Energy Performance of Buildings Directive (EPBD) agenda [15, 16]. This dissertation therefore investigates how occupant requirements can be translated into interaction strategies for automated façades, so that automated systems can achieve energy and IEQ targets while remaining acceptable, trustworthy, and usable in real office buildings.

1.1 Background

Within the EU, the EPBD framework increasingly positions building performance as a combination of energy outcomes and operational capability [15]. In this context, the Smart Readiness Indicator (SRI) provides a common approach to rate how well a building can use digital technologies to operate efficiently and respond to occupants' needs [16]. SRI assessments consider "smart-ready services" across multiple technical domains, including the dynamic building façade components, aiming to make "smartness" legible to stakeholders beyond technology providers, such as building owners, facility managers, and occupants. In other words, "smart" is not only the presence of automation, but the building's capability to coordinate services, provide feedback, and adapt operation to changing context and occupant needs [16].

This policy direction underscores the relevance of occupant-centered automation. If future building performance frameworks explicitly value responsiveness and occupant support, then interaction quality (how an automated action is communicated, shared, and overridden) becomes part of building performance rather than an optional add-on [17].

A central motivation for occupant-centered control is the performance gap, which is the measurable discrepancy between predicted performance (design-stage or modeled) and actual in-use outcomes [12]. In high-performance buildings, this gap is often linked to operational complexity and to how occupants interact with building systems, particularly when automated logic conflicts with real preferences, tasks, or contextual constraints [12, 13]. For automated façades, this mismatch is especially visible because façade actions can directly affect comfort and task performance in ways that trigger intervention [10, 11]. When occupants frequently override automated actions (e.g., lowering shades to restore view, blocking glare during meetings, opening windows despite HVAC logic), the façade may no longer operate as assumed in simulations, undermining both energy goals and comfort intent [11, 12, 18]. This dissertation treats occupant overrides and acceptance not as "noise" around an optimal algorithm, but as a quantifiable factor through which the performance gap emerges and persists in real building operation.

The façade of the building acts as both buffer and connector between indoor and outdoor environments, influencing energy use and multiple comfort domains, including thermal conditions, daylight and glare, view out, acoustics, and air quality [3, 5, 19]. Dynamic façade technologies extend this role by enabling the façade to vary key properties over time [6, 7]. Examples include movable blinds and roller shades, switchable glazing that changes optical transmittance, and operable openings that support natural ventilation [5, 6]. These technologies may be operated manually, respond passively to environmental changes, or be driven by sensors and actuators under automated or semi-automated control [10, 11]. In this dissertation, façade systems that include automated or semi-automated operation are collectively referred to as automated façades.

In principle, automated façades offer a means to manage transient conditions, such as solar variability, changing sky luminance, external noise, or evolving indoor loads, while maintaining comfort and reducing energy consumption [5, 6]. As a result, automated façade strategies have been widely studied for their potential to reduce cooling and lighting demand and to balance indoor conditions compared to static façades or purely manual operation [5, 10].

Operating an automated façade requires continuous balancing of competing objectives. For instance, glare prevention may conflict with daylight provision, cooling load reduction may conflict with view preservation, natural ventilation may conflict with outdoor noise or air pollution [5, 10], and heterogeneous occupant preferences can conflict with uniform control strategies [20]. Automated control is often introduced to address these trade-offs more systematically than manual operation can, using sensors (illuminance, solar radiation, temperature), schedules, or predictive logic [10, 21].

However, façade automation is rarely a simple on/off decision because systems differ in (i) the level of automation, (ii) the interaction model, and (iii) the characteristics of the control logic of actions such as timing and transition characteristics [10, 14, 22]. These operational features shape not only the environmental result, but also how occupants perceive control, stability, and trust in the system [11, 14, 23].

Occupants are not passive recipients of façade operation. Occupant requirements are multi-domain and context-dependent, and they vary substantially across individuals and situations [3, 24, 25]. In offices, occupants also evaluate control through psychological and interaction-related constructs, particularly perceived control, predictability, transparency, and the perceived right to intervene [14, 23].

A growing body of work in human–building interaction indicates that acceptance of automation is shaped not only by whether indoor conditions are “within limits,” but by whether automated systems operate in ways occupants find understandable, negotiable, and aligned with their priorities [14, 17, 25]. This includes how control is shared (e.g., override options), how the system communicates status and rationale, and how disruptive actions feel during work [10, 11, 23].

Despite their technical promise, automated façades often struggle in practice because the human dimension is insufficiently specified in both design and evaluation [9, 11]. Simulation-based studies often report clearer benefits than occupied-building evidence, reinforcing the performance gap problem. Modeled “optimal” sequences can fail when real occupants reject or reinterpret control logic [12, 18]. Additionally, manual control supports agency and can better match momentary preferences, but is unpredictable and may be energy-inefficient, whereas automated control can improve energy efficiency and stability but risks occupant resistance when it constrains autonomy or acts unexpectedly [14, 22, 24]. When occupants perceive automation as intrusive or misaligned, this can trigger cycles of annoyance and overrides that ultimately degrade both comfort and energy outcomes [11, 14]. Nonetheless, while “human-in-the-loop” control is widely proposed as a solution, the evidence about which interaction methods work remains fragmented across technologies, contexts, and measurement approaches [9, 17].

Current findings suggest that acceptance depends on the interaction strategy itself, particularly:

- Interface design (type, placement, accessibility): whether control is reachable and usable in the moment of need [11, 23].
- Information and feedback: whether the system communicates status and intent in ways that support trust and reduce confusion [14, 17].
- Control logic and transitions: whether actions occur at tolerable speeds, with minimal disruption, and with patterns that feel predictable rather than arbitrary [10, 11].

Yet many façade studies still treat automated control as a binary condition and under-report interface and behavioral drivers, limiting transferability to design practice [9, 10]. As a result, it remains difficult to specify how automated façades should expose control to occupants across contexts, façade technologies, and occupant profiles, so that they remain both effective and acceptable.

These challenges motivate the central focus of this dissertation: developing empirical evidence and scalable measurement approaches that translate occupant requirements into actionable interaction strategies for automated façade control.

1.2 Research Framework

1.2.1 Problem Statement

Despite advances in automated façade technologies and control strategies, how occupant requirements translate into acceptable and effective automated façade operation remains poorly understood. In practice, automated control must align multi-domain IEQ needs (e.g., glare, daylight, thermal comfort, view, air quality), personal control preferences, and behavioral drivers of automation acceptance.

When these human factors are not explicitly accounted for, automated façade actions that appear “optimal” in design or simulation can be experienced as disruptive or misaligned with work needs, leading to dissatisfaction, frequent overrides, and reduced operational effectiveness, thereby contributing to the performance gap.

To address this problem, this dissertation targets three interrelated gaps in current knowledge and methods:

1. Insufficiently characterized drivers of acceptance for automated façades: While it is well established that occupants interact with façades, the specific factors that drive acceptance, trust, and satisfaction with automated façade operation remain fragmented and poorly understood, particularly regarding the interaction strategy. Key missing evidence concerns:

- System logic and transitions: Research often treats automation as a binary condition, under-reporting how transition timing, speed, direction, and noise shape distraction, perceived stability, and perceived control.
- Control interfaces and agency: Interface design is frequently treated as secondary to control logic, limiting evidence on how reachability, feedback, and information provision shape perceived agency and willingness to accept automated decisions.
- Contextual interplay: There is limited understanding of how technology-related factors interact with personal and situational drivers (task, workday phase, social context) to influence acceptance and override behavior

2. Lack of scalable methods for capturing occupant preferences for automated control: Insights into occupant preferences are predominantly derived from small-scale laboratory studies or static surveys, which are difficult to generalize to dynamic real-world contexts. There is currently a lack of scalable assessment methodologies capable of capturing how control preferences vary across diverse office populations, different building services, and changing phases of the workday. Without these methods, it is difficult to develop automated systems to meet the heterogeneous needs of office building occupants.

3. Fragmented performance assessment: Current evaluations of automated façades are predominantly siloed. Studies typically focus on either energy efficiency, physical IEQ metrics, or subjective occupant satisfaction in isolation. Consequently, there is a lack of integrated evidence regarding the simultaneous impact of automated façades on all three domains. This fragmentation obscures the true cost-benefit trade-offs, making it difficult to optimize systems that balance energy reduction with the complex, multi-domain comfort requirements of occupants.

1.2.2 Research Questions

This research project aims to answer the following question, which serves as the primary driver for exploring the current limits of occupant-centered automated façade:

How do interaction strategies influence occupant responses to automated façades?

To address the main research question, the study is structured around five sub-questions. Each one is developed to fill the gaps described in Section 1.2.1 and to guide the corresponding methodological phases.

1. What is the combined impact of automated façades on energy efficiency, indoor environmental quality (IEQ), and occupant response? (Chapter 2)
2. What are the primary drivers of occupant acceptance regarding automated façades, and how do personal and interactive factors influence satisfaction? (Chapter 3)
3. How do the automated façade controls, specifically transition speed and direction, affect occupant distraction, adaptation, and acceptance? (Chapter 4)
4. How do control interface characteristics, such as information feedback, physical position, and device type, mediate occupant interaction and acceptance of automated systems? (Chapter 5)
5. To what extent do occupant interaction preferences vary across different personal profiles, building services, and operational contexts? (Chapter 6)

1.2.3 Research Strategy and Methods

This research employs a sequential methodology, structured in three parts, to evaluate occupants' indoor environmental requirements, personal control preferences, and acceptance of automation. First, a critical literature review (Chapters 2–3) examines the impact of automated façades on energy savings, environmental comfort, and occupant response, identifying also the factors playing a role in occupant interaction. Second, laboratory experiments (Chapters 4–5) investigate occupants' interaction with automated façades to assess how automation influences behavior and how different control interfaces impact satisfaction with building services, environmental quality, personal control and automation. Finally, to validate the generalizability of these findings (Chapter 6), a large-scale questionnaire is deployed to capture preferred levels of automation across varying workday phases and building services, as well as specific requirements for control interfaces, thereby informing the development of adaptive, occupant-centered automation strategies. The overall strategy is shown in Figure 1.1.

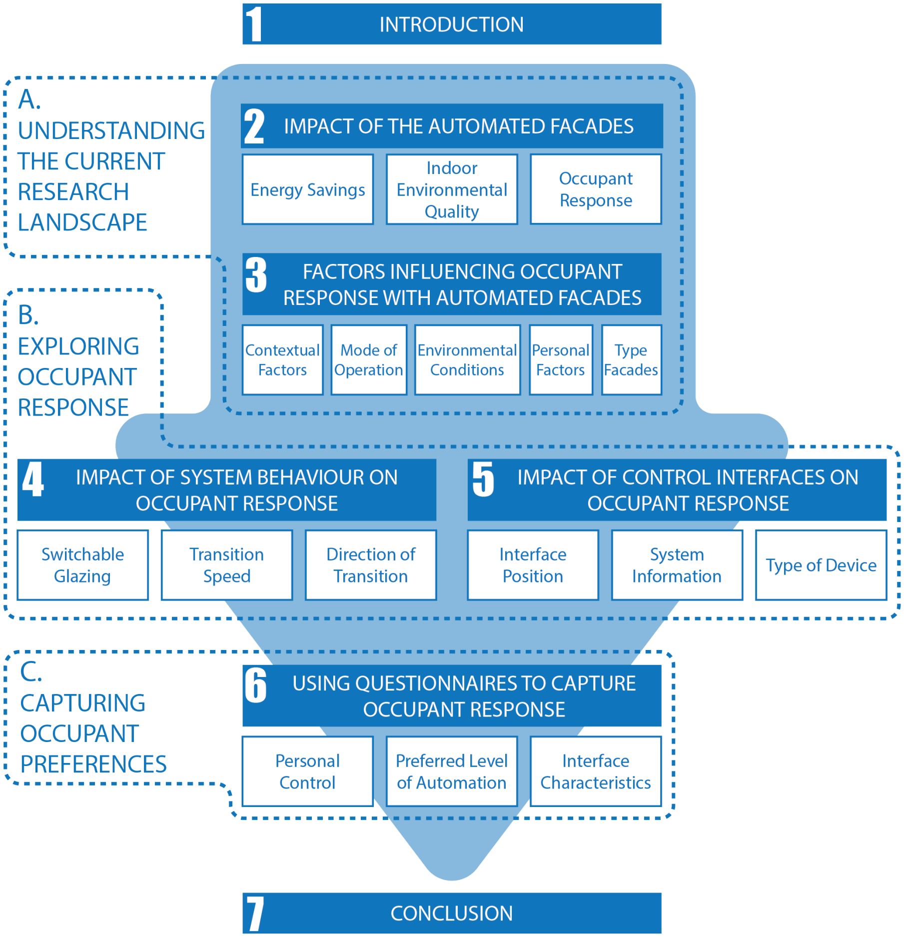


FIG. 1.1 The diagram shows the sequential research strategy employed to assess occupant requirements and preferences for automated façade control. The study is organized into three main parts: (A) understanding the current research landscape through critical literature reviews (Chapters 2–3), (B) exploring occupant response via laboratory experiments (Chapters 4–5), and (C) capturing occupant preferences using questionnaire studies (Chapter 6). Each part addresses targeted research questions on the impact of automated façades, influencing factors, system behavior, control interfaces, and methods for evaluating occupant experience, culminating in the conclusion (Chapter 7). Key topics and subtopics within each chapter are indicated, reflecting the stepwise approach to enabling effective, occupant-centered automation strategies.

Part A: Understanding the Current Research Landscape

The first part of this research comprises two chapters that establish the foundational background and explore the state of the art in the field.

Chapter 2, **Influence of Automated Façades on Comfort and Energy: A Critical Review**, offers a systematic literature review that evaluates current knowledge and identifies research gaps related to automated façade performance. It focuses on the influence of automated façades on energy savings, indoor environmental comfort, and occupant response, derived from three types of studies: laboratory experiments, field real buildings, and building performance simulations. By analyzing these findings, the chapter deepens the contextual background and highlights critical areas requiring further research. This chapter is based on work published in 2025 in Energy and Buildings.

Building on Chapter 2 findings, Chapter 3, **Influence of Automated Façades on Occupants: A Review**, addresses a gap in existing assessments: automated façade assessments often overlook how occupants experience automated controls. This chapter reviews empirical studies that directly measure occupant responses to automated façades. It introduces a classification scheme that organizes influencing factors into five categories and analyzes evidence on response types such as behavioral overrides, comfort, satisfaction, sensation, and acceptance. The methods used in these studies, ranging from sensors to questionnaires and monitoring, are examined. The chapter concludes that current understanding of multi-domain comfort preferences remains limited, assessment methods are fragmented, and contextual variability challenges replicability. This chapter is based on work published in 2022 in the Journal of façade Design and Engineering.

Part B: Measuring Occupant response

Chapters 4 and 5 investigate how occupant behavior is influenced by automated façade controls and interaction strategies through laboratory experiments involving human participants.

Chapter 4, **Occupant Interaction with Smart Glazing: Effect of Switching Speed Under Overcast Sky Conditions**, addresses the challenge of occupant acceptance of automated façades by presenting an experimental study conducted in a semi-controlled mobile laboratory. This experiment examined how the speed of automated façade transitions (fast versus slow) and the direction of change (dark to clear or clear to dark) affect occupants' satisfaction with indoor environmental conditions, distraction and annoyance during tasks, and perceived personal control. The study provided empirical evidence that, although transition speed and direction have limited impact on overall satisfaction, they significantly influence occupant behavior. These insights support the development of automated façade systems that balance minimizing occupant disruptions with optimizing energy efficiency. This chapter is based on work published in 2025 in Building and Environment.

Chapter 5, **Occupant Preferences in Lighting and Shade Control Interfaces Through Usability Testing**, focuses on occupant preferences for lighting and roller shade control interfaces through usability testing, emphasizing the importance of occupant-centered design in building controls. The study employed a controlled lab-office setup with recruited participants who interacted with six scenarios varying device type (analog vs. digital), interface position (wall, desk, split), and levels of system feedback. Data collection included PSSUQ surveys, interviews, and preference questionnaires. Results showed that digital, information-rich interfaces positioned on the desk were rated highest for ease of use and occupant satisfaction, whereas interfaces lacking feedback cues or placed inconveniently led to reduced perceived control. These findings emphasize the need for clear feedback, intuitive interface placement, and adaptable control options. The chapter concludes by offering design guidelines aimed at improving occupant acceptance while promoting energy-efficient behavior. This chapter is based on a manuscript currently under review at Building and Environment.

Part C: Capturing Occupant Preferences

To bridge the gap between laboratory findings and real-world application, **Chapter 6, Using Questionnaires to Capture Occupant Response,** expands the scope to a large-scale field study. Building on the interaction factors identified in previous chapters, this questionnaire quantitatively assesses occupant preferences for automation across three distinct workday phases (arrival, working, and leaving) and ten specific building services. Furthermore, it validates occupant requirements for control interfaces, specifically examining preferences for device type, physical positioning, and the necessary level of system information. These findings reveal distinct ’control profiles’ among occupants, providing the empirical basis for adaptive strategies that tailor automation to specific services and occupant routines. This chapter is currently under internal review and is being prepared for submission to Automation in Construction.

1.2.4 Research Impact

1.2.4.1 Societal Relevance

Buildings and their management systems are increasingly automated to improve energy efficiency and indoor environmental quality. However, their full potential remains unrealized due to persistent mismatches between technology objectives and occupant needs. This disconnect is a primary driver of the "performance gap", the significant discrepancy between predicted energy savings and actual operational consumption. In particular, automated façade control strategies frequently overlook individual preferences for personal control of building services, resulting in frequent manual overrides and diminished trust in the systems. Moreover, there is a notable gap in understanding how occupants perceive and interact with dynamic façade automation, which leads to control algorithms that fail to reflect real occupant requirements. Despite substantial investments by technology providers and building owners in optimizing energy performance and IEQ, these efforts are often undermined by neglect of the human dimension, as the assumption that all occupants can be managed uniformly disregards important individual differences. This omission not only generates annoyance and discomfort when control actions are perceived as disruptive but also negatively impacts cognitive performance, concentration, and overall well-being, with potential consequences for productivity and health.

By systematically investigating the gaps between occupant expectations and automated control practices, this research provides empirical evidence on occupant interactions with dynamic façades across varied environmental conditions and control scenarios. Through controlled laboratory experiments and real-world questionnaire validation, it identifies specific patterns of preference, tolerance thresholds for automation actions, and key drivers of override behavior. These insights inform the development of novel measurement instruments and protocols that practitioners can use to capture occupant requirements accurately.

Furthermore, this research translates empirical findings into concrete design guidelines, demonstrating how technical performance parameters, such as shading transition speed, feedback cues, and manual override interfaces, can be balanced to align with occupant comfort needs. By embedding these occupant-centered strategies into façade control systems, the research paves the way for reducing the performance gap, resulting in more trustworthy, effective, and energy-efficient building operations.

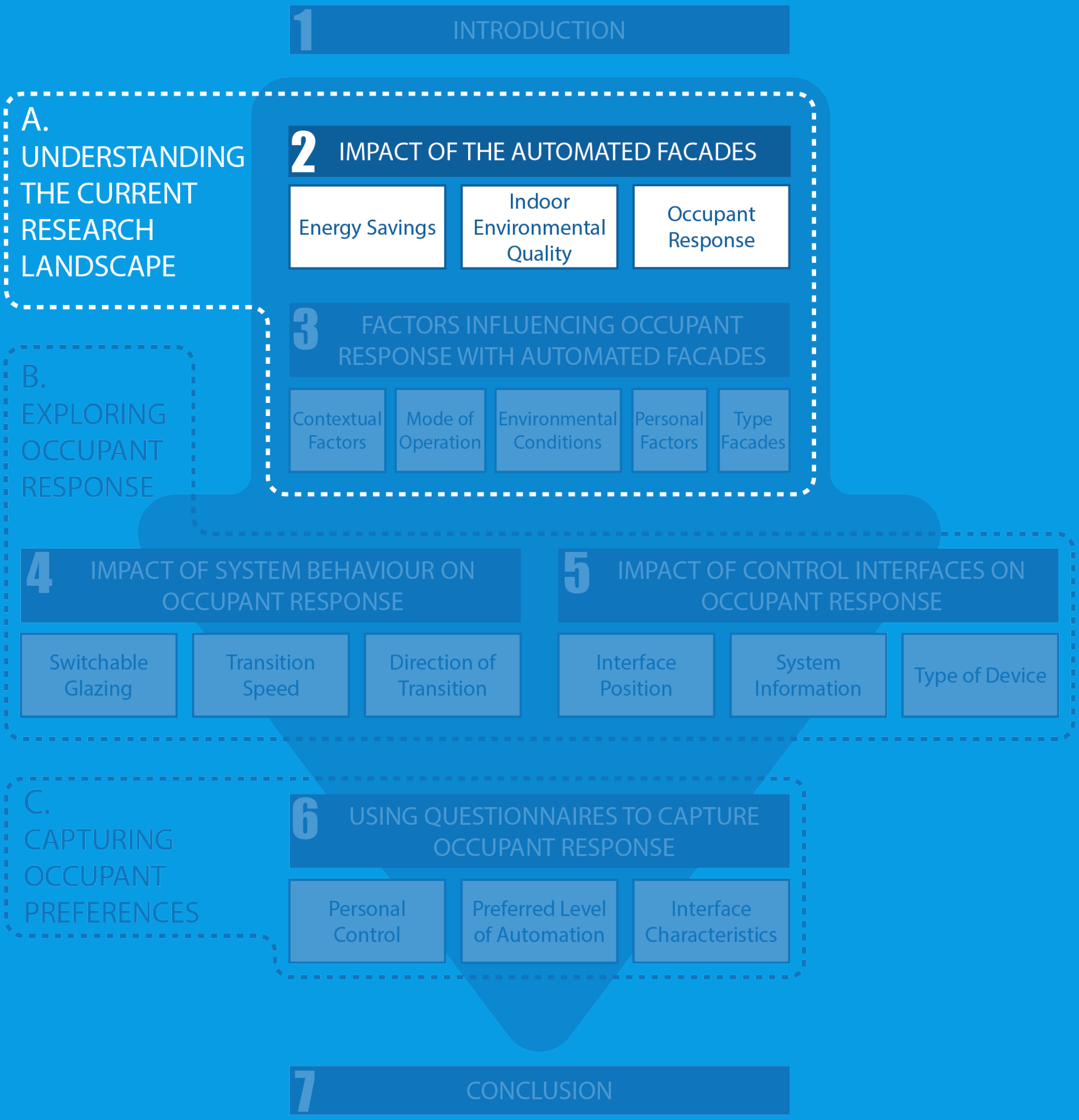
1.2.4.2 Scientific Relevance

This dissertation advances scientific knowledge on human–building interaction by providing concepts, data, and methods that other researchers can directly reuse and build upon. First, it offers a systematically designed mixed-methods research strategy, combining a critical literature review, controlled laboratory experiments, and large-scale questionnaire studies, that shows how occupant requirements can be embedded in the design, operation, and evaluation of automated façade control strategies. This integrated approach clarifies how personal, environmental, and technological factors jointly shape occupant responses to façade automation, and it introduces classification schemes that organize these drivers in a way that is transferable to other studies.

Second, the work develops and validates assessment methods that combine subjective perceptions (via questionnaires) with objective interaction logs (via measured data). These methods provide operationalizable metrics for key constructs such as perceived control, usability, and automation acceptance. By documenting instruments, procedures, and analysis steps in detail, the dissertation offers a replicable methodology that future researchers can adopt or adapt in their own experimental and field studies.

Third, the empirical findings deliver structured, empirically grounded insights into occupant preferences and override behaviors under different interface and automation conditions. These results can be used as input assumptions or benchmark datasets for building performance simulation and human–building interaction models, helping to produce more realistic predictions of comfort and interaction patterns under varied occupant scenarios.

Finally, the methodological innovations, particularly the use of feedback mechanisms and behavior-based inference techniques, such as surveys and monitoring, serve as a template for occupant-centric investigations in smart buildings. By demonstrating how to link interface design, automation strategies, and occupant feedback, this dissertation enables other scientists to design more robust studies, test new façade and control concepts, and ultimately accelerate the development of inclusive, adaptive, and occupant-centered control strategies across diverse office buildings and climate contexts.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2 Influence of Automated Façades

Influence of Automated façades on Comfort and Energy: A Critical Review

This chapter is based on work published in 2022 in Energy and Buildings.

This chapter introduces the dissertation by systematically reviewing existing evidence on automated façade systems in office buildings, focusing on their impact on energy performance, indoor environmental quality (IEQ), and occupant response. The aim is to consolidate three decades of fragmented evidence, identifying research trends, methodologies, and knowledge gaps that hinder integrating occupant requirements into control strategies. Peer-reviewed articles were selected through a structured search of scientific databases, targeting studies on automated or actively controlled dynamic façades involving laboratory experiments, real-building assessments, and simulations. The resulting dataset was screened and analyzed via descriptive mapping and thematic review. The analysis reveals growing interest in automated façades, shifting from laboratory studies toward more real-building and simulation research. However, significant gaps persist, particularly the limited consideration of occupant interaction in energy evaluations, under representation of certain climates and orientations, and a lack of integrated multi-domain comfort assessments. These findings clarify the current research landscape and frame the subsequent experimental investigations. By synthesizing current knowledge and identifying these gaps, this chapter lays the foundation for Chapter 3, which examines the personal, environmental, and technological factors shaping occupant responses.

2.1 Introduction

The façade or envelope of a building is essential to achieve high performance in buildings, as its design and operation directly affect energy demand and indoor environmental quality (IEQ) [26]. Previous studies have shown that dynamic façades can provide a means to adapt to transient requirements (for example, comfort of the occupant or changing weather) and improve the overall performance of the building [7] by regulating solar gains, natural ventilation, moisture, daylight, view and outside noise [27–29]. In particular, automated control of these dynamic and movable components (automated façades) has been associated with the reduction of energy demand [30, 31] and the improvement of IEQ [32] compared to manually controlled dynamic façades [33] and static façade technologies [34].

Bilgen et al. [35] made one of the first attempts to investigate the effect of automated façades on building energy performance. Their study indicated that energy savings on automated façade operation are greater when cooling or ventilation is necessary to maintain IEQ compared to a regular window solution (a glazed façade). These findings were followed by other studies, such as those by Vine et al. [36] and Lee et al. [37], showing that an automated façade improves indoor daylight levels while reducing indoor overheating risk by blocking incoming sun radiation when needed. More recently, research on automated façade performance has focused on comparing different dynamic façade technologies, control logic, and levels of occupant interaction.

Current studies have increasingly focused on the multi-domain influence of automated façades. Simulation-based research has generated substantial evidence demonstrating the advantages of automated façades across multiple domains, including the optimization of daylight access [38, 39], mitigation of discomfort glare [40], reduction of thermal loads [41], and enhancement of indoor air quality [32]. Notably, the work of researchers such as Loonen et al. shows the critical role of building performance simulation (BPS) in the development and comparative evaluation of innovative façade technologies [42]. Discrepancies emerge in laboratory and real office building studies, presenting the challenges posed by the simultaneous impact of façades on various indoor comfort domains [43, 44]. For instance, controlling solar gains can have a detrimental impact on access to outdoor views or daylight availability. Inconsistencies are also shown when energy savings on artificial lighting, cooling, and heating achieved by automated systems have been studied in real settings where occupants interact with the building systems [45]. There is still no clarity on the balance of occupant requirements in façade operation to achieve satisfactory control and efficient building performance, as occupant requirements differ between occupants and depend on many contextual factors.

Three previous literature reviews have examined the performance of dynamic façades with a focus on occupant comfort and energy efficiency. Konstantoglou and Tsangrassoulis [5] analyzed automated controls for dynamic shading systems, finding that occupants are more likely to accept these systems when they have the ability to override controls, though this can reduce expected energy savings. The ease of system use also plays a crucial role in occupant acceptance. Moreover, strategies that optimize both visual and thermal performance tend to yield more balanced outcomes in terms of comfort and energy efficiency. Luna-Navarro et al. [46] explored interaction strategies and the requirements for effective occupant-façade interaction for dynamic façades, emphasizing the need for multidisciplinary approaches that foster communication between different fields of expertise. Shafaghat & Keyvanfar [6] investigated the state-of-the-art in dynamic façades, highlighting their physical performance in terms of thermal comfort, visual environment, ventilation, and electricity generation. This study demonstrated that dynamic façades can actively and selectively manage heat transfer and energy flow, thereby improving IEQ conditions and potentially reducing heating and cooling loads. However, none of these reviews has critically assessed the current evidence on the benefits of automated façades for improving energy savings in cooling, heating, and lighting, as well as overall environmental comfort and occupant satisfaction. While several studies suggest that automation could theoretically enhance these factors, the extent to which this is realized in practical applications remains unclear. This lack of clarity presents a barrier to the effective uptake of such façade technologies in the market.

The lack of understanding of occupant requirements, the scattered evidence on the impact of automated façade on building performance, and the absence of prior reviews highlight the need for a thorough study. Therefore, this review aims to evaluate the current evidence on the influence of automated façades on energy savings, IEQ, and occupant satisfaction to identify current opportunities and limitations of automated façades. This work reviews experimental, real office building, and simulation studies focusing only on office building contexts to evaluate current evidence on automated façades.

This literature review is relevant to inform and guide future research and industry efforts to improve office building energy and environmental performance. First, Section 2.2 explains the review methodology, including databases, selection criteria, and keyword clustering. Section 2.3 shows the general information on the current research landscape. Section 2.4 presents the current reported evidence on the effect of automated façades on energy savings, IEQ, and occupant response to automated façade operation. These results are then discussed in Section 2.5. Finally, Section 2.6 draws this paper’s conclusion and highlights potential future challenges and investigations based on the conducted review.

2.2 Methodology

A systematic review was conducted to examine previous work on the influence of automated façades on energy savings (cooling, heating, and lighting), indoor environmental conditions, and occupant response in office-building contexts. Advanced queries based on the keywords in Table 2.1 were performed. We selected papers that provided evidence from laboratory experiments, real office-building assessments, and simulation studies on the impact of automated dynamic façade operations on energy demand, IEQ, and occupant response. We excluded studies that (i) solely examined manually controlled systems without automated features, (ii) focused exclusively on façades that did not incorporate active automated control strategies, and (iii) were conducted in building types other than office environments.

The keywords were divided into three groups: (1) façade operation, (2) façade technology, and (3) study type. The review was carried out by searching for laboratory and real office-building studies separately from simulation studies in the following databases: ScienceDirect, Scopus, and Web of Science (WoS). A total of 6,079 references were collected (ScienceDirect: 618; WoS: 2,481; Scopus: 2,980). The article selection process was performed in three steps: (1) screening titles and keywords, (2) screening abstracts, and (3) full-text assessment. After this process, 91 studies met the selection criteria, published between 1998 and 2025.

TABLE 2.1 Summary of keywords used for the systematic search of studies on automated façades (search date: 15-12-2024). Keywords are categorized into three groups: (i) façade operation, (ii) façade technology, and (iii) study type. Separate queries were conducted for studies focusing on laboratory experiments, real-building assessments, and simulations.

Keyword group	Inclusion criteria in Title, Abstract, and Keywords
Façade operation	(adaptive OR responsive OR dynamic OR kinetic OR intelligent OR advanced OR smart OR interactive OR active OR automated OR switchable)
	AND
Façade technology	(façade OR envelope OR skin OR shading OR glazing OR glazed OR window OR Venetian OR roller OR blind)
	AND
Type of study	**Laboratory and real office-building studies:** (laboratory OR on-site OR field OR experimental OR post-occupancy OR testbed OR test room OR campaign OR monitoring) **Simulation studies:** (simulation OR model OR calculation)

2.3 Literature Review Results

2.3.1 Distribution of Studies per Time, Aim and Methodology

Figure 2.1 illustrates the distribution of studies (1994–2025) on the impact of automated façades on energy savings, IEQ and occupant response. This figure classifies studies into laboratories, real office buildings, and simulations, further distinguishing those with and without participants.

The number of studies across real office building, laboratory, and simulation environments increased from 1 in 1994 to 79 in 2024. Initially, research was entirely laboratory-based (100% in 1994). Real office building studies increased to 6̃0% in 2000 before stabilizing at 25%–33%. Laboratory research remained dominant (50%–60%) until recently, declining to 41%–44%. Simulation studies emerged in 2007 and grew steadily, reaching 32% in 2025. Over time, research shifted from a laboratory focus to a more balanced distribution across real office buildings and simulations. The increasing inclusion of human participants reflects a growing emphasis on human-centered research.

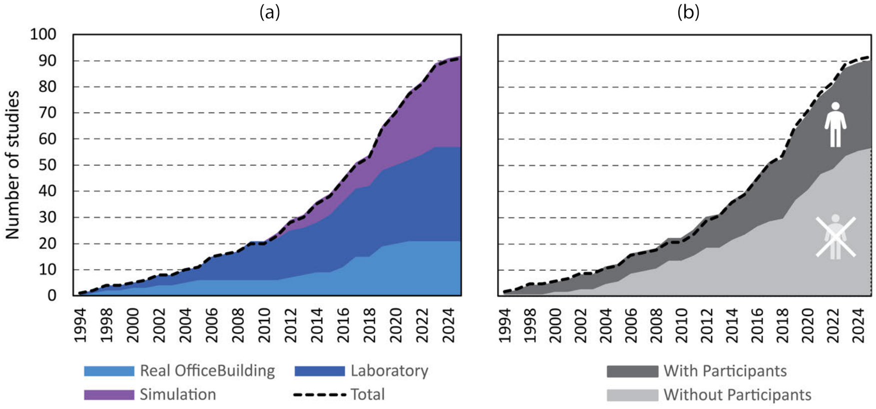

FIG. 2.1 Cumulative number of studies over time, presented in two stacked area charts: (a) Distribution of studies by laboratory, real office buildings, and simulation studies setting; (b) Distribution of studies according to the inclusion of human participants.

Figure 2.2 presents the distribution of studies on automated façade systems by location. Europe has the highest number of studies with 41 studies, primarily in laboratories (n = 15) and simulations (n = 19). North America followed with 32 studies, mainly in real office buildings (n = 13). Asia has fewer studies, distributed across laboratories (n = 8), simulations (n = 10), and real office buildings (n = 2). Oceania and South America have four and three studies respectively, while Africa has no studies.

FIG. 2.2 Number of studies per world region divided by laboratory, real office building, and simulation setting. The plot shows that the majority of the studies have been carried out in Asia, Europe, and North America.

This distribution of studies shows the need for a broader geographical representation to ensure that automated façade research addresses diverse cultural contexts.

Most studies were conducted in laboratory settings (n = 34) and simulations (n = 34), while 23 were performed in real office buildings. As shown in Figure 2.3, participant involvement is more frequent in real office buildings, likely due to the challenges of recruiting participants for laboratory environments. In fact, 74% of real office building studies included human participants, compared to 38% in laboratories. Real office building studies primarily monitor occupant behavior, comfort, satisfaction, acceptance, perception, and sensation, particularly in relation to façade operation and characteristics.

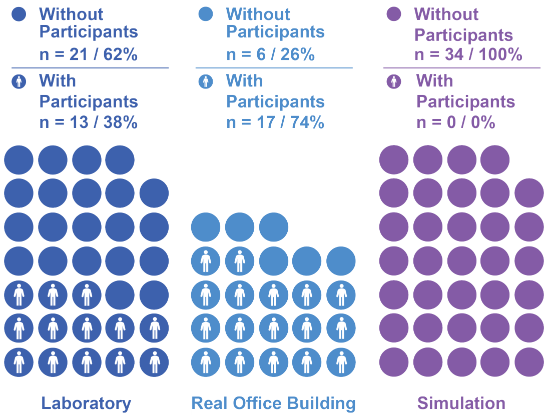

FIG. 2.3 The distribution of studies divided by laboratory, real office building, and simulation, indicating whether these studies involve human participants. Number of studies / percentage.

Among the laboratory studies, 21 did not involve human participants but assessed automated façade performance through physical measurements. Twelve of these used standard comfort models, such as Daylight Glare Probability (DGP), Predicted Glare Sensation Vote (PGSV), and Predicted Mean Vote (PMV), or environmental quality thresholds like work plane illuminance and indoor air temperature. Thirteen studies included participants, employing objective IEQ measurements, comfort models and questionnaires to analyze occupant behavior and perception.

In real office buildings, six studies did not include human participants, focusing solely on energy efficiency assessments or standard comfort models to evaluate façade impact. The 17 studies involving participants used questionnaires to examine occupant interaction with the façade, perceptions of automated systems, and their influence on indoor environmental satisfaction.

Figure 2.4 illustrates the distribution of laboratory experiments, real office buildings, and simulations by research objective. Laboratory and real office building studies primarily addressed (i) control algorithm development, (ii) occupant impact, (iii) energy savings, and (iv) combined occupant and energy impact. In contrast, simulations focused on (i) energy savings and (ii) IEQ.

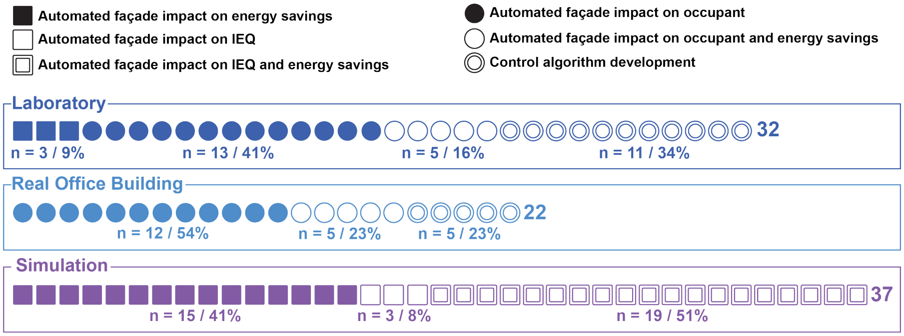

FIG. 2.4 Distribution of laboratory experiments, real office building assessment, and simulation according to their research aim, namely automated façade's impact on energy savings, impact on occupants, and control algorithms development. Additionally, several articles focused on the effect of automated façades on energy savings and occupant response. Number of studies / percentage.

2.3.2 Orientation and Climatic Context of Previous Studies

Studies on dynamic façades have mainly focused on southern orientations, as shown in Figure 2.5.

Real office building studies examined the orientations of the south (n = 9) and southeast (n = 4), with fewer studies in the east (n = 3), west (n = 3), north (n = 1), and northwest (n = 1). In laboratory experiments, south (n = 22) was most studied, followed by east (n = 4) and southeast (n = 4). The simulations showed a similar trend, focusing on the south (n = 28), then the east (n = 6), and the north (n = 5). Some studies covered multiple orientations, and four did not specify orientation. However, the limited investigation of other orientations, such as north-facing façades

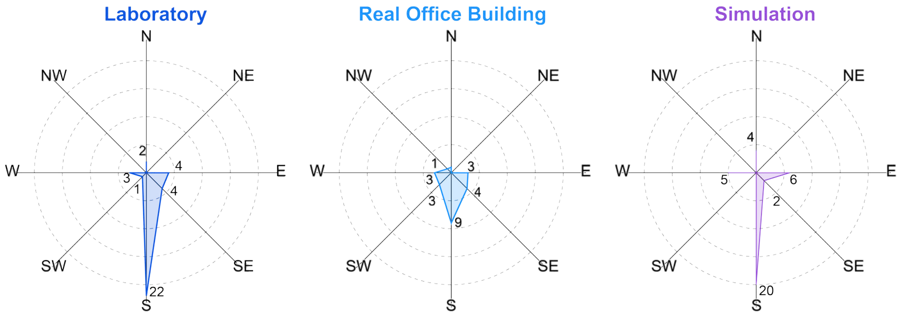

FIG. 2.5 Distribution of studies per orientation divided by laboratory, real office building, and simulation setting. The plot shows that most laboratory experiments have been conducted on south-oriented façades. Real office building orientations are distributed among west, south, and east orientations.

with diffuse daylight or west-facing façades with afternoon overheating risks, may result in gaps in understanding façade performance under different environmental conditions.

The climate context for laboratory experiments, real office building studies, and simulations is shown in Figure 2.6. Most studies were conducted in Temperate Oceanic Climates (5 laboratories, 10 real office buildings, 14 simulations), Humid Subtropical Climates (8 laboratories, 4 real office buildings, 10 simulations), and Warm-Summer Mediterranean Climates (4 laboratories, 2 real office buildings, 1 simulation). Fewer studies were conducted in Hot Desert Climate (3 simulations) and Cold-Summer Mediterranean Climates (1 laboratory, 6 real office buildings). Other climate types, such as Tropical Monsoon (n = 2) and Warm Summer Humid Continental, were minimally represented (n = 7). This shows a focus on temperate and subtropical climates, with arid and tropical regions underexplored in dynamic façade research.

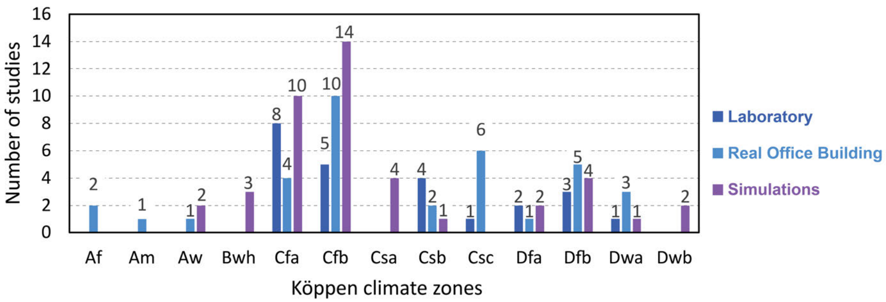

FIG. 2.6 Description of the frequency of climates considered by reviewed studies (classification according to the Köppen Climate). The climates are Tropical Rainforest Climate (Af), Tropical Monsoon Climate (Am), Tropical Wet and Dry Climate (Aw), Hot desert climate (BWh), Humid Sub-Tropical Climate (Cfa), Temperate Oceanic Climate (Cfb), Hot-Summer Mediterranean Climate (Csa), Warm-Summer Mediterranean Climate (Csb), Cold-Summer Mediterranean Climate (Csc), Hot-Summer Humid Continental Climate (Dfa), Warm-Summer Humid Continental Climate (Dfb), Humid Continental Climate (Dwa).

2.3.3 The Domain of Investigation and Type of Façade Technology Investigated

Studies have examined IEQ across five domains: visual, thermal, acoustic, indoor air quality, and personal control (Figure 2.7). Of these studies, 59 assessed the impact of dynamic façades using objective measurements, while 25 combined sensor data with subjective participant feedback. In the visual domain, studies focused on indoor daylight conditions (n = 64), view access (n = 15), discomfort glare (n = 30), and perceived privacy (n = 3). Thermal aspects investigated included indoor air temperature (n = 30) and solar gains (n = 12). Personal control and occupants' interaction were analyzed in terms of perceived control (n = 8), override options (n = 9), and control type (n = 4). Acoustic studies addressed noise levels and perception (n = 2). Indoor air quality was assessed through CO_2, VOC measurements, and occupant surveys (n = 5) [11, 23, 36, 44, 47].

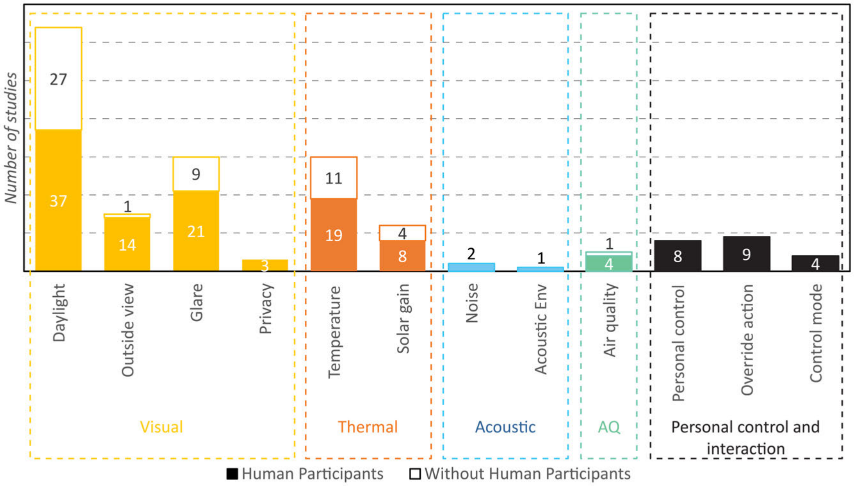

FIG. 2.7 Number of studies investigating indoor environmental domains with and without participants.

The impact of automated façades on energy performance was analyZed in terms of cooling, heating, and artificial lighting. Thirty-four studies focused on lighting energy savings, while thirty-three examined cooling and twenty-one heating demands. Figure 2.8 illustrates the distribution of studies considering energy savings across these domains, distinguishing cases with and without participants. Only three studies assessed occupant overrides, and none examined the impact on ventilation energy demand. Façade energy harvesting was investigated in one study featuring an automated system with integrated photovoltaics [48].

The reviewed studies on laboratory and real office buildings primarily examined four dynamic façade types: switchable glazing, roller shades, venetian blinds, and window openings. Simulation studies included additional variants such as switchable suspended particle devices (SPD), modular façades, PCM Trombe walls, switchable

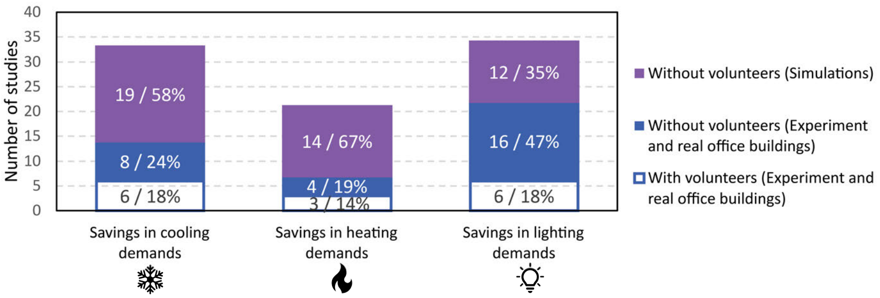

FIG. 2.8 Distribution of savings in energy demands in cooling, heating and artificial lighting assessed by studies with and without participants.

ethylene-tetrafluoroethylene (ETFE) foil cushions, and thermochromic glazing. These façades were tested using various control strategies categorized by (i) feedback ability, (ii) source of information, and (iii) data interpretation. Feedback ability distinguishes between closed-loop systems, which adjust based on real-time feedback, and open-loop systems, which operate without it. The source of information refers to sensor-based inputs (from direct measurements) or model-based inputs (from digital simulations). Data interpretation can follow rule-based or predictive approaches: rule-based algorithms apply predefined actions, while predictive algorithms analyze data patterns to anticipate and optimize façade control.

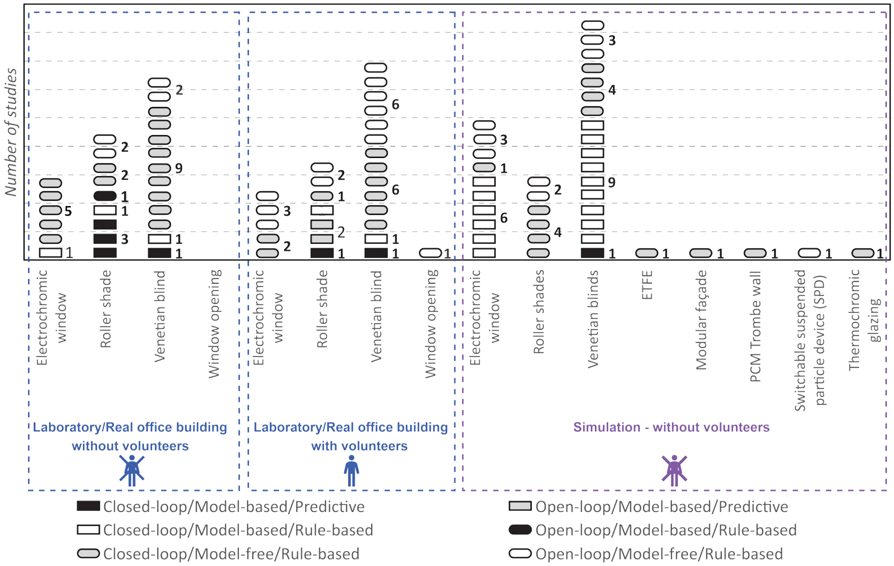

FIG. 2.9 Dynamic façades and control strategies investigated by studies. There were identified six control strategies that are the result of three aspects: (i) feedback ability (closed-loop/open-loop), (ii) source of information (sensor or digital model), and (iii) data interpretation (rule-based/predictive algorithm).

Figure 2.9 presents the distribution of studies on automated façades based on control strategies, categorized by feedback ability, information source, and data interpretation. Studies were classified based on whether human participants were involved. Most studies investigated closed-loop, model-free, rule-based control, with 9 studies involving participants and 29 without participants. Closed-loop, model-based, rule-based control was examined in 2 studies with participants and 17 without participants. Open-loop control was more common in studies without participants (n = 14), particularly model-free, rule-based approaches (12 with participants, 13 without). Predictive algorithms were used in 7 studies, mostly for venetian blinds and roller shades, including 3 studies with participants and 2 without.

2.3.4 Control objectives tested for automated façades

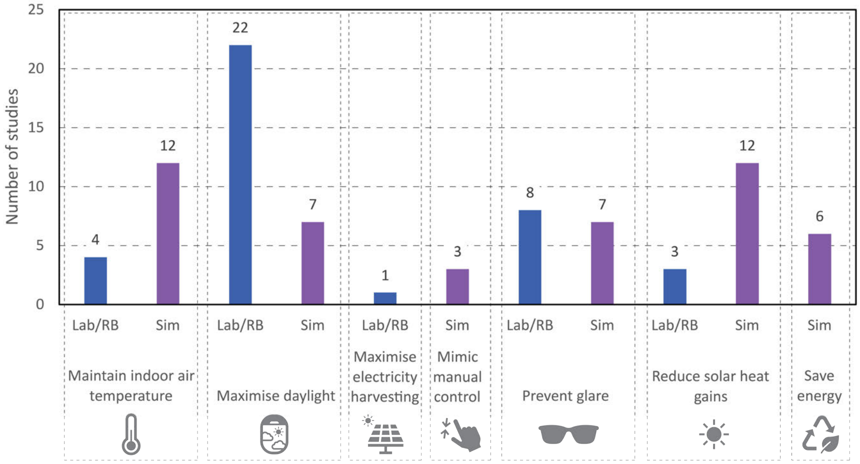

FIG. 2.10 Distribution of automated façade control objectives among the papers analyzed. Each control objective is described regarding simulation study and laboratory and real office building assessment.

Figure2.10 summarizes automated façades control objectives, with most studies focusing on maximizing daylight (n = 28), of which 22 were conducted in laboratory or real office building settings and six through simulations. Glare prevention was examined in 15 studies (8 Laboratory/real office building, 7 Simulation), while maintaining indoor air temperature was explored in 16 studies (4 Laboratory/real office building, 12 Simulation). Fewer studies investigated mimicking manual control (n = 3) or maximizing electricity harvesting (n = 1). Multi-objective strategies, combining daylight with glare control (n = 8) or temperature regulation (n = 4), aimed to enhance energy performance. There is a lack of control strategies that address occupant needs for privacy, improved views, or other aspects of occupant experience that directly impact the operation of façades. This gap may be attributed to the complexity of understanding and dynamically integrating occupant preferences into control strategies, a challenge that, if overcome, could significantly improve the effectiveness of automated façade systems.

2.4 Current evidence on the influence of automated façades on energy demand, IEQ and occupants

2.4.1 Automated Façade Influence on Building Energy Demand

As shown in Figure 2.11, the energy savings of automated façades in office environments were analyzed in 68 articles, comparing automated windows with unshaded windows (n = 34), static shading (n = 15), and manually controlled windows (n = 13). Additionally, five studies evaluated model-based and adaptive algorithms based on occupant illuminance preferences against conventional automated systems that use desk-level indoor illuminance controls.

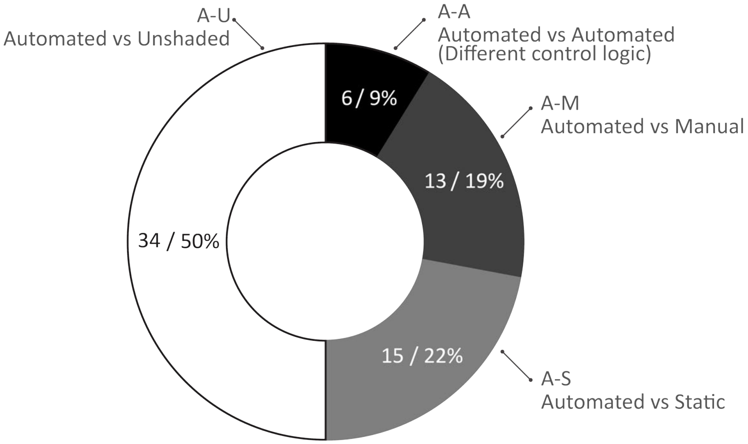

FIG. 2.11 Distribution of studies comparing automated façade control systems with other operational modes. The plot shows the proportion of studies that compare automated systems to unshaded façades (A-U), static façades (A-S), manual control (A-M), and different types of automated logic (A-A).

Figure 2.12 shows the number of studies where occupant interaction was considered, dividing them into simulations, laboratory and real office building assessments. Among the simulation studies, 29 did not account for occupant interaction with the building, while one included glare probability as a proxy of occupant interaction to compare automation against manual control [49]. In the laboratory and real office building assessments, 26 studies did not incorporate occupant interaction, whereas two studies allowed occupants to interact with façade elements.

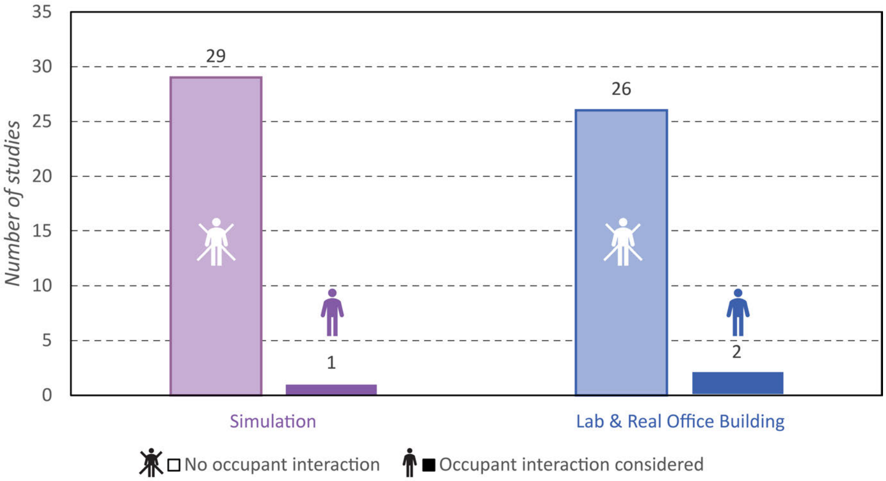

FIG. 2.12 Distribution of the studies considering occupant interaction when evaluating the energy performance of automated façades. The plot shows the number of papers in two categories: simulation, and laboratory and real office building experiments.

Energy consumption findings are summarized in Figure 2.13, categorizing evidence into cooling (blue), heating (orange), lighting (yellow), and overall energy consumption (grey) while distinguishing between simulation studies and laboratory or real office building assessments. Simulations indicate that automated façades can reduce cooling energy consumption by 0–40%, depending on location and orientation [50–56], with reductions of 85% in Riyadh [57] and 93% in Nottingham [58], both for south-facing façades. However, no laboratory or real office building studies implemented control strategies specifically for cooling energy savings. Despite this, automated venetian blinds achieved reductions in cooling energy between 12% [33] and 28% [59] compared to static shading. Conversely, one study reported a 10% increase in cooling energy consumption with automated roller shades [60]. While laboratory and real office building research on optimizing cooling energy use remains limited, existing evidence highlights the potential of automated façades to enhance cooling efficiency, particularly in high solar-gain climates.

The impact of automated façades on heating energy consumption varies significantly across studies. Some simulations reported increases of up to 103% when using ethylene-tetrafluoroethylene (ETFE) foil cushions [58], while others found reductions ranging from 77% [61] and 42% [57] (switchable suspended particle device (SPD) and roller shades with occupant interaction) to 5% [51, 62, 63] (electrochromic windows, roller shades, and venetian blinds). Laboratory and real office building studies provide limited evidence on heating energy consumption. Two studies reported contrasting results: rule-based venetian blinds controlled by indoor illuminance increased heating energy consumption by 5% compared to unshaded windows [35], while irradiance-controlled venetian blinds with photovoltaic cells achieved 6–14% energy savings compared to similar automated blinds with different control logic [64]. These discrepancies may be due to insufficient solar gains with automated control compared to manual operation, while the second study compares different control logics for automated venetian blinds. Only one simulation study examined the effect of manual control or occupant interaction on heating energy demand.

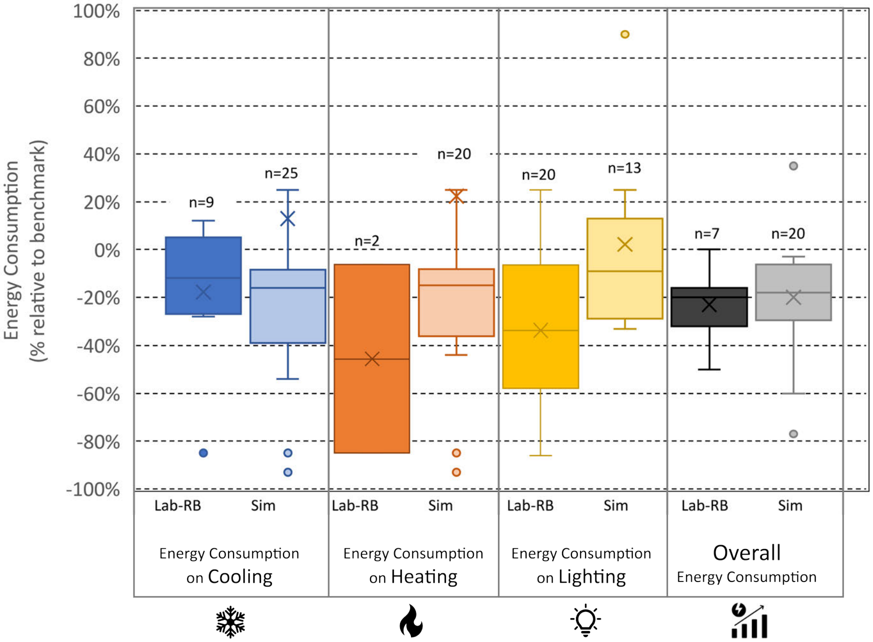

FIG. 2.13 Box plot illustrating the reported energy demand reduction (%) achieved by automated façades across different study types: Laboratory-Real Office Building (Lab-RB) and Simulation (Sim). Each box represents the range of energy performance outcomes, with the horizontal line indicating the median and 'X' marking the mean. The number of studies included in each category (n) is shown above the respective box plot for context.

When programmed for lighting energy savings, automated façades consistently reduce lighting energy consumption. Simulation studies report reductions from 31% with electrochromic windows compared to unshaded windows [50, 65–69] to 81% with venetian blinds compared to static louvers [40, 70]. In laboratory and real office building studies, electrochromic windows achieved up to 68% savings compared to static 15% visual-transmittance glazing [61], while roller shades reduced up to 75% [71] and venetian blinds reached 86% [37, 72–75]. However, the highest savings occurred in studies without occupant interaction. When occupants could override automation, savings dropped to 10% for venetian blinds [45, 76], and 25% for roller shades [77]. This raises uncertainty about whether similar savings would be achieved in real office buildings with occupant intervention.

Thirty-four of the 68 studies compared automated façades to static glazing without shading [54, 78–84]. However, such comparisons are insufficient to demonstrate the benefits of automation, as unshaded windows are already known to increase energy demand and are rarely used in real office buildings. A more relevant comparison was made in 15 studies, which evaluated automated shading against manually controlled systems. However, these studies only considered automation without allowing occupants to override the system. Since previous research suggests that occupant overrides can significantly reduce the efficiency of automation [85], the reported benefits may not fully reflect real-world performance. Only two studies [45, 77] accounted for occupant interaction in both manual and automated scenarios, providing a more robust comparison. Their findings suggest that automation, even with occupant interaction, can still lead to lower energy consumption.

Two laboratory studies and one simulation-based evaluation assessed model-based and adaptive control algorithms, primarily for reducing lighting energy consumption. A model-based system reduced lighting energy consumption by approximately 30% compared to a strategy using desk-level indoor illuminance [86]. In a real office building, a predictive control strategy with occupant overrides achieved a 25% reduction compared to a control based on desk illuminance and automated lighting switch-off [77]. Simulations reported an 81% reduction when comparing predictive control to static shading. Although evidence is limited, these findings demonstrate the potential benefits of advanced control strategies such as model-based and predictive algorithms.

Figure 2.14 illustrates the impact of automated façades on energy consumption by comparing studies that evaluated automation against manually controlled shading in laboratory, real office building, and simulation settings. Five studies provided relevant data, all indicating energy savings with automated control. Among laboratory and real office building studies, the greatest reduction was observed in lighting consumption for roller shades (39% [60]), followed by venetian blinds (11% [87]). However, automated roller shades controlled by an external illuminance sensor increased cooling energy consumption by 10% [60]. One simulation study [61] demonstrated that automated façades significantly improve energy efficiency, particularly when occupant behavior is suboptimal. Comparing three behavioral models (“careless occupant,” “intermediate occupant,” and “proactive occupant”)the study found that automation reduced cooling energy consumption by up to 95% in the "careless occupant" scenario. Even “proactive” occupants saw notable savings, highlighting the limitations of manual operation. Heating energy savings ranged from 0% to 30%, while lighting reductions were between 20% and 48%.

The overall energy savings indicate that automation yields greater energy savings in the summer [47] compared to winter [47, 88], primarily due to the reduction in solar gains received by the façade during winter. Additionally, some occupant profiles can

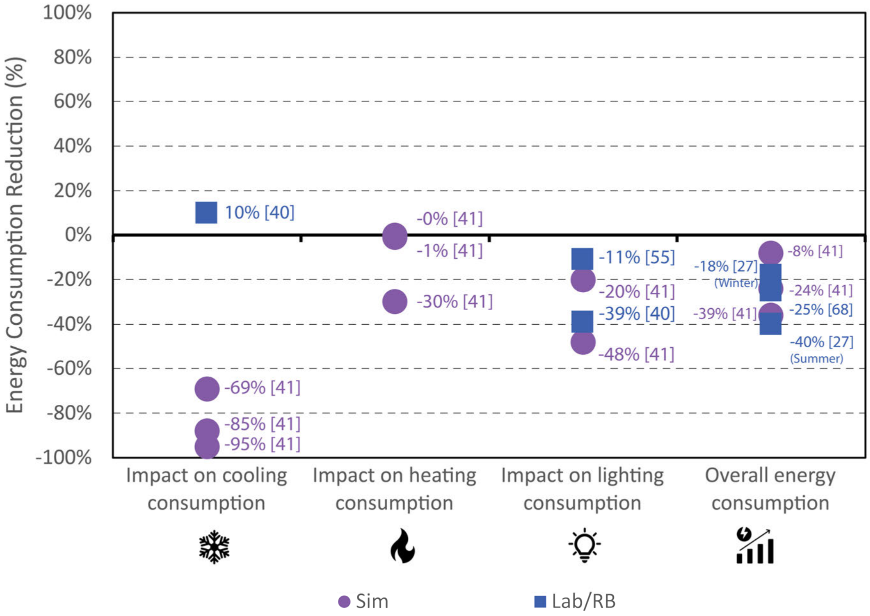

FIG. 2.14 Reported impact of automated façade operation on energy consumption, compared exclusively to manually controlled façades. Each point represents a study, with results shown as the percentage reduction in energy consumption for cooling, heating, lighting, and total energy demand. Purple circles indicate simulation studies, while blue squares represent laboratory or real building (Lab/RB) studies. The figure highlights the general trend of automated façades reducing energy demand, though not all studies reported savings in every category.

reduce the energy consumption gap between automated and manual control, influenced by individual control objectives or personal preferences. These findings underscore the significance of advanced control algorithms in optimizing the energy efficiency of automated façades. Moreover, effective strategies—whether model-based or rule-based—can result in substantial energy savings and improved IEQ, while inadequate manual control can undermine these benefits and lead to excessive energy consumption.

2.4.2 Automated Façade Influence on IEQ

The impact of automated façade operation on indoor environmental quality (IEQ) in office environments has been investigated through laboratory experiments (n = 15), real office building assessments (n = 7), and simulations (n = 13). Most studies employed rule-based control strategies based on workplane illuminance, Daylight Glare Probability (DGP), indoor air temperature, solar irradiance, and air quality (Figure 2.15). Automated façade control regulated the visual environment using workplane illuminance thresholds ranging from 510–700 lx to 500–3000 lx, ensuring glare probability remained below 0.35 (imperceptible rating). Thermal control targeted indoor temperatures between 21°C and 25°C, with shading devices activated when solar irradiance exceeded 250 W/m^2. Air quality control was addressed in a single study, where window operation was triggered when CO_2 levels surpassed 1250 ppm. Only two studies evaluated the performance of predictive control systems [40, 47].

Workplane illuminance thresholds, daylight glare probability, indoor air temperature, solar irradiance on the façade, and air quality are key environmental variables used to assess the performance of automated control strategies, as illustrated in Figure 2.16. In some cases, operative temperature was evaluated alongside control strategies primarily focused on indoor illuminance, while metrics such as view out and workplane illuminance were used to assess strategies based on solar irradiance. These variations highlight the interdependence of IEQ parameters, demonstrating how control strategies targeting a single environmental variable can influence overall environmental comfort.

The interdependence of IEQ variables is supported by studies on multi-domain IEQ [64, 89, 90], which assessed automated façade performance in relation to both visual and thermal effects. These studies indicate that controlling one environmental domain influences others, impacting overall occupant comfort. However, no studies have examined how to balance these effects or identify key competing factors. Additionally, only two studies have investigated the impact of automated façades across all IEQ domains [44, 91].

Regarding daylight access, a few studies have evaluated whether automated façade operation enhances visual conditions by comparing average workplane illuminance

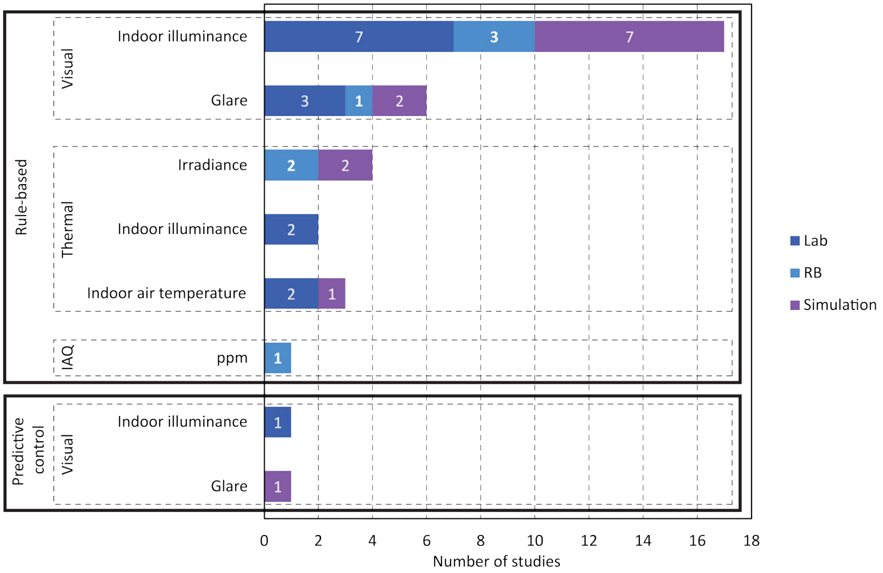

FIG. 2.15 Distribution of control strategies and evaluated environmental domains in the studies reviewed. The bar chart distinguishes between two control strategies: rule-based and predictive control. For rule-based control, studies are further grouped by environmental domain (visual, thermal, and IAQ), with the specific variables assessed indicated within each domain. For predictive control, only the visual domain is represented. Bar segments are color-coded by study type (laboratory, real building, and simulation), and the numbers within the bars indicate the count of studies addressing each variable.

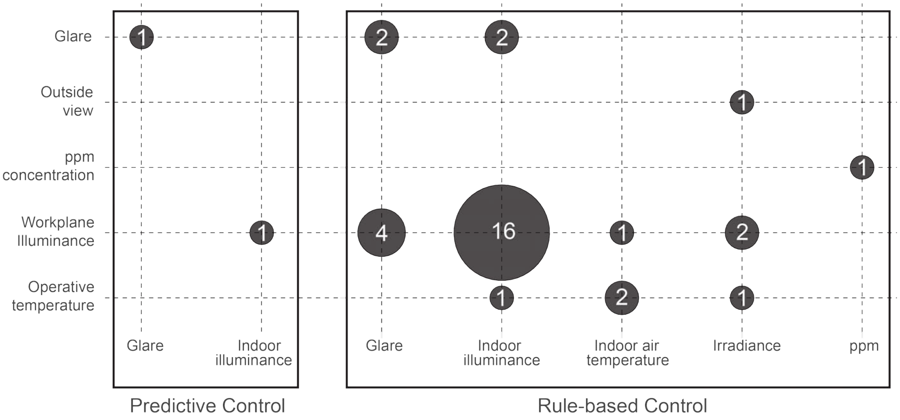

FIG. 2.16 Distribution of studies based on the environmental variables used to evaluate the performance of automated façades, visualized as a bubble plot. The y-axis lists the evaluation variables, such as glare, outside view, ppm concentration, workplane illuminance, and operative temperature. The x-axis categorizes the studies by control strategy, distinguishing between predictive control and rule-based control. The size of each bubble indicates the number of studies considering a given variable within each control strategy. Numeric labels within bubbles denote the study count.

levels. These studies applied different target illuminance thresholds to assess visual performance, considering the duration within specific ranges: 510–700 lx [36], 484–538 lx [92] 484–538 lx [87], 570–670 lx [60], <2000 lx [93], 500–3000 lx [28, 94–96], and 600–3000 lx [89, 90, 97]. Findings indicate that manually controlled scenarios tend to exhibit higher daylight levels and an increased risk of glare (e.g., [28, 34]) compared to automated systems, which are typically programmed to minimize cooling loads [44] or mitigate excessive brightness [60, 98] and glare [28, 60, 96, 99]. For instance, Clear et al. [9] demonstrated that an automated electrochromic window reduced illuminance from 2990±2165 lx to 830±520 lx compared to manually controlled blinds. Similar results were reported by Vine et al. [36], Kim et al. [33], and Lee et al. [60] in comparisons with manual controls. Thus, automated systems effectively prevent excessive brightness by continuously adjusting the façade, which manual controls do not achieve with manual control. This trend was also present when a fully automated venetian blind was compared to a semi-automated control strategy with an override option, but with smaller differences, as described by Vine et al. [36], from 735±162 lx (semi-automated) to 598±60 lx (fully-automated).

Glare in indoor spaces was assessed using either DGP [28, 94, 96, 99] or window luminance (cd/m^2) [34, 93, 98, 100]. Automated control effectively reduced glare when operating Venetian blinds and roller shades, outperforming manual systems [28, 93]. However, electrochromic windows showed no substantial improvement over semi-automated operation [34, 93], as their darkest tint state does not provide adequate protection when the sun is within the field of view. These findings indicate that the effectiveness of automated control depends on the façade typology and its ability to regulate specific environmental variables. Additionally, automated façades were compared to a fully closed roller shade, however, using either a fully raised or fully closed blind does not constitute a suitable reference scenario.

Regarding thermal quality, two studies found automated controls to be more effective in preventing overheating [91, 101], while others reported no significant differences [44, 89]. When compared to a static shade, an automated roller shade programmed to regulate indoor air temperature reduced overheating from 15% to 8% of the total time [101]. However, air temperature alone is insufficient; operative temperature must also be considered [89, 90], along with the impact of solar radiation on occupants' thermal comfort, as solar irradiance plays a key role in assessing façade influence on thermal comfort. Additionally, one study found no substantial difference in thermal comfort between manually controlled and semi-automated scenarios. Automated controls that disrupt occupants are frequently overridden and often fail to effectively regulate solar gains [46]. The only study that compared automated strategies to window openings or vents versus manual controls reported better air quality when the control was automatic [32]. The automated windows' opening overpasses the concentration of carbon dioxide ($CO^2 > 1500$ppm) for about 9% of the time, compared to a manual window opening that showed 31%. This means the automated control system better controlled the air quality inside the room tested.

There were no studies comparing different shading devices with the same control strategy, which is a valuable information for designing effective automated façade strategies. Only three studies allowed occupants to override the automated system, which was programmed to maintain illuminance under certain thresholds. Therefore, the semi-automated scenario measured higher indoor illuminance levels than expected [36]. Thus, there was a tendency in manually controlled strategies to provide brighter [28, 33, 36] or more glary indoor conditions [28], while only one study showed lower light levels [60] and poorer indoor air quality [32]. Regarding orientation and climate, east and west orientations showed that the automated system was inadequate to balance competing indoor comfort domains (glare/view access, overheating and daylight) [33].

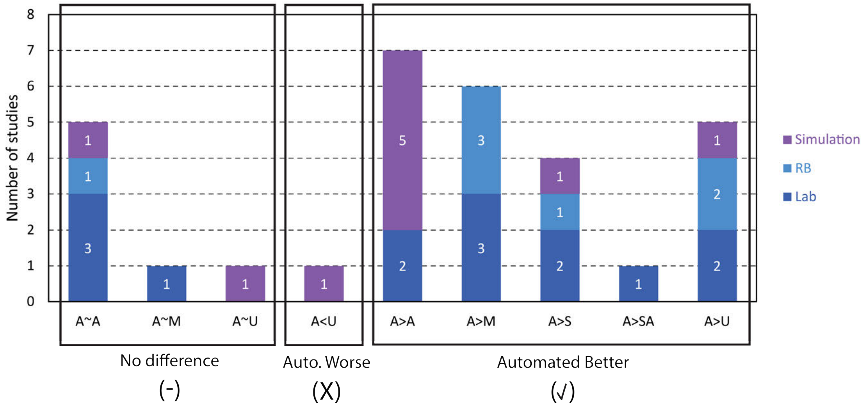

FIG. 2.17 Comparison of the environmental performance of automated façades relative to other control strategies, visualized as a stacked bar chart. The x-axis groups studies by performance outcome: "No difference," "Automated Worse," and "Automated Better." Subcategories indicate the control strategy used for comparison with automated façades, such as unshaded windows (A-U), static façade (A-S), manual shading (A-M), semi-automated (A-SA), and other automated controls (A-A). Bars are stacked and color-coded to represent study types: laboratory (Lab), real office building (RB), and simulation (Simulation). The height and composition of each bar indicate the number and type of studies reporting each performance outcome.

Figure 2.17 summarizes the performance of automated façade systems relative to other control strategies across three categories: "No Difference," "Automated Worse," and "Automated Better." The y-axis represents the number of studies, while the x-axis distinguishes the comparisons: automated versus another automated system (A-A), manual control (A-M), unshaded conditions (A-U), and static shading (A-S). Most studies (n = 22) indicate that automation enhances environmental conditions compared to semi-automatic, manual, static, and unshaded windows. Cases showing no difference include comparisons between different automated control logics [39, 47, 93, 102, 103], studies where automation prioritized illuminance but was evaluated based on indoor temperature [89, 90], and those focusing on solar heat gain control while assessing daylight availability [63, 104]. One study found unshaded windows to outperform automated façades due to the evaluation criterion being the percentage of time with an unobstructed outdoor view [49].

2.4.3 Occupant Response to Automated Façade Operation

The impact of automated façades on occupants in office environments has been investigated across multiple environmental domains, including visual, thermal, acoustic, and air quality. Research methods, such as questionnaires, surveys, and interviews, have been employed to assess occupant satisfaction (n = 26), perception (n = 15), discomfort (n = 2), and interaction frequency (n = 7) with control systems. Studies have been conducted in both laboratory settings and real office buildings, often integrating monitoring systems to track occupant interactions and override actions.

The dynamic façade components analyzed were venetian blinds (n = 9), electrochromic glazing (n = 4), roller shades (n = 4), and window openings (n = 1). Occupant responses were compared across different operation modes: unshaded windows (n = 2), manually operated shading (n = 8), semi-automated shading with override options (n = 3), and manual window opening (n = 1). Additionally, six studies examined advanced control strategies, including adaptive [47], predictive [105], learning-based [106], and multi-variable algorithms [107], compared to conventional controls based on temperature, irradiance, and indoor illuminance measurements.

Table 2.2 presents evidence on the impact of dynamic façades in the visual domain, focusing on occupant satisfaction (n = 11), perception (n = 4), discomfort (n = 2), and dissatisfaction (n = 1). The studies assess indoor lighting, glare, brightness, and access to outdoor views. Findings regarding automated versus manual control are mixed. Three out of six studies comparing automated to manual façades reported improved satisfaction with automated daylight control [23, 33, 108]. In contrast, other studies found greater satisfaction with manually operated venetian blinds and roller shades [36, 89, 109]. While occupants appreciated automated daylight control, they preferred manual operation for selecting control modes and accessing outdoor views. However, one study [108] reported occupant satisfaction with automated control for view access.

Three studies compared fully automated to semi-automated controls. Semi-automated systems demonstrated improved satisfaction with lighting conditions compared to fully automated scenarios [36] and were more effective in reducing glare perception [30, 36]. One study [10], which did not compare automation with other control modes, reported low brightness and glare perception under automated control.

When comparing rule-based controls to advanced automated systems capable of predicting occupant behavior and adapting to their preferences, the latter showed slightly better results for glare perception and access to outdoor views [110]. However, two studies reported higher dissatisfaction with daylight under advanced control operation, potentially indicating the impact of the control objectives over occupant satisfaction [86, 110].

Thus, evidence on occupant response with the visual domain suggests that while automated façade can enhance occupant satisfaction, occupants prefer manual operation for selecting control modes and accessing outdoor views. Semi-automated systems offer a middle ground, improving satisfaction and reducing glare perception compared to fully automated controls. However, advanced automation, despite slight benefits in glare management and view access, can lead to increased dissatisfaction with daylight, indicating the need for carefully calibrated control objectives. The mixed results indicate the diversity of occupant preferences, underscoring the importance of adaptable control strategies that balance automation with personal control.

TABLE 2.2 Evidence on the Visual Domain. The table presents the type of occupant response reported, the control logic tested, the metrics used in each study, and the corresponding results. ([LA]: Level of Automation; [Res]: Result); [A]: Automated; [M]: Manual; [SA]: Semi-automated; [S]: Static; [PR]: Pre-program; [AD]: Advanced).

R.	Occupant response	Control logic	Metric	[LA]=[Res]
[33]	Satisfaction with lighting.	(1) Automated, (2) manual	Occupants satisfied (%)	[A]=88% [M]=0%
[34]	Perception of glare.	(1) Automated based on indoor illuminance (2) Semi-automatic, (3) fixed 60% glazing.	1=very dissatisfied 5=very satisfied	[A]=3.7 [SA]=3.8 [S]=3.2
[34]	Perception of lighting.	(1) Automated based on indoor illuminance, (2) Semi-automatic (3) fixed 60% glazing.	1=very dissatisfied 5=very satisfied	[A]=3.3 [SA]=3.1 [S]=3.5
[36]	Satisfaction with lighting.	(1) Automatic based on illuminance, (2) Semi-automated, (3) Manual mode.	Occupants satisfied (%)	[A]=57% [SA]=71% [M]=64%
[36]	Perception of glare.	(1) Automatic based on illuminance, (2) Semi-automated, (3) Manual mode.	Occupants perceiving glare (%)	[A]=0% [SA]=0% [M]=14%
[10]	Perception of brightness.	(1) Automated based on direct sunlight.	1=never 5=always	[A]=1.9
[10]	Perception of glare.	(1) Automated based on direct sunlight.	1=never 5=always	[A]=1.9
[10]	Perception of brightness.	(1) Automated based on direct sunlight.	1=never 5=always	[A]=1.10
[10]	Perception of glare.	(1) Automated based on direct sunlight.	1=never 5=always	[A]=2.1
[10]	Perception of brightness.	(1) Automated based on direct sunlight.	1=never 5=always	[A]=1.8
[11]	Satisfaction with lighting conditions.	(1) Pre-programmed action, (2) illuminance-based automation.	100=Too high -100=Too low	[A]=-15.1 [PR]=1.3
[11]	Satisfaction with glare.	(1) Pre-programmed action, (2) illuminance-based automation.	100=Very much -100=Not at all	[A]=14.2 [PR]=26
[11]	Satisfaction with view access.	(1) Pre-programmed action, (2) illuminance-based automation.	100=very dissatisfied -100=very satisfied	[A]=-1 [PR]=21
[23]	Satisfaction with lighting.	(1) Automated based on exterior illuminance, (2) manual.	Occupants satisfied (%)	[A]=56.8% [M]=37.3%
[44]	Discomfort with lack of daylight.	(1) Automated based on exterior irradiance, (2) manual.	Discomfort events (n)	[SA]=16 [M]=7

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TABLE 2.2 Evidence on the Visual Domain (continued)

R.	Occupant response	Control logic	Metric	[LA]=[Res]
[44]	Dissatisfaction with lack of view access.	(1) Automated based on exterior irradiance, (2) manual.	Interactions (n)	[SA]=18 [M]=7
[44]	Dissatisfaction with glare conditions.	(1) Automated based on exterior irradiance, (2) manual.	Interactions (n)	[SA]=10 [M]=4
[44]	Satisfaction with lighting.	(1) Automated based on exterior irradiance, (2) manual.	1=dissatisfied 5=satisfied	[SA]=4.5 [M]=4.2
[44]	Satisfaction with glare conditions.	(1) Automated based on exterior irradiance, (2) manual.	1=dissatisfied 5=satisfied	[SA]=3.1 [M]=4
[44]	Satisfaction with view access.	(1) Automated based on exterior irradiance, (2) manual.	1=dissatisfied 5=satisfied	[SA]=3 [M]=3.7
[86]	Satisfaction with lighting.	(1) Automated based on DGP and work plane illuminance, (2) control based on desk illuminance.	0=very dissatisfied 10=very satisfied	[AD]=7.5 [A]=7
[86]	Perception of glare.	(1) Automated based on DGP and work plane illuminance, (2) control based on desk illuminance.	0=no perceived 10=perceived	[AD]=1.8 [A]=2.2
[89]	Satisfaction with lighting.	(1) Automated based on indoor illuminance (2) manual.	% time of IR=0.	[A]=67% [M]=81%
[91]	Discomfort with the visual env.	(1) Automated based on the sun of the field of view, (2) manual.	Discomfort events (n)	[SA]=14 [M]=1
[91]	Satisfaction with glare protection.	(1) Automated based on the sun of the field of view, (2) manual.	1=agree 5=disagree	[SA]=4.5 [M]=4
[91]	Satisfaction with daylight.	(1) Automated based on the sun of the field of view, (2) manual.	1=agree 5=disagree	[SA]=3.7 [M]=3.7
[91]	Satisfaction with view access.	(1) Automated based on the sun of the field of view, (2) manual.	1=agree 5=disagree	[SA]=4.8 [M]=4.3
[110]	Satisfaction with view access.	(1) Automation based on indoor illuminance, irradiance, and temperature (2) automated based on irradiance.	Satisfied subjects (n)	[AD]=20 [A]=5
[110]	Satisfaction with lighting.	(1) Automation based on indoor illuminance, irradiance, and temperature (2) automated based on irradiance.	Satisfactory answers (n)	[AD]=22 [A]=17
[110]	Satisfaction with lighting.	(1) Automated based on indoor illuminance, irradiance, and temperature (2) automated based on irradiance.	Satisfactory answers (n)	[AD]=7 [A]=13
[109]	Satisfaction with lighting.	(1) Manual, (2) automated (3) Semi-automated.	1=dissatisfied 7=satisfied	[A]=4.5 [SA]=5 [M]=5.4
[109]	Satisfaction with view access.	(1) Manual, (2) Automated, (3) Semi-automated.	1=dissatisfied 7=satisfied	[A]=5.3 [SA]=5.9 [M]=6.3

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TABLE 2.2 Evidence on the Visual Domain (continued)

R.	Occupant response	Control logic	Metric	[LA]=[Res]
[108]	Satisfaction with view access.	(1) automated control, (2) fixed glazing.	1=very poor 5=excellent	[A]=4.4 [M]=3.7
[108]	Satisfaction with lighting.	(1) automated control, (2) fixed glazing.	1 = very poor 5 = excellent	[A]=4.6 [M]=4.3
[10]	Perception of glare.	(1) Automated based on direct sunlight.	1=never 5=always	[A]=1.8

Occupant responses to the thermal environment were evaluated across four studies, focusing on thermal sensation (n = 1), satisfaction (n = 3), dissatisfaction (n = 1), and discomfort levels (n = 1). As summarised in Table 2.3, findings on the impact of automated control strategies on thermal responses are mixed. One study reported improved thermal sensation with automation compared to manual control [32], while another found no significant differences between adaptive and rule-based controls [86]. Studies on semi-automated controls consistently indicated higher satisfaction and fewer discomfort events compared to manual controls [44, 91]. While semi-automated controls reliably enhance satisfaction and reduce discomfort, the effects of fully automated systems remain inconclusive, with some studies reporting benefits and others showing no significant differences. These discrepancies may be attributed to variations in façade types, control strategies (e.g., CO_2 concentration, solar irradiance, indoor illuminance), study settings (laboratory vs. real office buildings), and the limited number of studies examining occupant responses to automated façades in the thermal domain.

TABLE 2.3 Evidence on the Thermal Domain. The table presents the type of occupant response reported, the control logic tested, the metrics used in each study, and the corresponding results. ([LA]: Level of Automation; [Res]: Result); [A]: Automated; [M]: Manual; [SA]: Semi-automated; [AD]: Advanced)

R.	Occupant response	Control logic	Metric	[LA]=Res
[32]	Sensation of thermal env.	(1) Automated, (2) manual	TSV neutral votes (%).	[A]=77% [M]=66%
[44]	Dissatisfaction with thermal env.	(1) Automated based on exterior irradiance, (2) manual.	Interactions (n)	[SA]=5 [M]=1
[44]	Satisfaction with thermal env.	(1) Automated based on exterior irradiance, (2) manual.	1=dissatisfied 5=satisfied	[SA]=3 [M]=4
[86]	Satisfaction with thermal env.	(1) Automated based on DGP and work plane illuminance, (2) control based on desk illuminance.	1 = cold 10=hot	[AD]=5.2 [A]=5
[91]	Discomfort with thermal env.	(1) Automated based on the sun of the field of view, (2) manual.	Discomfort events (n)	[SA]=12 [M]=7
[91]	Satisfaction with thermal env.	(1) Automated based on the sun of the field of view, (2) manual.	1=agree 5=disagree	[SA]=3.2 [M]=1

Three studies have focused on acoustic satisfaction, perception and discomfort, as shown in Table 2.4. While Vine et al. [36] found no significant differences, Luna-Navarro et al. [44, 91] reported increased acoustic discomfort due to actuator noise and background sound levels. Higher perceived noise levels were associated with semi-automated modes, possibly due to frequent system actuation resulting from occupant overrides [36].

TABLE 2.4 Evidence on the Acoustic Domain. The table presents the type of occupant response reported, the control logic tested, the metrics used in each study, and the corresponding results. ([LA]: Level of Automation; [Res]: Result); [A]: Automated; [M]: Manual; [SA]: Semi-automated).

R.	Occupant response	Control logic	Metric	[LA]=Res
[36]	Perception of noise.	(1) Automated based on illuminance, (2) semi-automated, (3) manual mode.	Occupants perceiving noise (%)	[A]=14% [SA]=21% [M]=14%
[44]	Satisfaction with acoustic environment.	(1) Automated based on exterior irradiance, (2) manual.	1=dissatisfied 5=satisfied	[SA]=4.5 [M]=2
[91]	Discomfort with acoustic environment.	(1) Automated based on sun in the field of view, (2) manual.	Discomfort events (n)	[SA]=3 [M]=1

Two studies [44, 91] found no significant differences in perceived indoor air quality between semi-automated and manually controlled shading (Table 2.5). The limited impact on air quality may be due to automated shading primarily regulating solar radiation, daylight, and glare, rather than air quality. The only study examining automated openable vents did not assess air quality perception [32].

TABLE 2.5 Evidence on the Indoor Air Quality Domain. The table presents the type of occupant response reported, the control logic tested, the metrics used in each study, and the corresponding results. ([LA]: Level of Automation; [Res]: Result); [M]: Manual; [SA]: Semi-automated).

R.	Occupant response	Control logic	Metric	[LA]=Res
[44]	Satisfaction with air quality.	(1) Automated based on exterior irradiance, (2) manual.	1=dissatisfied 5=satisfied	[SA]=4 [M]=4.5
[91]	Discomfort with air quality.	(1) Automated based on exterior irradiance, (2) manual.	Discomfort events (n)	[SA]=0 [M]=1

Studies on occupant behavior, summarized in Table 2.6, examined interactions with automated façades in relation to specific occupant requirements, including increasing daylight availability (n = 1), reducing glare (n = 2), improving the view (n = 1), and regulating the thermal environment (n = 1). One study [111] did not provide a baseline for comparing occupant responses to the automated façade. Overall, findings indicate that occupants interact more frequently under manual control than in semi-automated scenarios [47, 90, 91, 112]. This increased interaction under manual control is attributed to occupants' need to adjust their environment according to individual preferences. This aligns with the design of the automated systems studied, which were programmed to regulate daylight and minimize direct sunlight in the field of view, thereby reducing the need for occupant intervention. Additionally, studies suggest that interactions in semi-automated scenarios may result from automated actions triggering occupant responses, potentially disrupting concentration and productivity [44, 111]. Luna-Navarro et al. [44] noted that gradual, silent automated controls are less likely to be overridden.

TABLE 2.6 Evidence on occupant behavior to automated façade. ([LA]: Level of Automation; [Res]: Result; [M]: Manual; [SA]: Semi-automated; [AD]: Advanced).

Ref.	Occupant response	Control logic	Metric	[LA]=Res
[47]	Interaction with control system.	(1) Adaptive control based on interactions, (2) temperature-based automation.	Interactions average per day.	[AD]=3.1 [SA]=3.2
[111]	Interaction with control system.	(1) Automation based on exterior illuminance.	Interactions increasing daylight (avg).	[SA]=11
[111]	Interaction with control system.	(1) Automation based on exterior illuminance.	Interactions to reduce glare (avg).	[SA]=2
[90]	Interaction with control system.	(1) Automated based on indoor illuminance (2) manual.	Desired actions not executed (n)	[SA]=0.5 [M]=0.6
[90]	Interaction with control system.	(1) Automated based on indoor illuminance (2) manual.	Interactions (n) average	[SA]=1.7 [M]=2.8
[91]	Interaction with control system.	(1) Automated based on sun in field of view, (2) manual.	Interaction due to glare discomfort (n)	[SA]=7 [M]=18
[91]	Interaction with control system.	(1) Automated based on sun in field of view, (2) manual.	Interactions due to lack of view/daylight (n)	[SA]=9 [M]=11
[91]	Interaction with control system.	(1) Automated based on sun in field of view, (2) manual.	Interactions due to thermal discomfort (n)	[SA]=1 [M]=0
[112]	Interaction with control system.	(1) automated based on indoor temperature, (2) manual.	Interactions over the year (n)	[SA]=9 [M]=661

Control strategies significantly influence occupant satisfaction, as shown in Table 2.7. Manual control is generally preferred over fully automated systems [36, 44, 91]. However, findings on automated control are inconsistent. While some studies report lower satisfaction with automation [36, 44], others indicate higher satisfaction [34]. Clear et al. [34] investigated an indoor illuminance-based automated control system using electrochromic windows, which adjust opacity gradually. Because these changes occur slowly, occupants may not immediately perceive them, resulting in minimal disruption. This characteristic may account for the differing findings on occupant satisfaction with automation.

TABLE 2.7 Evidence on occupant perception of automated façade. ([LA]: Level of Automation; [Res]: Result; [M]: Manual; [SA]: Semi-automated; [AD]: Advanced).

Ref.	Occupant response	Control logic	Metric	[LA]=Res
[91]	Discomfort with control system.	(1) Automated based on sun in field of view, (2) manual.	Discomfort events (n)	[SA]=4 [M]=0
[91]	Discomfort with control system.	(1) Automated based on sun in field of view, (2) manual.	1=agree 5=disagree	[SA]=2.6 [M]=1.3
[36]	Satisfaction with control system.	(1) Auto based on illuminance, (2) Semi-automated, (3) Manual.	Occupants satisfied (%)	[A]=7% [SA]=29% [M]=57%
[44]	Satisfaction with control system.	(1) Automated based on exterior irradiance, (2) manual.	1=dissatisfied 5=satisfied	[A]=3 [M]=4
[34]	Satisfaction with control system.	(1) Automated based on indoor illuminance, (2) Semi-automatic (3) fixed 60% glazing.	1=very dissatisfied 5=very satisfied	[A]=4.1 [SA]=3.8 [S]=3.5

Finally, shown in Figure 2.18, no strong consensus emerges in favor of either manual or automated operation regarding overall occupant satisfaction. Instead, preferences vary across environmental domains, indicating the need to balance automation with manual control. In the visual domain, automated shading effectively reduces glare and excessive daylight, but manual control is preferred when maintaining an outdoor view is a priority. Semi-automated systems with override options provide a better balance, improving satisfaction. For thermal comfort, occupants favor manual or semi-automated control for temperature regulation via shading and ventilation, as predictive automation can optimize conditions but may cause dissatisfaction when actions are unexpected. In terms of acoustic comfort, automated windows can help control noise in urban settings, though manual control remains preferred for greater discretion. For indoor air quality, no clear preference exists due to limited research, though air quality sensors can trigger ventilation adjustments.

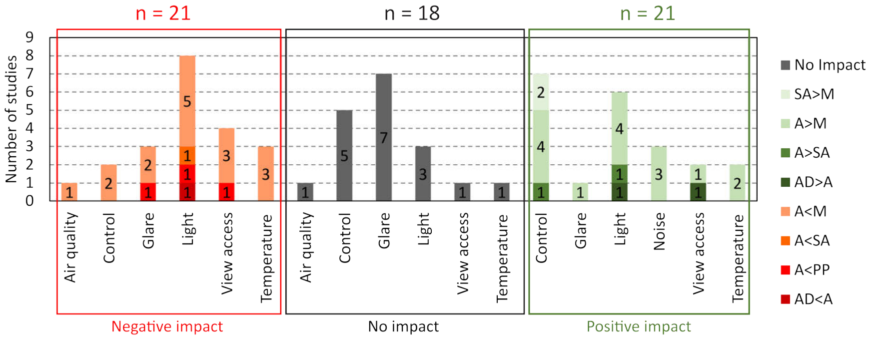


FIG. 2.18 Distribution of evidence provided by studies showing the cases in which the automated façades have a “negative impact” (n=21), “no impact” (n=18), and “positive impact” (n=21). In each category, the evidence is divided by environmental domain. SA=Semi-automated control, M=Manual control, A=Automated, AD=Advanced control, PR=Pre-programmed control.

Satisfaction with control depends on perceived control, predictability, and alignment with occupant expectations. Systems that allow occupant overrides tend to be better received, whereas fully automated ones risk rejection due to loss of agency. Manual control results in a higher interaction frequency, while automation reduces interaction, particularly when well aligned with expectations. However, unexpected system-driven changes, such as sudden shading adjustments, may lead to overrides, especially in work environments.

Thus, evidence indicates the importance of occupant-centered control to enhance the acceptance of automated façades. Although the role of automation in façade operation is not clearly defined yet, automated controls should support rather than replace occupant control, ensuring effectiveness when manually controlling the façade of the building.

2.5 Discussion

2.5.1 Energy Performance of Automated façades

Current evidence shows that automated controls can increase energy savings [37, 47, 57, 61], in particular, in the lighting domain [28, 45, 77]. The highest energy savings were achieved when comparing fully automated shadings to unshaded windows [34, 73, 94, 99, 113, 114] or static shading systems [37, 98, 99, 101, 115]. However, buildings rarely have unshaded windows, while the alternative to automated blinds or dynamic glazing is usually a manually controlled façade.

Nevertheless, in the few studies that compare fully automated façades to manually controlled ones, this trend is also confirmed in the lighting domain (from 10% to 75% [28, 33, 45, 47, 60, 116]), and for both seasons (-18% in summer and -40% in winter [47]). Simulation-based studies tend to report higher energy savings than empirical studies, since discrepancies between predicted and actual performance are common in real office buildings [78].

While early design assessment of dynamic and automated façades required a dynamic simulation workflow to guide their technological developments [117], the discrepancy between predicted and monitored performance is now the bottleneck for automated façades up-scaled [118–120]. This requires empirical studies to: (i) increase practitioners, contractors and building owners' experience with automated façades, and (ii) provide confidence that these systems can provide a robust and reliable benefit in comparison with manually controlled façades for a wide number of buildings and occupants, thereby enabling sufficient generalization of research results. In this sense, the limited number of studies involving human participants (only 25 out of 91) is a barrier to up-scaling of these façade technologies. Moving forward, future research should focus on evaluating the performance of these technologies in real office building settings, particularly for façade technologies that are already well-developed and have a high level of technology readiness.

2.5.2 Balancing IEQ with Automated Façades

This review confirms that automated façades can effectively regulate indoor environmental quality (IEQ) parameters, particularly visual and thermal comfort. Automated shading systems have been shown to enhance daylight access [34, 36, 60] and mitigate glare [96, 99] by controlling indoor brightness levels [37, 60, 61]. They can also reduce solar heat gains, thereby supporting thermal comfort [91, 101]. A key challenge for automated control systems lies in managing trade-offs between competing IEQ parameters. For example, glare reduction strategies may limit daylight access, while optimizing thermal comfort can obstruct views to the outside [28, 33, 89, 90]. Some studies have demonstrated that algorithms preventing glare effectively protect the occupants from excessive brightness [28, 93]; however, this often comes at the cost of reduced indoor illuminance, which can lead to occupant dissatisfaction [36, 44, 109]. Similarly, while automated shading can reduce solar heat gain and enhance thermal comfort, its effectiveness may be compromised by obstructed views [32, 86, 91]. This limitation is particularly evident in systems that rely on single-parameter control strategies. In response, studies have proposed integrated control approaches that simultaneously account for glare, daylight, and temperature, in an effort to balance competing IEQ requirements [64, 89, 90]. Nonetheless, more research is needed to determine which IEQ parameters should be prioritized, particularly in dynamic and potentially personalized control scenarios.

2.5.3 Comparability of Studies on Occupant Response to Automated Façades

The evaluation of automated façades in studies often relies on a variety of metrics, each targeting different aspects of indoor environmental performance. These include DGP [28, 34], used to assess visual discomfort from glare, horizontal illuminance [36], which relates to task lighting levels, and the percentage of hours within comfort thresholds [91], which reflects overall performance over time. However, because these metrics are grounded in different physical principles and operational goals, direct comparisons between studies can be challenging unless the metrics address similar comfort dimensions.

In this context, the ISO 52016-3 [121] represents a step forward by offering standardized methods to assess the energy and indoor environmental performance of adaptive façades, covering heating, cooling, lighting demand, thermal comfort, visual comfort, and air quality. However, while this standard provides robust objective criteria, it does not fully capture the variability and subjectivity of occupant preferences, which may differ based on individual needs, cultural norms, or contextual factors. Several studies emphasize that acceptance of automation by occupants depends not only on environmental outcomes, but also on how the systems behave, how intuitive they are, and whether they respond appropriately to occupants' expectations [11, 122]. To integrate the impact of dynamic façade operation with occupant preferences, performance assessments should go beyond physical metrics to include subjective and behavioral dimensions, such as perceived control, satisfaction, or acceptance of automation. This can be achieved through methods, such as post-occupancy evaluations, stated preference surveys, and behavioral monitoring that track occupants' interactions with the system. For example, adaptive algorithms could be designed to learn from occupants' overrides or feedback to adjust control strategies. This challenge aligns with recent work from IEA EBC Annex 79 by O'Brien et al. [17], which stresses the importance of integrating subjective and behavioral data with traditional metrics.

Furthermore, research should investigate potential disruptions caused by automation, such as noise from actuation mechanisms, limited accessibility to personal control, and delayed system response times, to strengthen the still-developing body of evidence on these issues [23, 91]. This is essential to ensure that energy savings are not achieved at the expense of occupant comfort. For example, in the study by Luna-Navarro et al. [91], the noise generated by automated systems was identified as a potential source of dissatisfaction, detracting from the overall experience of occupants and diminishing their acceptance of the technology. Similarly, Meerbeek et al. [23] examined how occupants interact with automated shading systems, revealing that many preferred disabling automatic modes in favor of manual control. This suggests that automated systems may not always align with occupant preferences and comfort needs. These findings highlight the need to develop evaluation methodologies that recognize occupant comfort preferences and responses to automation, as understanding these factors is crucial for enhancing both comfort and acceptance of automated systems.

2.5.4 Occupant data collection to define personalization factors

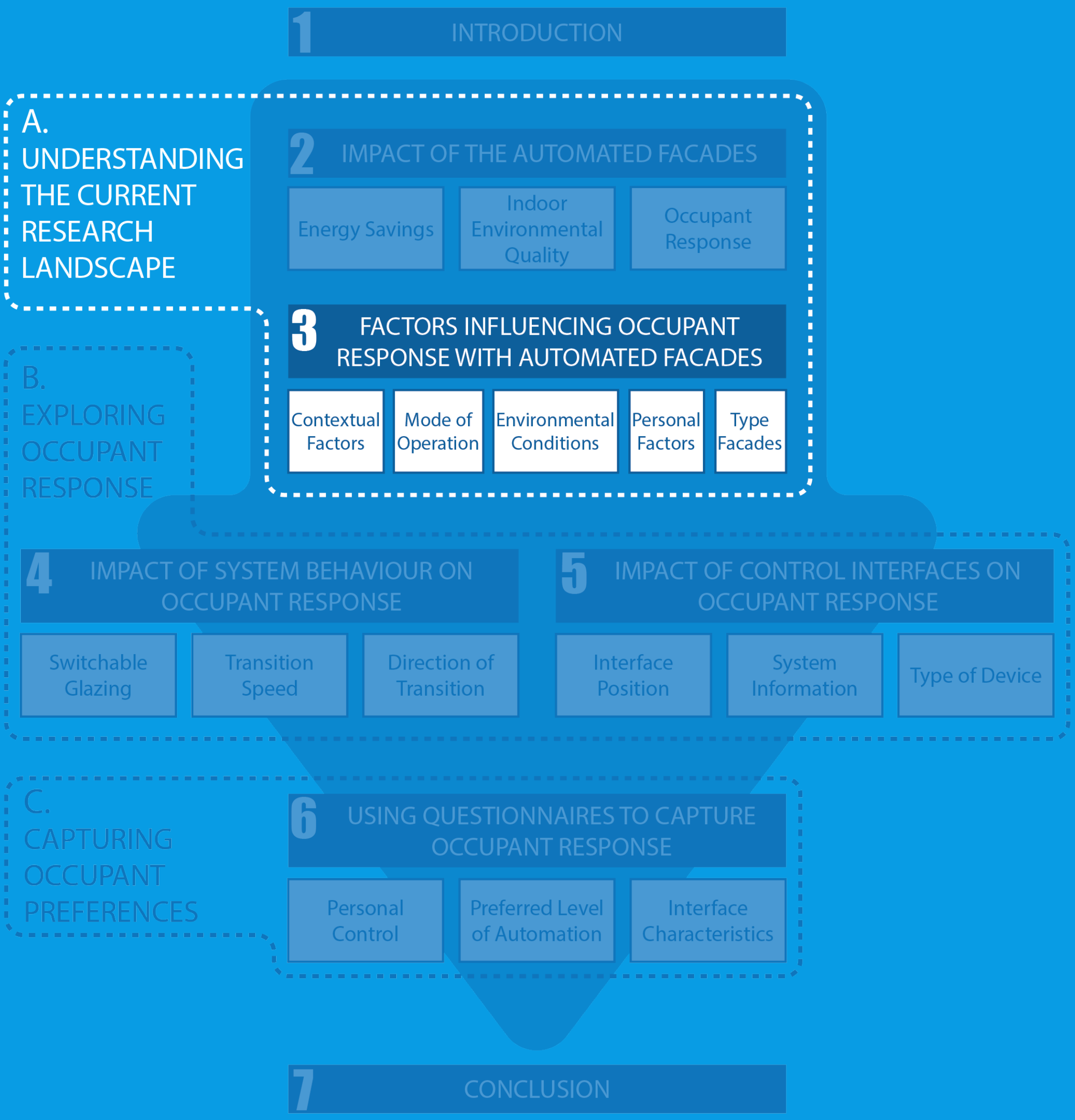
Advanced control strategies, including adaptive approaches [47] and learning algorithms [77], have demonstrated the potential to improve occupant satisfaction and reduce override actions. By actively aligning automation with occupant preferences and control requirements, these systems enhance the occupant experience and address common concerns associated with automated controls. However, implementing these strategies presents barriers, particularly in defining and collecting occupant data and translating them into effective automation actions, such as determining system operation times or identifying conditions where manual control is more appropriate. For instance, five studies [34, 47, 90, 111, 112] suggest that frequent manual overrides may indicate dissatisfaction or the need for more refined automation strategies. Although overrides may also indicate a desire for personal control, a response to disruptions caused by automated actions, or a lack of understanding of the building control systems. The factors explaining these occupants' responses with automated systems [123–125], such as usability (e.g., ease of use, clarity of control interfaces), system responsiveness (e.g., speed of reaction, accuracy), personal control preferences (e.g., the need for manual overrides), trust in automation (e.g., reliability, transparency), and comfort-related factors (e.g., noise or environmental disruptions), are well-established in other fields. Nevertheless, the challenge remains in effectively transferring these data into control systems that can detect and respond to individual preferences in real-time, ensuring that automation remains aligned with occupants' needs and expectations.

2.6 Conclusion

A systematic review was conducted to examine the current evidence from previous work on automated façades' influence on energy savings in cooling, heating and lighting, IEQ and occupant satisfaction. A total of 91 studies were analyzed, with 30 involving human participants. These studies showed that automation systems outperformed manual controls in energy savings. Automated façades also contribute to mitigating indoor environmental issues such as glare, controlling daylight, and preventing overheating. Although automated façades can effectively enhance indoor environmental conditions, no strong consensus was found on their overall impact on occupant satisfaction.

Despite the potential of automated façades to increase energy savings and improve IEQ without affecting overall occupant satisfaction with the control system, the review identified limitations in existing research that could hinder a broader adoption of such systems. The challenges include: First, methodological limitations, such as (i) the low number of empirical studies involving human participants, which are crucial for validating performance outcomes focused on occupant preferences and response, and (ii) the lack of standardization in metrics and experimental designs, including inconsistent illuminance and temperature thresholds, different benchmark scenarios (e.g., unshaded, static, or manual façades), and various control approaches, which limit the comparability and generalization of results. Second, performance trade-offs, including (iii) challenges in balancing competing IEQ parameters, such as glare reduction versus daylight access or thermal comfort versus outside views, and (iv) the critical role of control objectives, where prioritizing energy or visual comfort alone may fail to meet occupant needs for autonomy, view, or thermal conditions. Lastly, contextual constraints on performance outcomes, such as (v) the persistent discrepancy between simulation-based predictions and experimental results, where empirical outcomes are more variable, and (vi) the high contextual sensitivity of façade performance across different building orientations, climates, automated control strategies, and occupant profiles.

Future research should prioritize (a) empirical studies in real office buildings to capture occupant behavior, preferences, and override patterns; (b) developing multi-domain evaluation to describe façade control strategies' performance across the wide range of environmental domains; (c) establishing consistent metrics and benchmarks for evaluating automated façade systems to improve comparability between studies; (d) refining adaptive and learning-based systems to detect and respond to individual preferences in real-time, accounting for usability, trust, contextual disruptions, and manual override behavior; and (e) applying multi-criteria analysis to determine which environmental parameters (e.g., glare, thermal comfort, energy savings) should be prioritized for automation under different building contexts. By addressing these gaps, future research can contribute to the development of automated façade systems that not only optimize energy efficiency and IEQ, but also meet the diverse and evolving needs of building occupants.



1 INTRODUCTION

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3 Factors Influencing Occupant Response

Influence of automated façades on occupants: a review

This chapter is based on work published in 2022 in the Journal of façade Design and Engineering.

This chapter examines occupant perception, interaction, and response to automated façade systems, focusing on the factors shaping satisfaction and acceptance. Building on the research landscape mapped in Chapter 2, it synthesizes peer-reviewed evidence from laboratory, real-building, and simulation contexts to address the human dimension. The review is organized around a classification scheme of five key factors: personal characteristics, environmental conditions, type and mode of operation, façade technology, and contextual factors. It analyzes how these factors influence outcomes such as comfort and override behavior, while evaluating assessment methods ranging from self-reports to physiological monitoring. The analysis identifies limitations in current approaches, particularly regarding multi-domain comfort and real-time experience capture. Crucially, it highlights specific operational parameters as primary triggers for distraction and perceived control issues. These insights frame the experimental design in Chapter 4, guiding the selection of variables and measures to ensure subsequent experiments target the most significant drivers of occupant interaction.

3.1 Introduction

In buildings, façades act as a buffer and connector between indoors and outdoors [126] and affect building energy consumption and occupant multi-domain environmental comfort [44]. In particular, façades can affect occupant satisfaction with the thermal environment [127], acoustic [128], air quality [129], daylight and view out [19, 130].

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) [7] to effectively respond to changes in outdoor or indoor conditions. Dynamic façades can be manually controlled by occupants [18], or react to changes in environmental conditions, either by passively responding to them (e.g. phase change materials [131]), or by automatically being controlled by actuators and sensors [11]. 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 [77]. Previous work showed that automated controls can assist occupants and overcome the limitations of manual operation by reducing energy consumption [30, 31] or improving thermal or visual comfort [132]. Contrariwise, the automated control can also negatively impact occupants' satisfaction and behavior, when the control action does not match individual requirements [10, 133].

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 behavior and satisfaction, indoor environmental quality and energy consumption [46]. Several studies showed that occupant requirements are subjective and individual, affecting occupant response to the control system [77, 106]. These variances in occupant responses may be explained by a different personal significance of environmental comfort domains [23, 106] or differences in the level of knowledge of occupants with automated control [111]. 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 [33].

Four previous studies have performed a literature review on automated controls for automated façades. Konstantoglou & Tsangrassoulis [5] 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 [134] analyzed 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 occupant feedback, are better than open loop control strategies based on sensor measurements. However, Luna-Navarro et al. [46] 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. [135] reviewed the state-of-the-art regarding occupant-centric control strategies, showing that current interaction strategies are not effective to both improve occupant satisfaction and energy efficiency. Ultimately, there is the need for comprehensively reviewing existing studies on occupant-automated façade interaction and highlight what is the current evidence on the factors that influence individual occupant response to automated façade controls. This will facilitate the design and operation of automated façade in an occupant-centered manner. To achieve this, the aim of this work is to review previous experimental work that evaluates human volunteers' response to automated façades, either in lab experiments or field studies, and evaluate current evidence to indicate future research directions.

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, highlights potential future challenges and investigations based on the review conducted.

3.2 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 Table3.1. 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: occupant 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.

TABLE 3.1 Search keywords and number of records retrieved per database.

Database	Date of search	(1) Façade operation	(2) Façade technology	(3) Study type (experimental testing)	No. of articles
WoS	24-02-2022	(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)	(façade OR envelope OR skin OR shading OR glazing OR glazed OR window OR venetian OR roller OR blind)	(laboratory OR on-site OR field OR experimental OR post-occupancy OR testbed OR test room OR campaign OR monitoring)	2,328
Scopus	22-02-2022	(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)	(façade OR envelope OR skin OR shading OR glazing OR glazed OR window OR venetian OR roller OR blind)	(laboratory OR on-site OR field OR experimental OR post-occupancy OR testbed OR test room OR campaign OR monitoring)	2,795

Keywords were divided into four groups (Table 3.1): (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 before. Finally, we ended up with 26 studies that met the requirements for being examined for this literature review, published between 1998 and 2022.

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

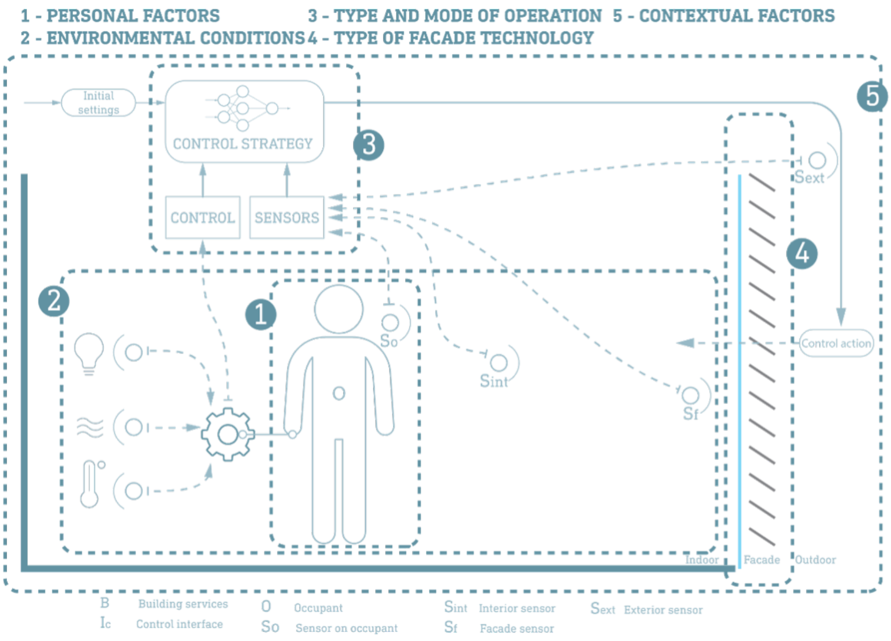


FIG. 3.1 The classification scheme used in this review to group the factors influencing occupant response that were identified through the literature review (after (Luna-Navarro et al., 2020)).

3.2.1 Factors that influence occupant response

The classification scheme from Luna-Navarro et al. [46] was used to group the factors that affect the occupants as follows (shown in Figure 3.1): 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).

3.3 Results and discussion

3.3.1 Type of occupant response to AF studied by previous work

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

Occupant response was evaluated in terms of behavior (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 3.2 shows the type of occupant response considered by each study. These different types of occupant response were studied by previous authors through questionnaires, surveys, and interviews. In addition, occupant behavior was monitored by tracking occupant override actions [11, 44, 77, 100, 106, 109, 111, 136], or occupant actions for deactivate the control logic [23], and set-points [34, 36, 47, 88].

Some studies used the term “comfort” and “satisfaction” interchangeably [106, 137 109, 138], while other studies used these terms to describe different state of mind. For instance, comfort was intended as the threshold or set-point that defines comfortable environmental conditions, which often was contrasted by surveys of the occupant perception to the environmental quality [11, 33, 34, 47, 88, 106, 111, 137 23, 36, 86, 109, 139]. Satisfaction was used to indicate occupant contentment with the visual environment [10, 23, 33, 34, 36, 44, 47, 89, 90, 106, 108–110, 137], thermal environment [10, 23, 34, 44, 90, 109, 140, 141], acoustic environment [34, 44, 89], air quality [44], or overall satisfaction with the automated façade [10, 23, 34, 44, 77, 90, 100, 106, 110, 137, 142]. Three studies incorporated acceptance as a descriptor of the level of agreement with the control system implemented. Acceptance was studied regarding the different modes of operation applied to venetian blinds [36] by registering occupant override actions that was intended as a lack of acceptance of the control logic operating the façade [77, 100]. Only one study considered occupant acceptance with the indoor environment (acceptance to the overall indoor environment [89]).

TABLE 3.2 Summary of type of occupant response reported by studies. Codes: CS = overall response to the control strategy and façade technology; IEQ = occupant response to indoor environmental quality; N = not reported.

	Occupant response to the indoor environment					
R.	Interaction - Behavior	Comfort	Satisfaction	Acceptance	Perception	Sensation
[36]	CS	IEQ	CS IEQ	CS	N	N
[88]	CS	IEQ	N	N	N	N
[47]	CS	IEQ	CS IEQ	N	N	N
[34]	CS	N	CS IEQ	N	N	N
[33]	N	IEQ	N	N	N	N
[111]	CS	IEQ	CS	N	N	N
[139]	N	IEQ	N	N	N	IEQ

Continued on next page...

TABLE 3.2 Summary of type of occupant response reported by studies (continued).

R.	Interaction - Behavior	Comfort	Satisfaction	Acceptance	Perception	Sensation
[137]	N	IEQ	CS	N	N	N
[11]	CS	IEQ	CS IEQ	N	CS	N
[23]	CS	IEQ	CS IEQ	N	N	N
[110]	N	IEQ	CS IEQ	N	N	N
[106]	CS	IEQ	IEQ	CS	N	N
[142]	N	IEQ	CS	N	N	N
[109]	CS	IEQ	IEQ	N	CS	N
[100]	CS	IEQ	CS	N	IEQ	N
[77]	CS	IEQ	CS	CS	N	N
[86]	N	IEQ	N	N	N	IEQ
[140]	N	N	IEQ	N	IEQ	N
[10]	N	IEQ	CS IEQ	N	N	N
[89]	N	IEQ	CS	IEQ	N	IEQ
[136]	CS	IEQ	N	N	N	N
[141]	N	IEQ	CS	N	N	IEQ
[143]	N	IEQ	N	N	N	IEQ
[90]	N	IEQ	IEQ	N	N	IEQ
[112]	N	IEQ	CS	N	N	N
[44]	CS	IEQ	CS IEQ	N	N	N

Few studies also assessed perceived health [144] and productivity [109, 144]. 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) [89, 90].

3.3.2 Contextual factors affecting occupant response to AF

All the studies provide information about the context where the experiments or the field measurements took place. Table 3.3 describes the contextual factors summarized 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 (Figure 3.2).

!

TABLE 3.3 Summary of contextual factors described by previous works to assess the influence of façades on occupant response.

		Orientation							Layout		
R.	**Location**	**N**	**W**	**SW**	**S**	**SE**	**E**	**ND**	**Open**	**2 - 3**	**Single**
[36]	Oakland, California - US						✓				✓
[88]	Lausanne - Switzerland				✓						✓
[47]	Lausanne - Switzerland				✓						✓
[34]	Berkeley, California - US				✓						✓
[33]	Seoul - South Korea		✓		✓		✓		✓		
[111]	Berkeley, California - US		✓								✓
[139]	Hiratsuka - Japan							✓			✓
[137]	Beijing - China						✓				✓
[11]	Eindhoven - The Netherlands		✓								✓
[23]	Eindhoven - The Netherlands				✓					✓	
[110]	Aalborg - Denmark				✓						✓
[106]	Beijing - China						✓				✓
[142]	Leicester - UK							✓		✓	
[109]	West Lafayette, Indiana - US				✓						✓
[100]	Brussels - Belgium						✓				✓
[77]	Ottawa - Canada			✓							✓
[86]	Lausanne - Switzerland		✓		✓						✓
[108]	Toronto - Canada							✓		✓	
[10]	Charlotte / Richmond / Virginia - US			✓					✓		
[89]	Trondheim - Norway				✓						✓
[136]	Lausanne - Switzerland				✓						✓
[141]	Lausanne - Switzerland				✓					✓	
[143]	Guangzhou - China						✓				✓

Continued on next page...

TABLE 3.3 Summary of contextual factors described by previous works (continued).

R.	Location	N	W	SW	S	SE	E	ND	Open	2-3	Single
[90]	Trondheim - Norway				✓						✓
[112]	Plymouth - UK	✓			✓						✓
[44]	Cambridge - UK				✓					✓	

In terms of the relevance of the weather conditions, Clear et al. [34] pointed out that two parameters were strongly correlated to occupant behavior, such as the variation of the sky conditions and the outdoor vertical illuminance. Korsavi et al. [112] have also reported that occupant behavior can be impacted by building-related features such as orientation and floor level on automated window operation. Lolli et al. [89] and Luna-Navarro et al. [44] 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 façade (14 studies).

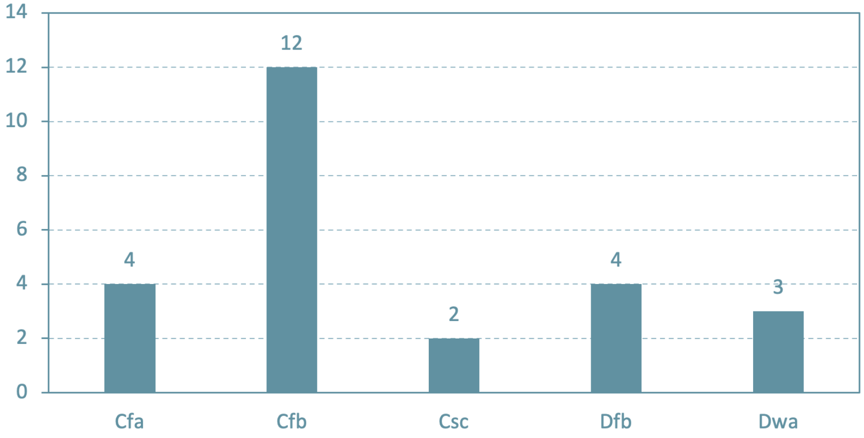


FIG. 3.2 Climate where the reviewed studies were performed (classification according to the Koppen Climate). The climates are: humid sub-tropical climate (Cfa); temperate oceanic climate (Cfb), cold-summer Mediterranean climate (Csc), warm-summer humid continental climate (Dfb), Monsoon-influenced hot-summer humid continental climate (Dwa).

Concerning where the study took place, two main location were found: laboratory and real office building (Figure 3.3). Laboratory refers to a room fully equipped with sensors and other instruments and that can be adjusted to present the desired experimental conditions and collect relevant data from the indoor environment and occupants. In addition, laboratories are occupied by occupants only for the purpose of conducting an experiment. In contrast, real office building includes real-world occupied buildings. Approximately half of the studies were conducted in both field and lab environments.

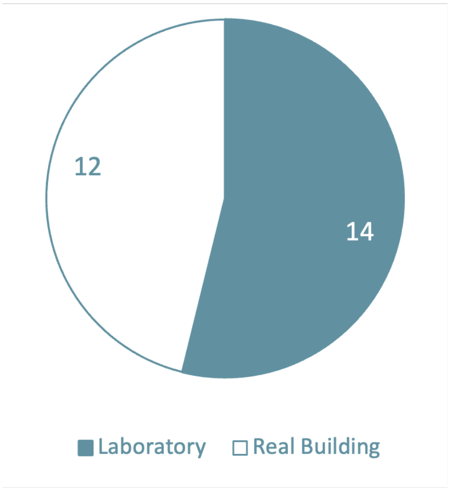


FIG. 3.3 Pie chart diagram with the number of studies performed on laboratories and real buildings.

Some studies showed that the number of occupants and room characteristics may impact occupant response. Clear et al. [34] mentioned that visual dissatisfaction reported by occupants was not only produced by the window's sun exposure but also by the interior walls and object reflection. Additionally, occupants indicated that the room's color 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 [114]. Also, indoor room characteristics, such as type of layout, wall color, amenities, office features have been proven to affect comfort perception, satisfaction and occupant response [11, 34].

Regarding the number of occupants in the same room, Cheng et al. [106] and Bian et al. [143] stated that the situation of multi-person in the general place and performing different tasks should affect the occupant's response to the automated control, changing even along the day. However, only few studies occupant response in shared office spaces.

3.3.3 Personal factors affecting occupant response to AF

Personal factors might affect occupants' behavior and perception, being different from person to person and depending on specific occupants' attributes [34]. Based on the articles reviewed, personal factors that might affect occupant response are shown in Figure 3.4 and 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, glasses usage, vision disability, handedness, eye color, and ethnicity [110]. 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 [34]. 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 [109].

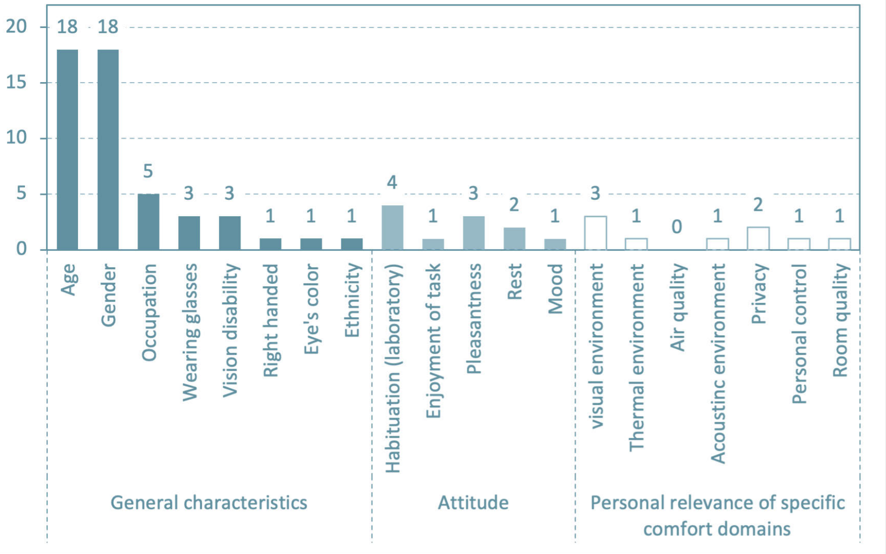


FIG. 3.4 The number of studies that investigated personal factors in previous works as affecting occupant response to automated façades are shown per type of personal factor studied: general characteristics, attitude and personal relevance of indoor environmental condition.

The most reported personal characteristics were age and gender, while the level of rest was rarely considered. Five studies included occupants' attitudes [34, 44, 110 86, 109], being Luna-Navarro et al. [44] 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 [34, 109, 110]. Clear et al. [34] gave a detailed summary about all of them.

Although 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 relevance 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. [34] reported that age, gender, and other characteristics affected occupants' responses to the electrochromic window operation. This was found by finding correlations between subjects' characteristics and appraisals of the different test modes. The main findings were a significant correlation (explained by the level of fitness R2) between the importance of quiet and sensitivity to environmental noise (R2 = 0.48), the importance of access to outdoor view and the importance of windows (R2 = 0.25), the importance of good lighting and the importance of light and window control (R2 = 0.22), and the importance of good temperature control and the sensitivity to both heat and cold (R2 = 0.26). Karlsen et al. [110] analyzed 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. [142] examined the data for studying occupant 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 can determine whether the selected control threshold would lead to a satisfactory indoor environment [111, 142]. For instance, personal relevance to specific surroundings impacts occupant tolerance to indoor environmental conditions. Karlsen et al. [110] suggested that the participants might tolerate some glare disturbance depending on the relative importance of the access to outside view. Even the occupants' knowledge (regarding habituation) about the system functionality may impact the ability to interact with the automated façade [11, 109, 111]. Additionally, specific occupants' characteristics, such as wearing glasses [111] and visual conditions [142], could explain why some occupants are more likely to prefer different lighting conditions.

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

3.3.4 Impact of occupant response to indoor environmental conditions on occupant overall satisfaction with AF

Occupant response to indoor environmental condition was taken into account by 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 3.4).

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 the 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.

TABLE 3.4 Summary of environmental domains measured by sensors and occupant responses captured by questionnaires investigated in previous works.

	Environmental domains measured by sensors						Occupant response to the indoor environment					
	Visual environment											
R.	Outside view	Daylight	Glare	Thermal env.	Acoustic env.	IAQ	Behavior and Interaction	Comfort	Satisfaction	Acceptance	Perception	Sensation
[36]		✓		✓	✓		✓	✓	✓	✓		
[88]	✓	✓		✓			✓	✓				
[47]		✓					✓	✓	✓			
[34]		✓					✓		✓			
[33]		✓		✓				✓				
[111]		✓		✓			✓	✓	✓			
[139]		✓						✓				✓
[137]		✓						✓	✓			
[11]	✓	✓		✓			✓		✓		✓	
[23]	✓								✓		✓	
[110]		✓	✓					✓	✓			✓
[106]		✓					✓	✓	✓	✓		
[142]		✓	✓					✓	✓			
[109]	✓	✓	✓	✓			✓	✓	✓		✓	

Continued on next page...

TABLE 3.4 Summary of environmental domains measured by sensors and occupant responses captured by questionnaires (continued).

R.	Outside view	Daylight	Glare	Thermal env.	Acoustic env.	IAQ	Behavior and Interaction	Comfort	Satisfaction	Acceptance	Perception	Sensation
[100]		✓	✓	✓			✓	✓	✓	✓		
[77]		✓		✓			✓		✓	✓		
[86]		✓	✓					✓				✓
[108]		✓							✓		✓	
[10]		✓	✓	✓				✓	✓			
[89]		✓	✓					✓	✓			✓
[136]		✓	✓	✓			✓	✓				
[141]		✓	✓					✓	✓			
[143]		✓	✓					✓				✓
[90]		✓	✓					✓				✓
[112]					✓	✓		✓				
[44]		✓	✓	✓	✓	✓	✓	✓	✓			
Total	**4**	**24**	**12**	**11**	**3**	**1**	**13**	**20**	**18**	**4**	**4**	**6**

Although several studies captured occupant response to indoor environment, only few reported that occupant response to indoor environmental conditions affected occupants response to AF (Figure 3.5), 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 [11, 34, 36, 47, 111, 137]. Sadeghi et al. [109] and Goovaerts et al. [100] reported that override actions to open the façade were carried out when increasing daylight was needed, while Motamed et al. [86] 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 [106], changing even along the day [143]. Vine et al. [36] 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.

Glare discomfort is the most frequent factor affecting occupants' response to the automated control (16 studies). When automated control did not effectively protect against glare, occupants overrode [77, 89, 100, 109] or adjust the control parameter as allowed [143]. Glare competes with daylight provision. When the automated control was operated based on glare, occupants intervened to improve daylight quality [23, 77]. When the automated control did avoid discomfort from direct sun and or glare, occupants preferred more daylight [23, 86, 89].

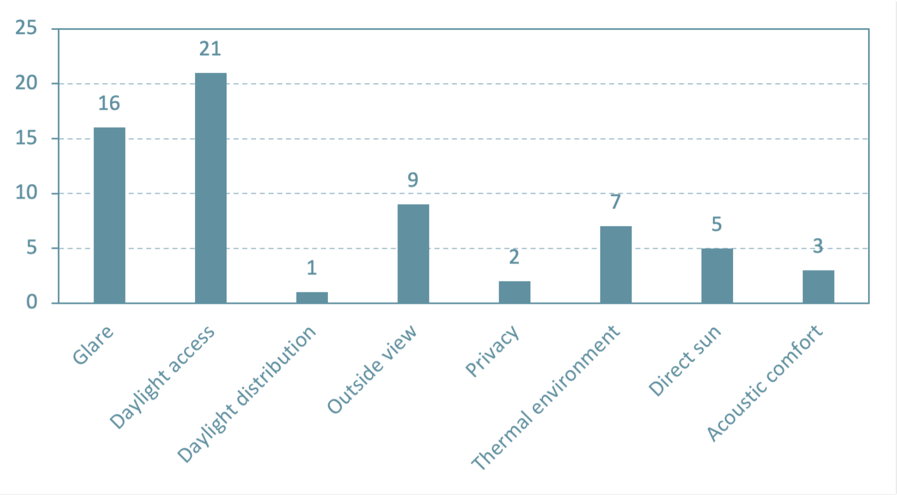


FIG. 3.5 The number of studies that showed that environmental factors affect occupant response with the AF operation.

Other studies also suggested that the outside view impacts environmental occupants' preferences (9 studies), influencing even the choice of the preferred control strategy [44, 110]. Clear et al. [34] and Meerbeek et al. [23] 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 intervented 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. [109] mentioned privacy as the most important factor affecting lowering blind actions together with discomfort glare. However, privacy depends on contextual characteristics such as the surrounding environment and position in the building. For instance, Meerbeek et al. [23] explain that subjects surveyed were not worried about privacy because the office was located on the third story, 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 [89, 109] or to provide air flow, as suggested by Korsavi et al. [112] and Lolli et al. [90]. A few studies surveyed occupants to calculate the predicted mean vote (PMV) [33].

A few studies also reported acoustic environmental conditions and acoustic satisfaction (4 studies). Luna-Navarro et al. [44] pointed out 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. [100] informed that DGP underestimated the impact of direct sunlight, which generated the set-point lowered by occupants when direct sunlight was present. A similar problem was reported by Taniguchi et al. [139] 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 [143].

The majority of the studies investigated the impact of control strategies on occupant visual domain. On the thermal domain, articles did not report conclusions on how automated façade affects the thermal environment. How distance from the façade affects occupant interaction with the façade is still undetermined. Only Day et al. [10] mentioned that the window's proximity improves occupants' satisfaction. Moreover, the impact of indoor environmental conditions on occupant response to automated façade has not been researched sufficiently, making it difficult to extrapolate results throughout different façades technologies, control logics, and under different weather conditions to improve current control strategies.

What are the main drivers of occupant satisfaction with automated façades is still undetermined, in particular whether there is or not 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 [108, 141] and that they are often the main reason for overriding an automated façade control system [23]. 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 [46]. However, there is no clear evidence on whether exists or not a hierarchy of comfort domains.

3.3.5 The effect of control and interaction logic on occupant response to AF

The control and interaction strategy influences occupant response to the automated façade [11]. As a way to improve occupant satisfaction with the automated façade, studies have tested different control strategies. Table 3.5 summarizes the main characteristics of the control logics studied up to now. Additionally, the table gives information on the sensor position (interior/exterior).

TABLE 3.5 Summary of control logic aspects investigated by previous works to assess the influence of automated façades on occupant response.

	Control loop		Source of information			Control logic			Control domain					Sensor place			
									Visual env.								
R.	Closed loop	Open loop	Sensor based	Model based	Others	Rule based	Adaptive	Predictive	view out	Daylight	Glare	Thermal env.	Air quality	Exterior	Interior	On occupant	Occ. interaction
[36]	✓		✓		✓	✓				✓	✓			✓			✓
[88]	✓		✓	✓		✓	✓		✓	✓		✓	✓		✓	✓	✓
[47]	✓		✓	✓		✓	✓		✓	✓		✓	✓		✓	✓	✓
[34]	✓		✓			✓			✓	✓				✓			✓
[33]		✓	✓			✓				✓		✓		✓			
[111]	✓		✓		✓	✓				✓	✓			✓			✓
[139]	✓		✓	✓	✓	✓				✓	✓			✓			
[137]	✓		✓	✓	✓	✓	✓			✓	✓		✓	✓			
[11]	✓	✓	✓		✓	✓				✓				✓			✓
[23]		✓	✓		✓	✓				✓				✓			✓
[110]		✓	✓		✓	✓	✓	✓	✓	✓	✓			✓	✓	✓	
[106]	✓		✓	✓		✓				✓				✓	✓		✓
[142]		✓	✓			✓	✓			✓	✓			✓			
[109]		✓	✓		✓	✓				✓				✓			✓
[100]		✓	✓		✓	✓	✓			✓	✓		✓	✓			✓
[77]	✓		✓		✓	✓	✓			✓				✓			✓
[86]	✓		✓	✓		✓	✓			✓	✓			✓	✓		
[108]		✓	✓			✓				✓				✓			
[10]		✓	✓			✓				✓				✓			
[89]		✓	✓			✓				✓	✓			✓	✓		
[136]	✓		✓		✓	✓				✓				✓	✓		✓
[141]		✓	✓	✓	✓	✓				✓	✓			✓		✓	
[143]				✓											✓		
[90]	✓		✓		✓	✓				✓				✓	✓		
[112]	✓		✓						✓					✓			
[44]		✓	✓							✓			✓		✓		✓

Sadeghi et al. [109] reported a dependency between façade configuration (shade position or window transmittance) and occupant satisfaction with the indoor environment. Clear et al. [34] and Day et al. [10] 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 of algorithms to develop occupant models inside building controllers [77]. 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 [106] and recursive learning [77]. Only three studies implemented a predictive algorithm to analyze and integrate outdoor weather and indoor lighting conditions into a model-based system [47, 88] to anticipate occupant interaction with the automated façade system [77]. Automated façade control can improve indoor environmental quality [33, 34, 89, 136], although the effect on occupant satisfaction varies from case to case. For instance, Lolli et al. [90] reported that automated control improved the desired indoor environmental quality. Similarly did Luna-Navarro et al. [44], which showed that, when the control strategy is properly designed, automated control can provide larger satisfaction than manually controlled environment. However, if the automated control is disruptive to occupants, manual control outperforms automated ones. On the contrary, Motamed et al. [86] showed that the subjects' visual performance was not improved by automated control strategies. Therefore the type of control strategy is important factor for occupant satisfaction. The impact of façade control operation affects differently the indoor space zones. Day et al. [10] reported that occupants placed in the interior far away from the window did not receive enough daylight when the switchable glazing got dark, and occupants were ultimately displeased with their workspaces.

In regards to what are the aspects of the control strategy that affect occupant the most, current evidence is fragmented. In terms of control thresholds, Goovaerts et al. [100] showed that different controls could achieve equal indoor illuminance levels on the desk in the same context but still affect differently satisfaction among occupants. Therefore, personalizing 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 [137] and behavioral responses under different control algorithms [112]. However, to what extent personalization 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 [23]. A predictive lighting and blinds control algorithm can significantly reduce electric lighting consumption in perimeter office spaces whilst maintaining occupant comfort [77]. The predictive control strategy should incorporate as many profiles as occupants are in the indoor space [112]. Painter et al. [142] 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 occupant 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 façade taking into account the multi-domain influence of façades on occupants [44], however there is still discussion on whether one environmental domain should be prioritized 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. [100] showed that occupants overrode the automated control to increase daylight when it was configured to avoid discomfort glare. Karlsen et al. [110] 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. [77] 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 [23]. For instance, Bakker et al. [11] 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 restore comfort when the system is not efficient in controlling environmental parameters [10]. Guillemin Morel [47] reported that occupants interacted with 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 when they need to. Limited indoor environment control has detrimental effect on occupant comfort [90]. 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 [11].

3.3.6 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 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 3.6 summarizes the façade systems and the position of the shading system. Regarding façade technologies, the main shading system tested in previous work are venetian blinds (16 studies), followed by roller shades (8 studies). Switchable glazing has also been evaluated in studies (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 were up and down positions, switchable glazing allowed to modify glass visual transmittance, while for window opening was the window aperture percentage.

TABLE 3.6 Summary of façade technologies included by previous works to assess the influence of façades on occupant response.

	Façade System				**Sahding device placement**		
R.	**Switchable glazing**	**Roller shade**	**Venetian blind**	**Window opening**	**Interior**	**In the cavity**	**Exterior**
[36]			✓		✓		
[88]			✓				
[47]			✓				
[34]	✓		✓		✓		
[33]			✓		✓		
[111]	✓						
[139]			✓		✓		
[137]			✓				✓
[11]		✓			✓		
[23]			✓		✓		
[110]			✓		✓		
[106]			✓				✓
[142]	✓						
[109]		✓			✓		
[100]			✓		✓		
[77]		✓			✓		
[86]		✓					✓
[108]	✓						
[10]	✓	✓	✓		✓		
[89]			✓		✓		
[136]		✓					✓
[141]			✓				✓
[143]			✓		✓		
[90]		✓		✓	✓		
[112]				✓			
[44]		✓	✓		✓	✓	

The type of façade also defines how disruptive a control strategy will be. For instance, Luna-Navarro et al. [44] reported that placing the blinds within the cavity resulted in more effective control of the solar heat gains and less disruptive to occupants, especially for their associated noise. Bakker et al. [11] reported that occupants close to the operation of roller shades were the most disrupted by them. Vine et al. [36] mentioned that the transition from one position to another, the activation frequency, and the sound generated was considered distraction source.

Moreover, Wu et al. [141] pointed also out that the speed of switching also had an impact on occupant satisfaction, who preferred slower and smooth transitions.

3.4 Conclusions

This work reviewed twenty-six previous laboratory experiments and field studies that monitor occupant response with automated façades. These studies were reviewed to gather and analyze 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 behavior 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.

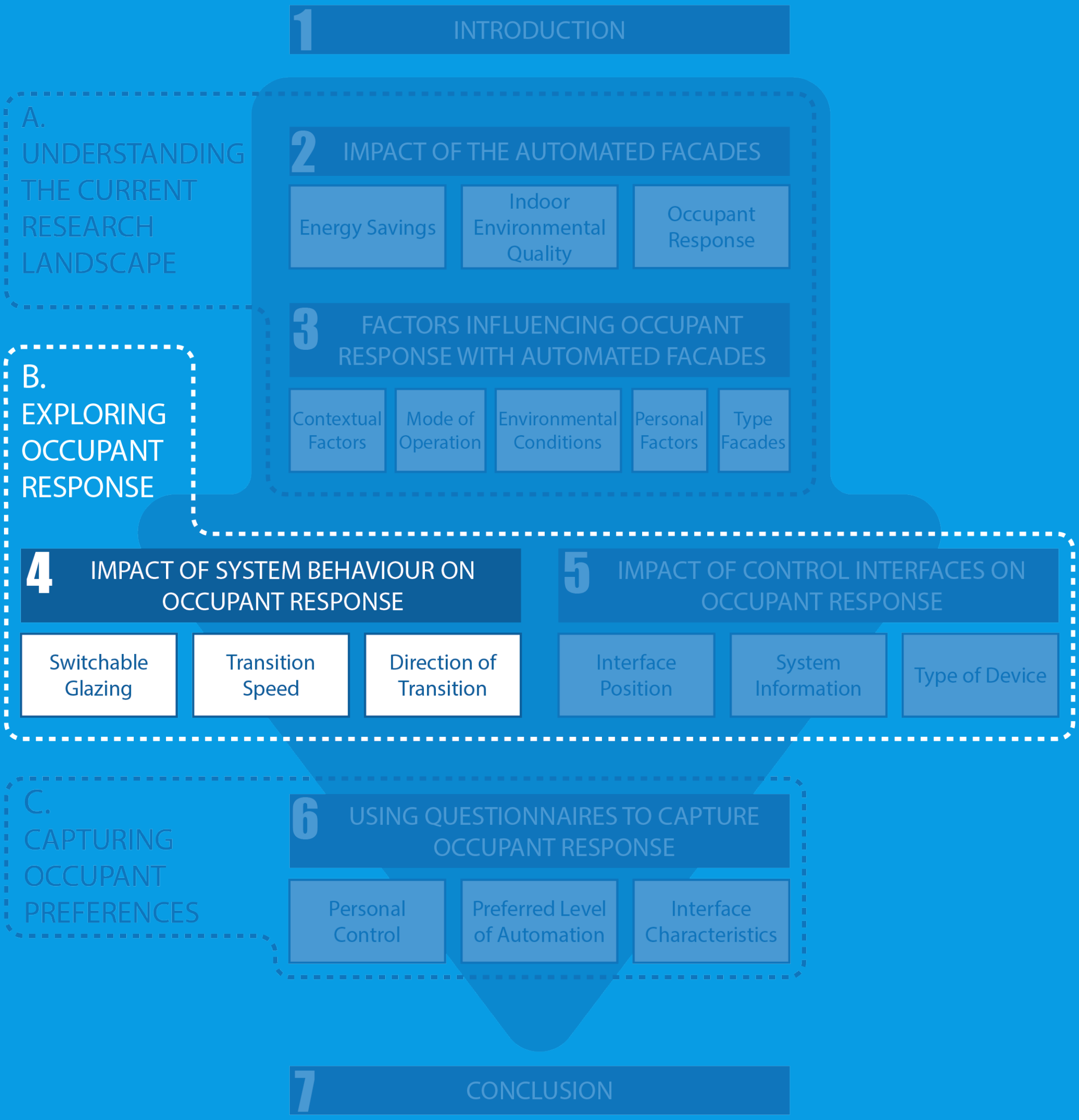
Regarding the aspects affecting occupant response to AF operation, studies indicated personal factors impact occupants' behavior and perception of the indoor environment, being different from person to person and depending on specific occupants' attributes. Most of the studies reported personal characteristics, 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 when they need to. Additionally, occupant interaction with the AF is driven primarily to fulfill personal environmental requirements, such as increasing daylight, privacy, view access and avoiding glare discomfort. Although AF can provide "comfortable" indoor environmental conditions, it does not ensure the achievement of individual environmental requirements and preferences properly.

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 higher or lower. In particular, differences in façade effects are noticeable when technologies compromise one environmental domain over the other. 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 on 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 occupant-centered automated façade solutions;
3. the lack of research to define to what extent learning and personalized control are possible and, in case, how to deal with multiple occupants in the same room operating a unique automated façade.

In addition, extending testing scenario to different climates or contextual conditions would be very beneficial, since studies were mainly concentrated in few climates and conditions. This also undermines generalization, 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 if personalized controls are necessary to achieve higher occupant satisfaction whilst reducing the energy demand.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4 Impact of System Logic on Occupant Response

Interaction with smart glazing: Effect of switching speed under overcast sky conditions

Original publication title is " interaction with smart glazing: Effect of switching speed under overcast sky condition". This chapter is based on work published in 2025 in Building and Environment.

This chapter investigates how specific operational parameters—namely the speed and direction of switching in dynamic glazing—influence occupant perception, satisfaction, and behavior. Building on the framework established in Chapter 3, it addresses the scarcity of empirical evidence regarding the dynamics of automated actions, moving beyond static comparisons of manual versus automated modes. To address this gap, an experimental study was conducted in a semi-controlled laboratory equipped with switchable glazing, systematically varying transition speed (fast vs. slow) and direction (clear-to-dark vs. dark-to-clear). Participant responses were measured using a combination of subjective questionnaires on satisfaction and perceived control, alongside objective facial action analysis and gaze-tracking to detect attentional shifts during standardized tasks. The study quantifies the impact of these transition dynamics on perceived environmental quality and task disturbance, identifying behavioral markers of discomfort. Findings reveal operational thresholds that minimize distraction and reduce override behavior, providing critical insights that inform the subsequent control-interface experiments in Chapter 5.

4.1 Introduction

Several technologies have been deemed promising in the decarbonization of current building stock [4]. Among these technologies, appliances, devices, and components that enable the digital and automated control of buildings are expected to play a key role. These technologies, often named smart devices or smart building technologies, such as smart windows or predictive thermostats, can significantly improve energy efficiency and lead to worldwide associated emissions reductions of 350 Mt CO2 by 2050 [4]. Smart technologies can also drive and foster occupant behavioral changes [145], which in turn can leverage a reduction of almost 250 Mt CO2 in 2030 [4]. This can be achieved for instance, by dynamically adjusting cooling, heating or lighting setpoints.

Occupant acceptance of smart building technologies is a barrier to widespread adoption of these systems [46, 146–148]. This challenge has been recently recognized by the European Union Directive with the establishment of the “Smart Readiness Indicator” [16], which among several factors related to smartness, also rates the level of perceived convenience for occupants. The dynamic and automated control of building technologies, such as glazing or shading in the building envelope, or heating and lighting appliances in the indoor environment, has often been found to be disruptive to occupants [44, 146, 149–151]. Factors that drive this disruption are trust and privacy [146, 150], the mismatch between occupant requirements and automated control actions [46, 152, 153], lack of information and understanding of building control rationales [149] or poor interaction and interface design [154]; for instance, disruptive frequency and mode of actuation of the smart components [11, 46], or insufficient perception of personal control of the environment [150]. With the recent proliferation of artificial intelligence and cost-effective and pervasive sensing technologies, buildings will become increasingly smart, but it is essential that the technological progress is matched by advances in human-building interaction [147].

The occupant-centered design and operation of smart or adaptive façade technologies is especially challenging because these components tend to be very disruptive [155]. Changes in façade behavior (shading position or blind angle, glazing state or vent position) can be very noticeable. In addition, occupants tend to place significant importance on the personal control of the façade systems (e.g., windows, shadings, etc.) [10, 11, 46]. Smart shading devices are often disruptive because of the noise they generate in operation, while overall the speed, frequency and direction of movement can also have a detrimental impact on occupant acceptance or satisfaction [11, 44]. For instance, Bakker et al. [11] showed that less frequent but discrete transitions in façade configurations produced higher occupant acceptance and satisfaction than smooth transitions at a higher frequency transitions. Unlike smart shading systems, smart glazing technologies transition from one glazing state of visual and solar transmittance to another in a silent manner. However, the speed of change (often called transition time) can be disruptive.

Switchable glazing technologies such as electrochromic glazing can have slow transition time lasting several minutes, which can also result in low occupant acceptance [111, 142]. Other smart glazing, such as those based on liquid crystal technology, change state in a few seconds, and can lead to low acceptance because of the very short transition time.

Another factor in occupant acceptance of dynamic, switchable or smart façade technologies is the mismatch between the preferred façade state, in terms of transparency, and the one imposed by the automated controls for energy efficiency. In this sense, the transition direction (i.e., from high to low transparency or vice versa) plays a key role in meeting occupant expectations. For instance, several case studies reported that in the absence of significant glare, occupant overrides of automated control systems are very likely when automated control lowers the blinds or switches the glazing to its darkest state [111]. Bakker et al. [11] showed that the risk of disturbance and discomfort resulting solely from the frequency of change in façade state is low, however, several experimental campaigns showed contrasting results on this topic [44, 156].

It is therefore currently unclear whether the speed and direction of transition in fast switchable glazing affects occupant acceptance and satisfaction, and to what extent these factors should be taken into account when designing satisfactory interactions with smart façade technologies. This knowledge gap is also compounded by the fact that occupants may exhibit different individual preferences when interacting with smart systems [46, 157] and the lack of a comprehensive approach for capturing human responses to dynamic or smart façades [158].

Previous work by the authors of the present paper focused on the combination of environmental, perceptual and behavioral data to capture occupant response to façades [44]. In addition to traditional behavioral measures, such as occupant control over the dynamic glazing, other studies have shown that the use of facial action units (FAUs) and gaze angles can provide a more comprehensive understanding of occupant interactions with smart façades [159]. In addition to traditional behavioral measurements, facial action units or expressions describe the movement of facial muscles, and they are considered a proxy for human emotions [160]. For instance, Allen and Overend [161] evaluated the use of facial action units for gauging occupant well-being, and Kim and Ham [162] used facial expressions to study individual thermal preferences. These emotional cues could then offer insights into how occupants perceive environmental changes [163, 164] and can inform adaptive system adjustments for enhanced comfort [165]. However, it is unclear at this stage whether the use of facial expressions can positively complement other sources of data in the assessment of human-façade interaction. Similarly, the monitoring of gaze angle to assess occupant view direction in human-façade interaction has already been performed by previous studies investigating glare [166] or aesthetic pleasantness [167] or expert intention in façade inspections [168]. However, it is unclear if this method could also be effective in describing occupant interaction with automated glazing systems, in particular occupant distraction or attention with movement of automated façades.

This paper aims to investigate the impact of speed and direction of transitions on occupant satisfaction and acceptance. An experimental campaign was conducted on fast and smart switchable glazing technologies by recording perceptual data, behavioral data and facial action units. The influence of transition speed and direction on occupant response was collected through questionnaires and by monitoring facial expressions and behavior of occupants. In this study, we also tested the use of FAUs and gaze direction to evaluate respectively: (i) whether FAUs can describe changes on occupant facial expression due to changes in the emotional state [162] e.g., fear or surprise feeling because an unexpected change in the luminous environment; (ii) whether the change of transparency in the glazing can attract the visual attention of occupants, and whether this depends on the speed of transition. From the data collected, interaction preferences were also explored in terms of individual differences and the potential of occupant clustering.

4.2 Methodology

The experiment was conducted in a mobile laboratory located in Delft, The Netherlands. The laboratory, measuring 4.1 × 2.1 × 2.2 m, featured one glazed façade oriented towards southeast fitted with a liquid crystal dynamic (LCD) glazing. This glazing can transition between dark and transparent states, with a visual transmittance ranging from 0.11 to 0.53, respectively. The transitions were actuated by an automated system, which allowed manual override by means of a switch and a slider located on the desk of the occupant. The slider provided occupants with a graduated real-time control of the glazing transparency. The LCD glazing measured 1000 × 1500 mm, the window-to-wall ratio (viewed internally) was 0.40. The laboratory was also fitted with a 2000-watt electric convection heater, which was also manually adjustable by the volunteers through a manual dial on the radiator. Artificial lighting was provided by means of LED ceiling luminaire with LEDNED bulbs of 350 mA. Each volunteer was seated at a desk positioned orthogonally to the LCD glazing. The desk and chair arrangement relative to the façade was fixed as shown in Figure 4.1, thereby offering an unobstructed view of the outdoor environment. On the desk, a computer screen of average luminance of 300 cd/m2 was provided to perform a reading task.

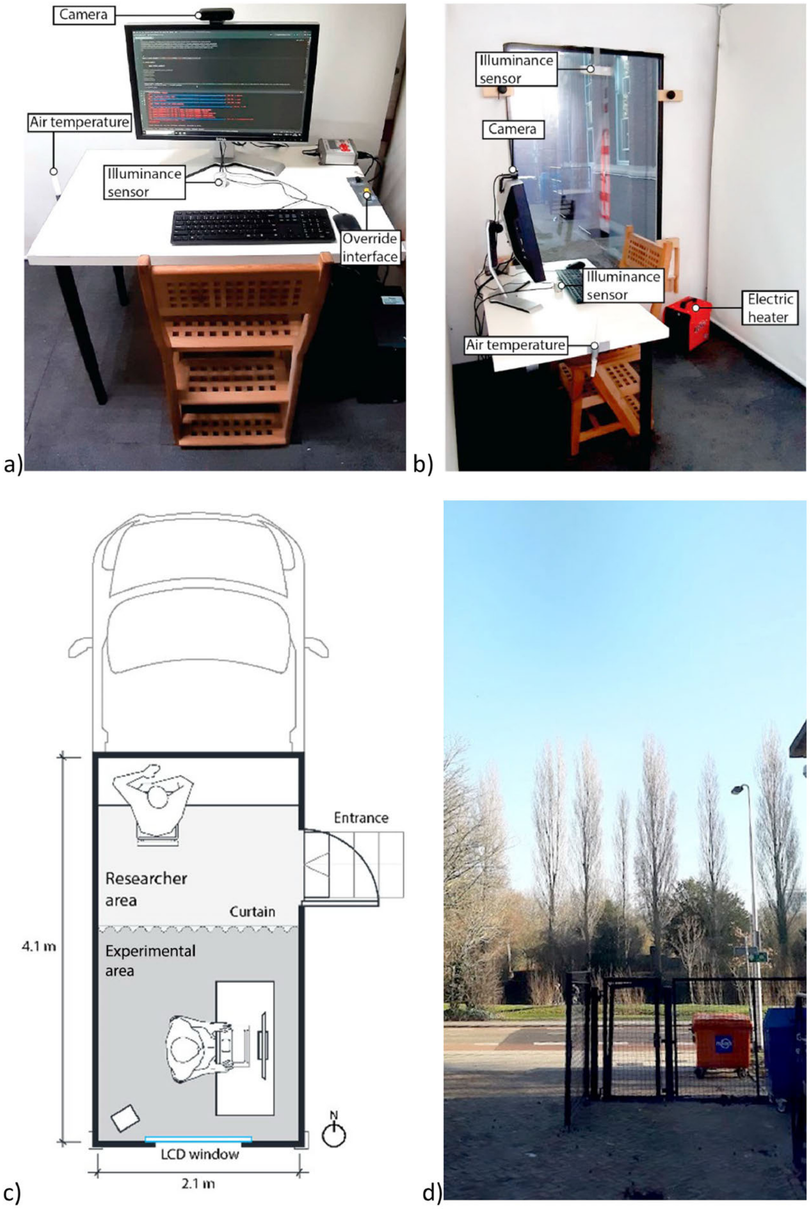


FIG. 4.1 View of the interior of the mobile laboratory: a) the position of the desk with respect to the façade and the location of the environmental sensors and the webcam for facial action unit recognition; b) the position of the sensors and the override interface in the desk; c) a floor plan view of the mobile laboratory; d) the view from the laboratory.

4.2.1 Experimental design and procedure

The experiments were conducted from December 2022 to February 2023 as repeated measures (within subjects). The sky condition was always overcast, with no direct sunlight. This was chosen to avoid glare conditions and eliminate the possible influence of visual discomfort on the preferred switching speed. A total of 30 participants were recruited for these experiments. The volunteers were recruited by email invitation. To ensure sufficient statistical power and detect meaningful effects, we conducted a power analysis prior to the study using G*Power. The power analysis was based on the assumption of a medium effect size (f = 0.25), which is typical for many behavioral studies and consistent with the anticipated effect based on prior research in similar settings. The power analysis indicated that 27 participants would be sufficient to achieve the desired power of 0.80. Given the goal of achieving an adequate balance between statistical power and practicality, we rounded up to 30 participants to ensure robustness in our results. The study was approved by the Human Research Ethics Committee (HREC) at Delft University of Technology. Each participant spent 90 min in the laboratory, during which they experienced four distinct automated control scenarios, described in Table 4.1.

TABLE 4.1 Description of the scenarios investigated in the experiment in terms of speed and direction of switching, transition time and override options.

Scenario	Speed of change	Name of the scenario	Direction of transition	Transition duration (s)	Override option	Behavior during the transition
1	Fast	Fast Clear	from darker to lighter	1	Yes	Linear
2	Fast	Fast Dark	from lighter to darker	1	Yes	Linear
3	Slow	Slow Dark	from lighter to darker	10	Yes	Linear
4	Slow	Slow Clear	from darker to lighter	10	Yes	Linear

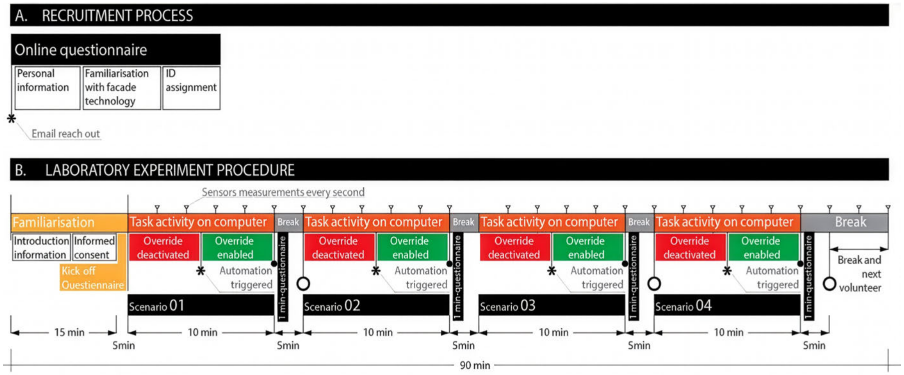


FIG. 4.2 Description of the experimental procedure. Every experiment lasted 90 min. Before the experiment, volunteers were asked to fill in a questionnaire. Volunteers were exposed to four control scenarios. At the end of every control scenario, they answered a survey.

Figure 4.2 shows the overall experimental procedure. Prior to the experiment, participants filled in a first questionnaire to provide background information and obtain an anonymized ID, as reported in Appendix A. On entering the laboratory, the participants were first asked to sit in the office space for 20 min, while reading the participant information sheet and answering a second questionnaire on general background information. Participants were then informed that the experiments involved automated control of heating, lighting and glazing, to avoid excessive focus on the operation of the glazing. After the habituation time, the participants experienced four sessions of 10 min corresponding to the four scenarios in Table 1, separated by 5 min of break, where participants were asked to relax their sight and stop the reading task. During each session, automated control actions of the glazing were programmed to occur halfway through each scenario (i.e. 5 min after the start of each scenario). After the automated control action was implemented at the start of each scenario, participants were then allowed to manually override the system. In order to not bias the perception of the participants, we did not inform the participants that the automated action had been implemented, but only that the control interface had been activated. To avoid biasing the participants' perceptions, we did not inform them when the automated action was implemented. Participants were only notified when they could override the automated action after 5 min had passed.

Additional questionnaires were then provided to capture information on participants' perception of the laboratory space, the control system for the façade, the indoor environmental quality, and familiarity with smart windows technologies (blinds or glazing). Questions were posed in terms of level of agreement. The level of agreement was indicated in a 5-point Likert scale from "strongly disagree" to "strongly agree". The questions are reported in Appendix 1. Several measurements, reported in Table 4.2, were taken to describe the impact of the dynamic switching on the indoor environment and participant response.

TABLE 4.2 Summary of the measurements and data collected in the experiment.

Type of measurement	Aim	Methodology
Indoor environment: illuminance and air temperature	To describe changes in the luminous and thermal indoor environment	Continuous monitoring with illuminance sensors and air temperature sensors as described in Table 3.
Occupant perception	To capture changes in perception across the scenarios	Questionnaires are provided at the end of each scenario to capture occupant perception.
Occupant behavior	To capture whether a different speed of switching could affect the number of overrides or delay potential overrides	interactions with the glazing are tracked by logging actions on the control interface, including timestamp and type of action.
Facial action units	To evaluate whether the speed of switching has a visible impact on participant facial expression due to potential changes in emotional state	Participants' facial action units are tracked using a webcam and analyzed from video frames with OpenFace 2.0, as described in Table 4.
Gaze angle	To detect whether the participant redirects gaze when changes in transparency are implemented at the glazing and whether this depends on the speed of switching	Gaze angle is monitored using a webcam and analyzed from video frames with OpenFace 2.0.

TABLE 4.3 Description of the characteristics of the sensing devices included in the experiment.

Parameter	Sensor	Characteristic	Datalogger	Unit	Sampling interval
Indoor air temperature	LSI Lastem Pt100	Range: -50–$70\,^{\circ}\mathrm{C}$ Resolution: $0.01\,^{\circ}\mathrm{C}$ Accuracy: $0.15\,^{\circ}\mathrm{C}$ $(@\,0\,^{\circ}\mathrm{C})$	LSI Lastem Alpha Log	Degree Celsius $(^{\circ}\mathrm{C})$	Every minute
Desk horizontal illuminance	LSI Lastem ESR000	Range: 0–$5000\,\mathrm{lx}$ Resolution: $0.5\,\mathrm{lx}$ Accuracy: 3%	LSI Lastem Alpha Log	Lux (lx)	Every second
Window vertical illuminance	LSI Lastem ESR001	Range: 0–$25{,}000\,\mathrm{lx}$ Resolution: $3\,\mathrm{lx}$ Accuracy: 3%	LSI Lastem Alpha Log	Lux (lx)	Every second

Environmental sensors were placed in the laboratory to measure indoor air temperature, desk horizontal illuminance, and vertical illuminance on the glazing. Table 4.3 shows a summary of the sensors used. Figure 4.3 shows the distribution of the horizontal illuminance (Figure 4.3a) and the vertical illuminance at the inner side of the window (Figure 4.3b). The indoor air temperature in the experiment was in the range of 22 °C ± 2 °C.

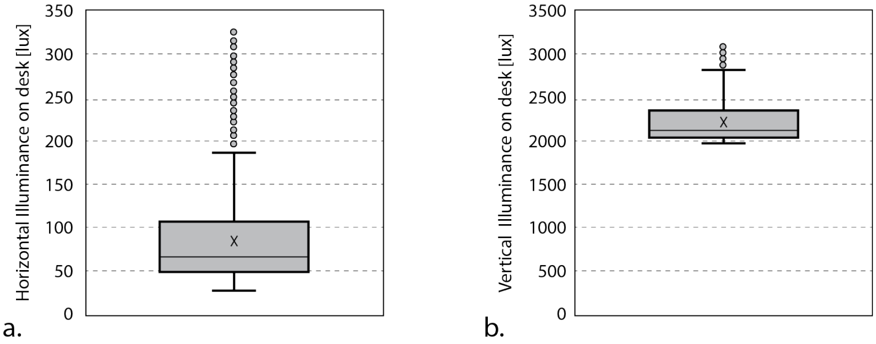


FIG. 4.3 Boxplots illustrate the distribution of horizontal illuminance at the desk level and the vertical illuminance during the experimental conditions. The plots provide a visual summary of the environmental parameters in which the experiment was conducted. The whiskers show the maximum and minimum value within 1.5 times the interquartile range, while the 95 % of the data is shown in the box. Crosses indicate the means and the black horizontal line the median.

In addition, data on participant interaction with the switchable glazing was captured by a logger connected to the switch and the slider of the control interface, which recorded the instances and glazing state of participants override.

Data on participant perception was gathered through bespoke questionnaires. Lastly, data on participants' gaze angle and facial action units (FAUs) were also collected by using OpenFace 2.0 software [169] and a webcam located in front of the participant above the screen. The camera orientation was calibrated to measure coherently the gaze angle. Table 4.4 shows the facial action units recorded by OpenFace 2.0. For each of the FAUs, the presence (in binary values of 0 – absent and 1 – present) and the intensity were measured. Throughout the experiment, facial expression data were recorded at a rate of one measurement per second. Specifically, at each second, the presence and intensity of the designated FAUs were registered for each participant. Only numerical data regarding the occurrence and intensity of FAUs were recorded; no images or videos of participants' faces were stored for privacy. This approach was chosen to prioritize participant privacy while still obtaining essential information about their emotional and cognitive states. In addition to the FAUs data, participants' gaze angles were measured concurrently using the gaze-angle-x and gaze-angle-y variables. This allows tracking of participants' visual focus in relation to the on-screen task and correlation of their facial expressions with the automated control of the glazing.

TABLE 4.4 List of facial action units monitored by the OpenFace 2.0 software during the experiment and combination of FAUs used to detect expressions related to emotions. In addition, OpenFace was used to monitor gaze angle.

FAU	Name
AU01	Inner brow raiser
AU02	Outer brow raiser
AU04	Brow lowerer
AU05	Upper lid raiser
AU06	Cheek raiser
AU07	Lid tightener
AU09	Nose wrinkler
AU10	Upper lip raiser
AU12	Lip corner puller
AU14	Dimpler
AU15	Lip corner depressor
AU17	Chin raiser
AU20	Lip stretcher
AU23	Lip tightener
AU25	Lips part
AU26	Jaw drop
AU45	Blink

4.2.2 Data Analysis

Participant responses in the questionnaires and facial action units were analyzed to evaluate whether there were significant differences in participant response depending on the speed and direction of switching. For this, statistical significance was tested using linear mixed models (LMMs), implemented in R programming language [170]. LMMs are particularly useful when dealing with repeated measurements or hierarchical data, as they account for both fixed effects (population-level trends) and random effects (individual variability), which is common in human subjects experiments. Post-hoc comparisons were performed with Tukey's method to assess interaction effects. In the LMM, both the scenario and the illuminance levels were considered as independent variables. However, no interaction between the scenario and illuminance levels was found, leading to the removal of the illuminance factor from the final model.

Data on participant overrides across scenarios were analyzed using the Kruskal-Wallis test, implemented through the scipy.stats library in Python. This non-parametric test was selected due to the ordinal nature of the data. Following the Kruskal-Wallis test, Dunn's post-hoc test with Bonferroni correction was applied to identify specific pairwise differences between scenarios. For this, the scikit-posthocs library was used to perform Dunn's test with Bonferroni adjustment, ensuring control for multiple comparisons and minimizing the risk of 'false positive' errors. Data on gaze angles were analyzed using the Mann-Whitney test [171], performed with the SciPy package in Python [172]. The choice of this non-parametric test was based on the distribution of the data. The main objective was to examine whether participants directed their gaze towards the glazing during switching intervals and whether the gaze angles differed from intervals when the glazing remained static.

To analyze participant personal background data, including familiarity with smart glazing or blinds, perceived importance of control, and perceived frequency of interaction, a two-step cluster analysis was conducted. This method was chosen due to the mixed data types (both quantitative and categorical variables) and the uncertainty about the optimal number of clusters based on the sample size. The two-step clustering was implemented using the sklearn library in Python. Additionally, pandas was used for data manipulation and organization, and matplotlib was utilized for visualizing the clusters. After the clusters were formed, the Adjusted Rand Index (ARI) was calculated using the sklearn.metrics package to assess the similarity between the clusters, taking into account chance agreement. The ARI, which ranges from 1 to 1, provides a measure of clustering quality, with values closer to 1 indicating better clustering and higher consistency in the detected participant profiles.

Lastly, Chi-squared tests were conducted using the scipy.stats library to examine associations between the participant clusters and their reported perceptions during the experiments. These tests provided insights into how participant self-reported preferences and behaviors were linked to their assigned clusters, offering a deeper understanding of participant interactions with dynamic façades.

4.3 Results

4.3.1 Occupant background in relation to switchable smart glazing

The background of the participants in terms of the level of familiarity, perceived level of importance and self-reported frequency of interaction with window opening and shading controls was assessed by means of questionnaires. Figure 4.4 shows that all participants assigned a high importance to occupant control of opening of windows and controlling window shadings, with the former ranking higher than the latter. It also emerged that participants were more familiar with smart blinds than smart windows, in both home and office settings. There was a large scatter of responses in self-reported frequency of occupant interaction with window opening or shading controls, implying that several of the participants had a tendency to be more active while others were more passive in terms of occupant-façade interaction.

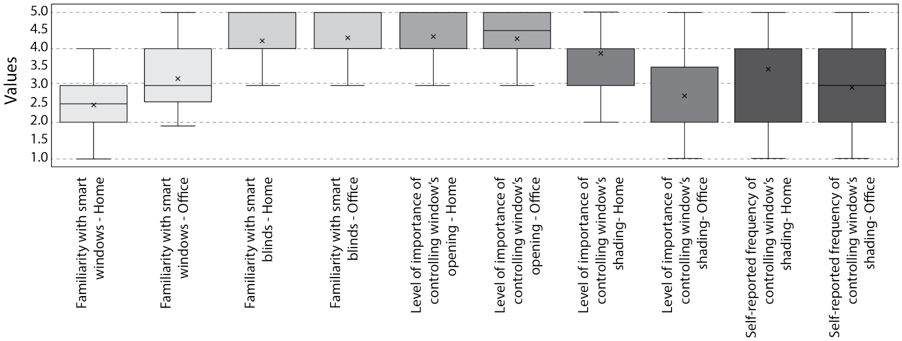


FIG. 4.4 Results from the background questionnaire completed by the participants at the start of the experiments. In particular, the scores (1=strongly disagree; 5=strongly agree) represent the level of agreement with statements related to their perceived level of familiarity with smart windows technologies (opening or shadings) at home and the office, the importance of personal control of window openings or shadings, and self-reported frequency of interaction with windows and shadings at home or at the office.

4.3.2 Occupant perception and behavior under different speed and direction of switching

At the start of the experiment and at the end of each session, participants were asked to fill in a short questionnaire on their perception of the environment (i.e. visual satisfaction, satisfaction with automated controls, perceived annoyance with the automated controls, self-reported perceived distraction from task) in the preceding ten minutes. The results across different switching speeds and directions show that participants consistently reported a similar perception in all scenarios (with mean agreement levels close to 3 – “neither disagree or agree”). No significant differences across the responses of participants were found also in comparison with the responses given at the start of the experiment. The only noticeable trend is that the distribution of reported agreement is smaller when the window was transitioning to its darkest state (scenarios “Fast dark” and “Slow Dark”), particularly for the items related to the window control, thereby indicating a lower number of people that were fully satisfied.

As shown in Figure 4.5, no significant difference was found in the perceived annoyance of participants with the heating (Figure 4.5a), the artificial light control (Figure 4.5b), or the with window control (Figure 4.5c). Since the control of the heating and the lights were unchanged across the scenarios, it was reasonably expected that to find very similar results across the scenarios.
In addition to assessing perception, data on overrides was collected across the four sessions, showing differences in override frequency between scenarios. In the "Fast Dark" and "Fast Clear" scenarios, 20 participants (67%) and 10 participants (33%) overrode the system, respectively. For the "Slow Dark" and "Slow Clear" scenarios, 17 participants (57%) and 7 participants (23%) overrode the system. This is consistent with the existing literature that reported higher overrides when the blinds are lowered or the glazing is darkened (Meerbeek et al., 2016; Bakker et al., 2014). The result also shows that there is a small difference in overrides (approximately 10%) induced by the speed of switching. This is explainable by the potential disruption caused to the participants by fast transitions, which may not allow sufficient time for visual adaptation. Overall, the number of participants that overrode changed depending on the direction of switching. Therefore, the transition direction plays a larger role than the transition speed in inducing participant overrides of the automated switching of switchable glazing.

Figure 4.6 illustrates the delay between the glazing transition actuation and participant interaction with the system, highlighting variations in override behavior among participants based on the scenario. As shown in Figure 4.6, faster transition rates were also associated with faster responses in participant overrides. Participants who executed an override reacted more quickly to the 1-second glazing transitions than to the 10-second glazing transitions. In all scenarios, there was a delay between the completion of the glazing transition and when participants initiated the override. A potential explanation for this effect is that when the glazing transitions slowly, participants’ reaction times are longer, as they may require more time to notice the changes in glazing transmittance due to the slower transition rates.

The Kruskal-Wallis test result suggests that there is a statistically significant difference between the scenarios (H-statistic = 8.04, p-value = 0.045), indicating that at least one scenario differs from the others in terms of the measured variable. However, the Dunn’s post-hoc test results with Bonferroni correction show that none of the pairwise comparisons between scenarios reach statistical significance. The p-values for all comparisons are greater than the corrected threshold (0.05/6 = 0.00833), indicating that while the Kruskal-Wallis test identified an overall significant

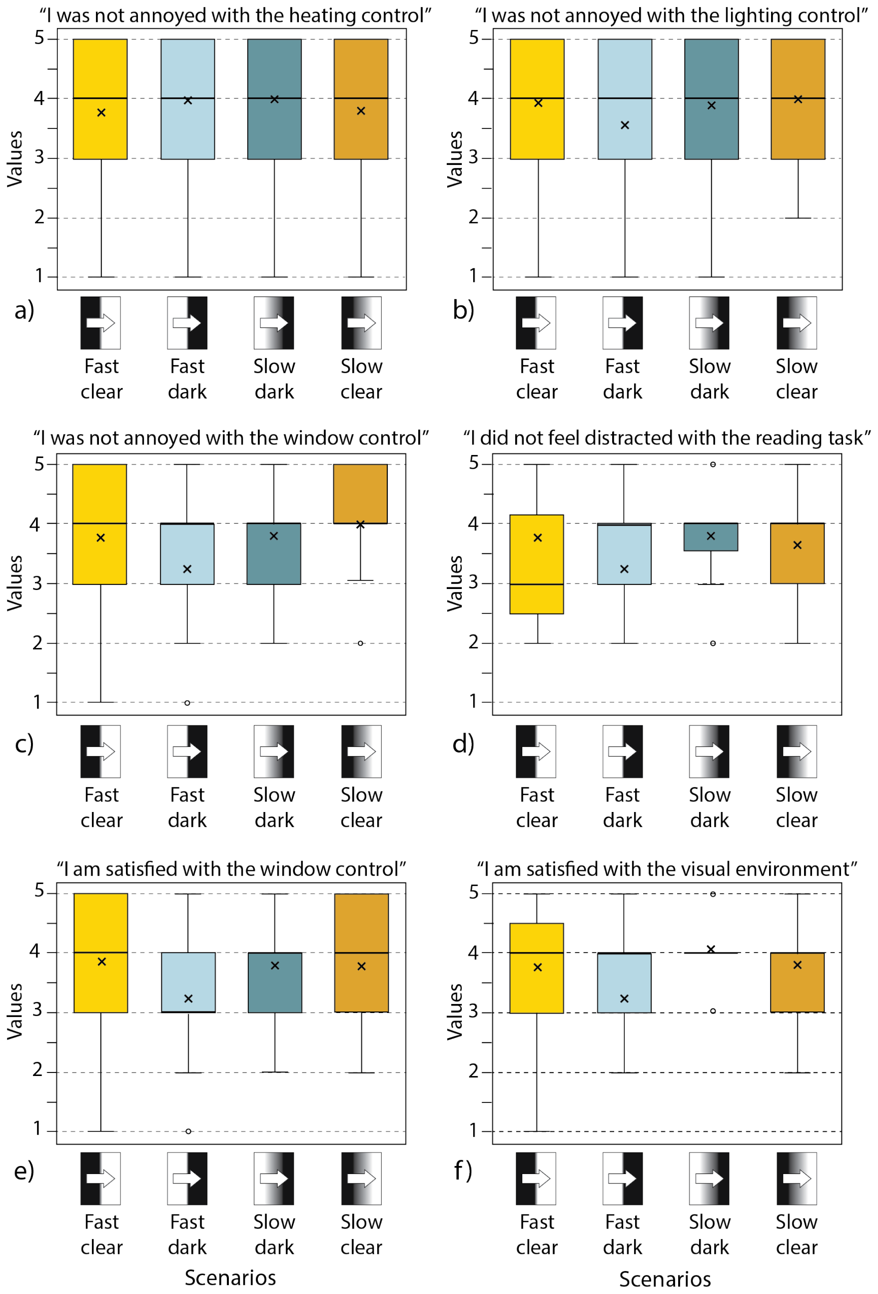


FIG. 4.5 Participant perception of annoyance with building controls and distraction with reading task. Participants' level of agreement with the following statements: (a) "I was not annoyed with the heating control"; (b) "I was not annoyed with the lights control"; (c) "I was not annoyed with the window control"; (d) "I did not feel distracted from the reading task". Perceived satisfaction with the control of the window and the visual environment: (e) level of agreement with the sentence "I am satisfied with the window control"; (f) level of agreement with the sentence: "I am satisfied with the visual environment". The black dot indicates the mean value while the green line indicates the median of the data distribution.

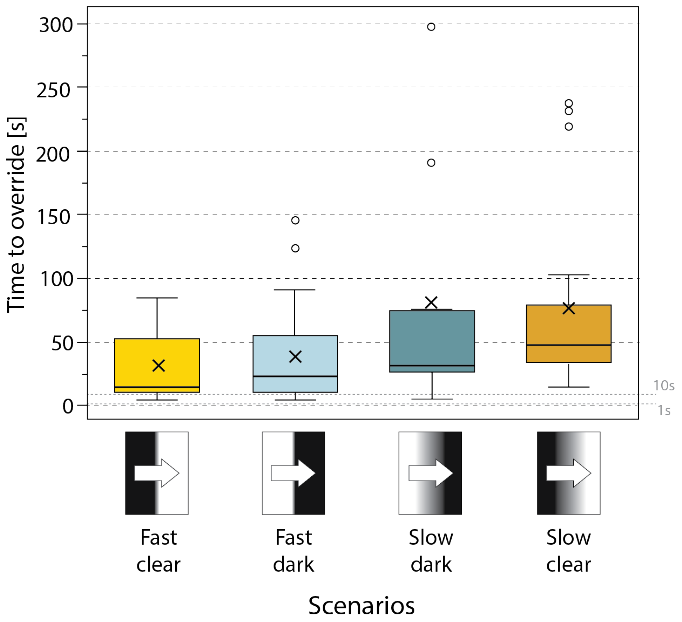


FIG. 4.6 Time of response of participants that have overridden the façade state. The black dot indicates the mean value while the green line indicates the median of the data distribution.

difference, there is insufficient evidence to pinpoint which specific scenario pairs differ from each other.

When grouping participants into those that overrode the automated glazing control and those that did not, there is a clear difference in their perceived levels of satisfaction with the visual environment, the window control, the perceived distraction from reading task and the feeling of annoyance from the window control (see Figure 4.7). As expected, this indicates that all the participants that override were not satisfied with these factors, however the definition of these clusters was found to be independent of the transition speed and the transition direction.

4.3.3 Occupant facial units and gaze direction under different transition rate and transition direction

Participant response was also captured by means of recording Facial Action Units (FAUs) and gaze angles. First, the direction of gaze was analyzed to compare the intervals when the glazing was in transition versus the intervals when the glazing was static. Figure 4.8 shows that there was a significant difference between the instances when the glazing was transitioning and the remaining time periods, indicating that

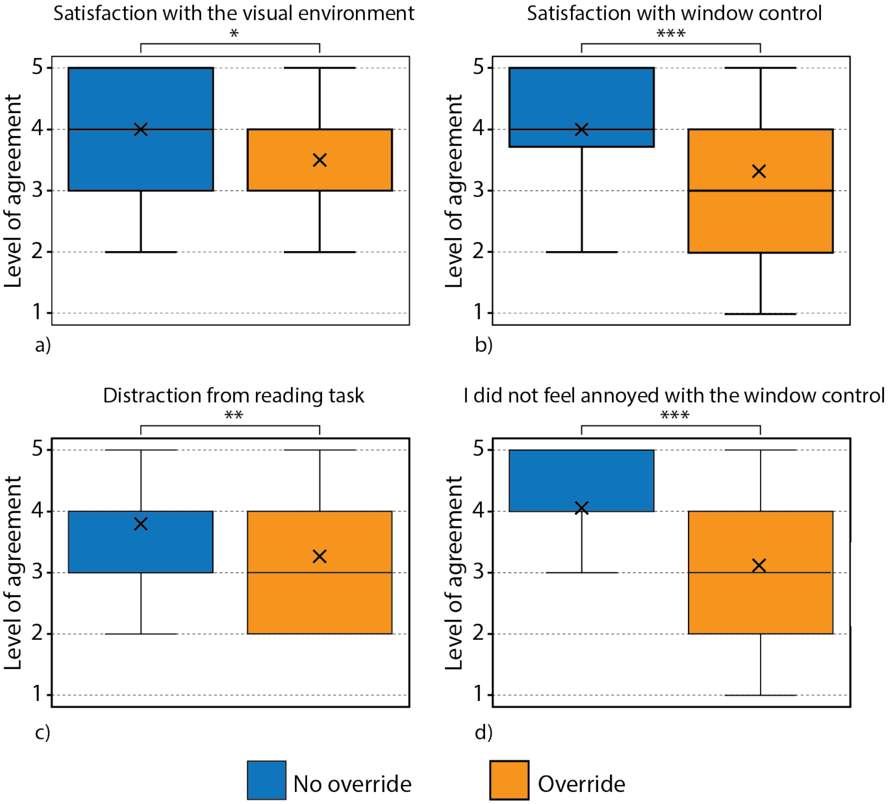


FIG. 4.7 Results on participant perception depending on participant behavior, participants that did override and did not override are grouped separately; (a) level of agreement with the sentence “I feel satisfied with the visual environment”; (b) level of agreement with the sentence “I feel satisfied with the window control”; (c) the sentence “I did not feel distracted in the past 10 min”, (d) the sentence "I did not feel annoyed by the window control”. The asterisks indicate the level of significance: (*) $p < 0.05$, (**) $p < 0.01$, (***) $p < 0.001$. The black dot indicates the mean value while the green line indicates the median of the data distribution.

participants looked towards the glazing when the glazing was in transition. This could be potentially led to distraction from the task. No significant difference was found between different rates or directions of the transition, indicating that participants always looked towards the glazing when this was actuated, regardless of the transition rate. No significant difference was found in gaze angles on the y-plane, since the glazing was positioned on the right side of participants.

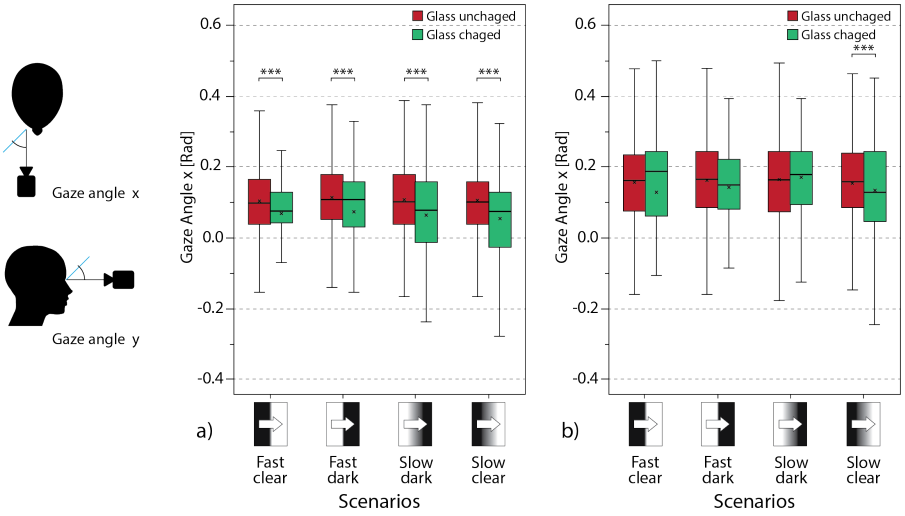
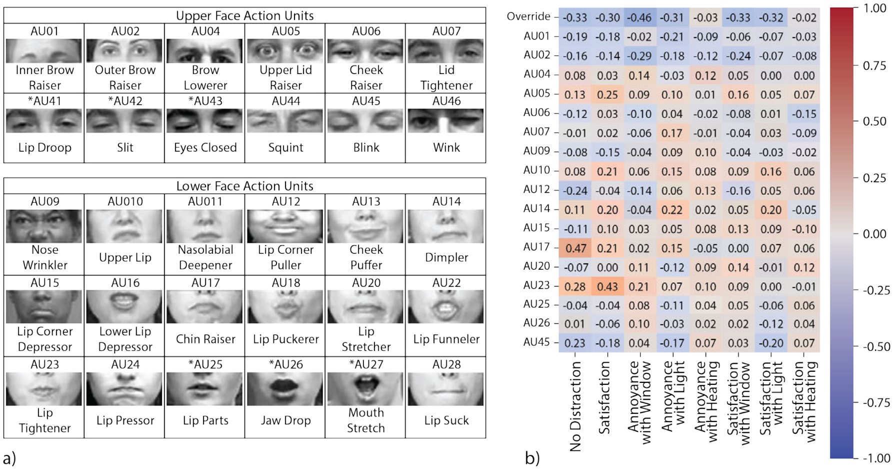


FIG. 4.8 Box-plots of gaze angles of the participants during experiment to evaluate differences between participants' gaze angle during the switching of the glaze and the rest of the time, and for different speed of switching. The box-plot shows the distribution of the gaze angles by showing the median, quartiles, and average (white-filled circle), providing insight into the central tendency, spread, and skewness of the data. a) Gaze angle on the x-plane as shown in the diagram on the left; b) gaze angles on the y-plane. The level of significance ($p < 0.05$) is shown by "***" for the sample groups connected with the line. The black dot indicates the mean value while the black horizontal line indicates the median of the data distribution.

Secondly, the FAUs related to the affective responses of participants were analyzed to investigate differences in facial actions for the same occupant throughout the distinct phases of the experiment. Figure 4.9 shows the correlation between the facial action units and corresponding emotion expressions from the questionnaire, including information on whether the participant overrode the automated glazing control or not, coded in the variable "override". There is a positive Pearson correlation (0.47) between the perception of not being distracted and the action unit of Chin Raisers (AU17), which suggests that when reading with higher focus participant would raise their chin. The action unit related to lip tightener (AU23) was also correlated with satisfaction with the visual environment (0.43). With the exception of override, all other correlations are mild and therefore are not considered meaningful. The "override" variable is correlated with satisfaction and annoyance with the window control, which confirms the results from Figure 4.7. Overall, there is no strong correlation between any of the items from the questionnaire and the facial expressions.



	No Distraction	Satisfaction	Annoyance with Window	Annoyance with Light	Annoyance with Heating	Satisfaction with Window	Satisfaction with Light	Satisfaction with Heating
Override	-0.33	-0.30	-0.46	-0.31	-0.03	-0.33	-0.32	-0.02
AU01	-0.19	-0.18	-0.02	-0.21	-0.09	-0.06	-0.07	-0.03
AU02	-0.16	-0.14	-0.29	-0.18	-0.12	-0.24	-0.07	-0.08
AU04	0.08	0.03	0.14	-0.03	0.12	0.05	0.00	0.00
AU05	0.13	0.25	0.09	0.10	0.01	0.16	0.05	0.07
AU06	-0.12	0.03	-0.10	0.04	-0.02	-0.08	0.01	-0.15
AU07	-0.01	0.02	-0.06	0.17	-0.01	-0.04	0.03	-0.09
AU09	-0.08	-0.15	-0.04	0.09	0.10	-0.04	-0.03	-0.02
AU10	0.08	0.21	0.06	0.15	0.08	0.09	0.16	0.06
AU12	-0.24	-0.04	-0.14	0.06	0.13	-0.16	0.05	0.06
AU14	0.11	0.20	-0.04	0.22	0.02	0.05	0.20	-0.05
AU15	-0.11	0.10	0.03	0.05	0.08	0.13	0.09	-0.10
AU17	0.47	0.21	0.02	0.15	-0.05	0.00	0.07	0.06
AU20	-0.07	0.00	0.11	-0.12	0.09	0.14	-0.01	0.12
AU23	0.28	0.43	0.21	0.07	0.10	0.09	0.00	-0.01
AU25	-0.04	-0.04	0.08	-0.11	0.04	0.05	-0.06	0.06
AU26	0.01	-0.06	0.10	-0.03	0.02	0.02	-0.12	0.04
AU45	0.23	-0.18	0.04	-0.17	0.07	0.03	-0.20	0.07

FIG. 4.9 Correlation matrix between participants facial expressions and perception: a) Facial action units from (De La Torre et al., 2015); b) correlation between participant perception and facial expression.

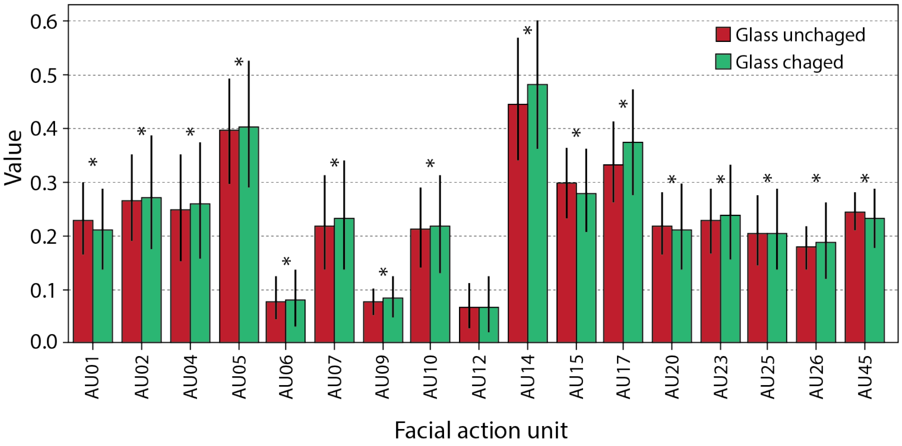


FIG. 4.10 Facial action units during the intervals where the glass remained unchanged, and the glass was changed. The asterisks indicate that the differences are statistically significant.

When comparing the variations of facial action units between the intervals where the glazing remained unchanged and where it was in transition, there is a significant difference across all the facial action units and the emotion-related expressions, as shown in Fig. 4.10. This indicates that the facial action units did capture the effect of the glazing transitions. However, this was not sensitive to the rate or direction of glazing transitions. The facial action units associated with blinking remained unchanged during glazing transitions, indicating that the change in glazing transparency does not induce eye blinking.

4.3.4 Clustering of occupants based on behavior with switchable glazing

Information on participants' self-reported familiarity with smart glazing or blinds, and their perceived importance of controlling the glazing was analyzed to evaluate whether it was possible to cluster participants based on these two features. In addition, data on the frequency of interaction with the switchable glazing was also analyzed for the purpose of clustering.

Figure 4.11 shows the results from the two-step cluster analysis. Two distinct cluster of participants were identified. In terms of familiarity with smart glazing or blinds, participants can be grouped in: (i) individuals with a self-reported high familiarity (Cluster 1), and (ii) individuals with a self-reported low familiarity with these technologies (Cluster 2), as shown in Figure 4.11a. In terms of the perceived importance of controlling window openings and shading (Figure 4.11b), two clusters were also identified. Cluster 1 exhibited strong importance of personal control, whereas Cluster 2 showed a lower perceived importance for controlling façade devices.

Lastly, in terms of the self-reported frequency of interaction with window openings and shading (Figure 4.11c), two clusters were identified as well, where Cluster 1 represented participants reporting a low frequency of interaction, while Cluster 2 was composed of participants who interacted with window devices frequently. Each of these analyses achieved a silhouette score of 0.6 for cohesion and separation. This score indicates that the data points within each cluster are well-separated from other clusters and are significant in their grouping. When examining participant behavior with the switchable glazing, particularly in response to automated control actions, two distinct participant clusters emerged (Figure 4.12), demonstrating statistically significant differences in behavior (Mann-Whitney U, $p = 0.017$). The first cluster consisted of participants who tended to override the controls predominantly when the glazing transitioned to a clear state, irrespective of whether the transition occurred at a fast or slow rate. These participants generally exhibited longer reaction times, indicating a more gradual response to the automation. In contrast, the second cluster comprised participants who frequently overrode the controls when the glazing transitioned to a dark state, with much shorter reaction

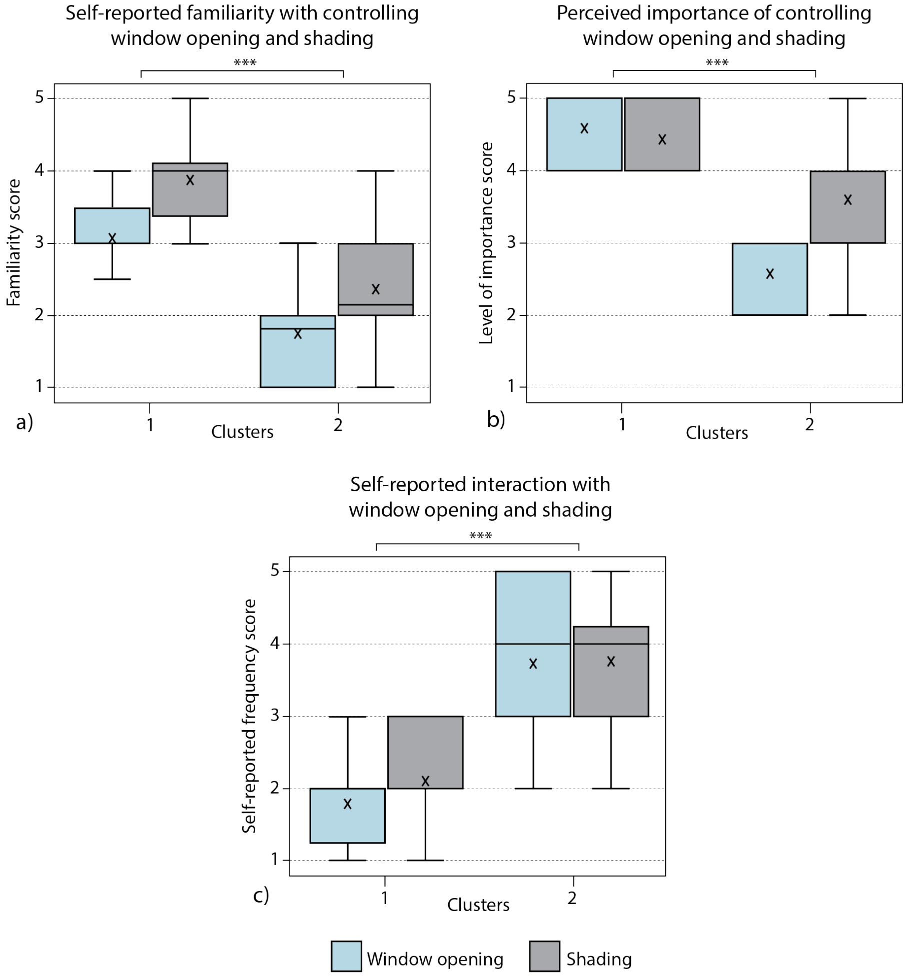


FIG. 4.11 Boxplots of the results of three cluster analysis performed regarding (a) level of familiarity with smart windows and smart blinds, (b) level of importance of controlling window's opening and window's shading, and (c) self-reported frequency of interaction on controlling window's opening and window's shading. Each analysis provided two clusters of participants. All the analysis were validated by using the silhouette measure of cohesion and separation, scoring 0.6 for each of them. The black dot indicates the mean value while the black line indicates the median of the data distribution. The asterisks indicate the level of significance: (***) $p < 0.001$.

times. These patterns reveal each cluster's consistency and likelihood of overriding under particular transition conditions, suggesting that participant preferences are closely tied to both the state of the glazing and the timing of control actions.

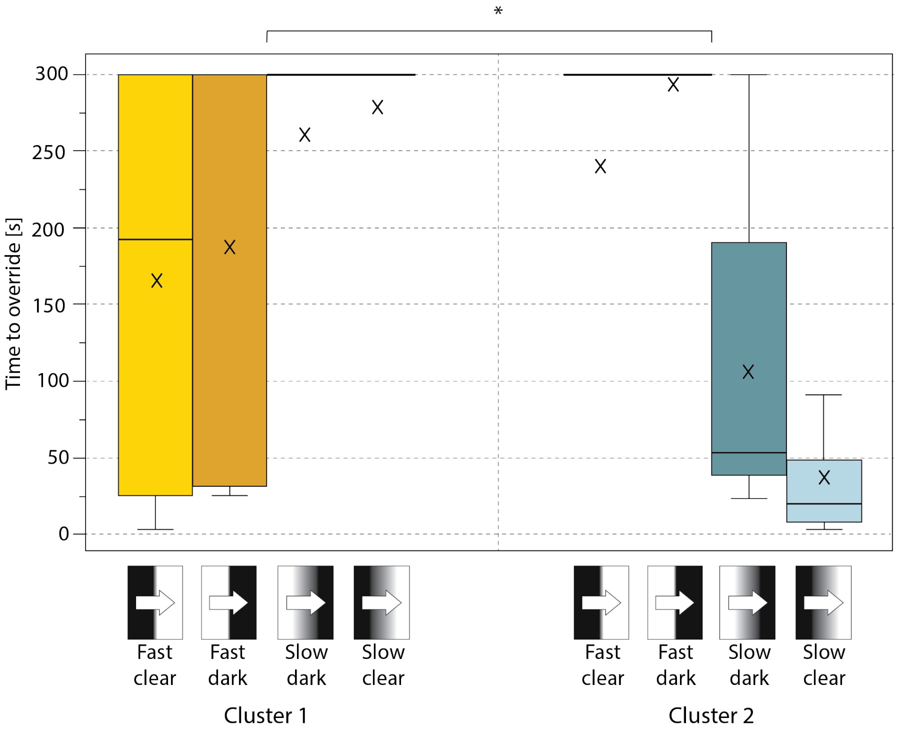


FIG. 4.12 Boxplot of the cluster analysis of participants override delay time of participants with the switchable glazing. This analysis provided two clusters of participants: Cluster 1 represent participants that override the automated control only when the glazing was turned at the darkest state; while Cluster 2 represent participants that override the automated control only when the glazing was turned clear. The analysis was validated by using the silhouette measure of cohesion and separation, scoring 0.5. The black dot indicates the mean value while the black horizontal line indicates the median of the data distribution. The asterisks indicate the level of significance: (*) $p < 0.05$.

The clustering of participants based on their perceived familiarity with the technologies, their importance of participant control of glazing, and self-reported frequency of interaction were compared to the clustering from their behavior during the experiment. The Adjusted Rand Index (ARI) was used to assess the degree of similarity between the clustering assignments based on self-reported information and those resulting from the analysis of override delay times, as shown in Table 4.5. A moderate ARI of 0.08 for clustering based on familiarity with smart façades indicates a reasonable alignment with actual behavioral patterns measured in the experiment. This means that participants that reported high familiarity with the technology were also the participants that override the façade with a longer reaction time. This could potentially be explained by the lower disruption perceived when familiar with the technology. Conversely, the negative ARI of 0.02 for clustering on the level of importance for controlling façades suggests a divergence from the override delay time clustering structure, indicating less agreement. Additionally, the low positive ARI of 0.01 in the clustering based on self-reported frequency of interaction with façades implies only a slight agreement between the derived clusters and the override reaction time clustering.

TABLE 4.5 The Adjusted Rand Index (ARI) between the clusters on participants' self-reported information (level of familiarity, importance and frequency of interaction) and the cluster on participants' behavior (override delay time), showing that clustering based on importance has the least agreement while familiarity shows the highest alignment.

	Clustering on the level of familiarity with smart façade	Clustering on the level of importance for controlling façade	Clustering on the self-reported frequency of interaction with façade
Clustering on the Override delay time	ARI = 0.08	ARI = -0.02	ARI = 0.01

Finally, participants' self-reported perception was compared to behavioral groups, as shown in Table 4.6. Chi-square tests were used to statistically assess whether there is a significant association between groups and participants' perception during participant glazing operations.

Clusters related to the level of familiarity with the technology, self-reported frequency of interaction with the façade, and behavior with switchable glazing were significantly associated with participant satisfaction with the visual environment, with corresponding p-values of 0.039, 0.014, and 0.002, respectively. Thus, the cluster of participants with high level of familiarity with smart glazing is also characterized by participants that expressed dissatisfaction with the visual environment. Clusters associated with high levels of interaction with the façade (both self-reporting and observed behavior with switchable glazing) also exhibited greater satisfaction with the visual environment compared to the participants in the cluster described by a low frequency of interaction.

Differences among clusters can also be explained by differences in participant perception. For example, the cluster demonstrating a high level of familiarity with smart windows is correlated with a greater number of participants expressing annoyance with window control (p-value = 0.017). Similarly, higher levels of self-reported interaction with façades are linked to a higher prevalence of dissatisfaction with window control. Conversely, a low measured frequency of overriding automated controls corresponded to a higher number of participants not noticing changes in the window state (p-value = 0.002). In contrast, the cluster associated with the importance of controlling façades stands out as the most dissimilar from the others (ARI = 0.02). Table 4.6 shows a higher frequency of neutral votes for window control annoyance in the high-importance cluster (p-value = 0.020), while the low-interaction cluster concentrates votes indicating no annoyance with lighting control.

TABLE 4.6 Correlation between the participant clusters, based on self-reported familiarity, importance, frequency of interaction and delay in participants response with participant perception. The chi-square test was used to test the correlation between the clusters and the perception reported by participants.

Perception of participants	Clusters	Level of familiarity		Level of importance		Self-reported frequency of interaction		Override delay time	
		High fam.	Low fam.	High imp.	Low imp.	High int.	Low int.	Low int.	High int.
		Cluster 1	Cluster 2	Cluster 1	Cluster 2	Cluster 1	Cluster 2	Cluster 1	Cluster 2
		n=48	n=72	n=100	n=20	n=73	n=47	n=120	n=192
Perceived change on the glazing state	Yes	96%	92%	92%	100%	93%	92%	85%	99%
	No	4%	8%	8%	0%	7%	8%	15%	1%
	p-value	0,0258		0,163		0,295		***0,002****	
Distraction perceived	Agree	17%	18%	20%	5%	19%	15%	63%	50%
	Neutral	33%	22%	28%	20%	26%	28%	19%	32%
	Disagree	50%	58%	51%	75%	53%	57%	17%	18%
	p-value	0,583		0,213		0,917		0,289	
Satisfaction with the visual environment	Agree	50%	58%	67%	75%	71%	64%	79%	61%
	Neutral	33%	22%	28%	20%	29%	23%	17%	33%
	Disagree	17%	18%	5%	5%	0%	13%	4%	6%
	p-value	***0,039****		0,45		***0,014****		***0,002****	
Window's control annoyance	Agree	31%	11%	18%	25%	21%	17%	67%	58%
	Neutral	17%	18%	21%	0%	19%	15%	13%	24%
	Disagree	50%	69%	59%	75%	58%	68%	21%	15%
	p-value	***0,017****		***0,020****		0,386		0,449	
Lighting control annoyance	Agree	6%	7%	6%	10%	5%	9%	65%	46%
	Neutral	19%	14%	18%	5%	14%	19%	15%	17%
	Disagree	46%	58%	50%	70%	58%	47%	2%	10%
	p-value	0,706		***0,022****		0,176		0,285	
Heating control annoyance	Agree	13%	17%	13%	25%	21%	6%	13%	17%
	Neutral	21%	11%	17%	5%	11%	21%	17%	14%
	Disagree	67%	63%	64%	65%	60%	70%	60%	67%
	p-value	0,555		0,108		0,104		0,533	
Satisfaction with windows	Agree	46%	65%	56%	65%	42%	81%	65%	53%
	Neutral	29%	19%	24%	20%	33%	9%	19%	26%
	Disagree	25%	11%	17%	15%	21%	11%	17%	17%
	p-value	0,078		0,631		***0,002****		0,552	
Satisfaction with the lighting	Agree	38%	47%	42%	50%	49%	34%	52%	38%
	Neutral	27%	17%	21%	20%	19%	23%	15%	25%
	Disagree	2%	11%	8%	5%	5%	11%	10%	6%
	p-value	0,209		0,09		0,183		0,462	
Satisfaction with the heating	Agree	65%	63%	63%	65%	59%	70%	63%	64%
	Neutral	15%	11%	14%	5%	8%	19%	15%	11%
	Disagree	21%	19%	18%	30%	26%	11%	15%	24%
	p-value	0,732		0,634		0,13		0,569	

* Indicate significance at p-value < 0.05.

4.4 Discussion

The perceptual data from this study shows that there was no significant difference in perception across the scenarios. Therefore, both the speed (1 or 10 s) and direction of glazing transition seem to have a low impact on occupant satisfaction with the visual environment and window control.

The analysis of behavioral data provides further important insights, highlighting the importance of considering both sources of data when assessing occupant-façade interaction. As shown in Fig. 6, approximately half of the participants overrode the glazing change of state, especially when the glazing was turned to its dark state (17 out of 30 for the lower transition rate, 20 out of 30 for the faster transition rate). Faster transition rates triggered a larger number of overrides in both transition directions. As expected, the slower the glazing transitions, the longer it takes for participants to react to the glazing change, since the reaction time between glazing transition and participant response was larger. The perception of participants who opted to override the glazing control was also significantly different and worse than those who did not override, confirming that overriding the control is induced by dissatisfaction with the visual environment or the window control (Figure 4.7). Thus, overriding of controls is a good proxy for occupant satisfaction with the automated control strategy.

The examination of facial expressions emerged as a valuable approach for gathering further insights when combined with perceptual and behavioral data. Notably, there was no significant variance in gaze angles observed across various glazing transition rates or directions. However, it is noteworthy that, during the transitions of the glazing, participants consistently directed their gaze towards the glazing, irrespective of the transition rate (Figure 4.8). This was also confirmed by the analysis of the facial expressions, which differed significantly between the intervals when the glazing remained unchanged and the periods when the glazing was transitioning (Figure 4.10).

The dispersion in participants' results shows that individual preferences may differ, and personalized interaction can be considered, in particular when designing transition to clear glazing states. For instance, if participants are grouped depending on whether they override or not the automated switching, there is a clear and significant difference in participants' satisfaction with the visual environment and the window control, perceived distraction from the reading task and perceived annoyance with the window control. The overriding behaviors are strongly associated with low levels of satisfaction, high levels of annoyance and perceived distraction from the reading task, as also shown in the correlation matrix (Figure 4.9).

Participants exhibited a range of backgrounds and preferences. Interestingly, the majority emphasized the importance of controlling both window openings and shading, particularly in home environments (Figure 4.4). Clustering analysis revealed two distinct participant profiles based on self-reported information on the level of familiarity with the technology, the importance of personal control of the glazing, frequency of interaction and override reaction times. However, the Adjusted Rand Index (ARI) values indicated random agreement between these profiles and actual participant behavior (Table 4.5). This suggests that while self-reported data provide insights into occupant background and perceived preferences, they do not consistently align with occupant behavior when interacting with the glazing system.

Although clusters on participants' backgrounds and preferences do not align with their actual behavior, they were shown to be associated with specific perceptual response regarding the level of distraction, annoyance, and satisfaction of smart glazing operation (Table 4.6). Consequently, the cluster of high familiarity exhibits a strong correlation with visual satisfaction and annoyance with window control. The cluster of low self-reported interaction shows a higher correlation with the satisfaction with window control. The low-importance-of-façade-operation cluster exhibits low correlation with visual dissatisfaction with lighting and window control. In contrast, the cluster of high actual participants' interaction shows good association with noticing changes in window states. Overall, the clustering reveals the importance of considering personal preferences when designing automated control strategies.

4.5 Conclusion

This study investigated the influence of speed and direction of transparency change in switchable glazing on occupant satisfaction and acceptance. An experimental campaign involving 30 participants was conducted in a controlled environment, wherein perceptual and behavioral data were collected and complemented with the analysis of facial action units. Clustering analysis was also employed to explore the relationships between occupants' backgrounds, preferences, and behavioral drivers. It was found that:

- No significant difference exists in participant perception across the scenarios, while a noticeable difference in participant behavior emerged from the variations in the direction and speed of transitioning;

- Participant overrides are mainly driven by the direction of the glazing transition. A larger amount of participants overrode the automated glazing control when transitioning towards the dark state. Approximately 10 % more participants overrode the glazing in response to faster transitions, in both directions of transition. When considering participants that overrode the automated control system, they exhibited low satisfaction with the visual environment and the control of the window.

- Capturing data with facial action units and gaze orientation revealed some further patterns in occupant response to the glazing transition rate, such as differences in response between participants that override and do not override.

- Occupants can be clustered based on their background knowledge and reported preferences. These clusters showed good correlation with the override delay times. However, the agreement with actual behavior was low, indicating that a larger number of variables and clusters should be tested to predict occupant behavior based on self-reported preferences.

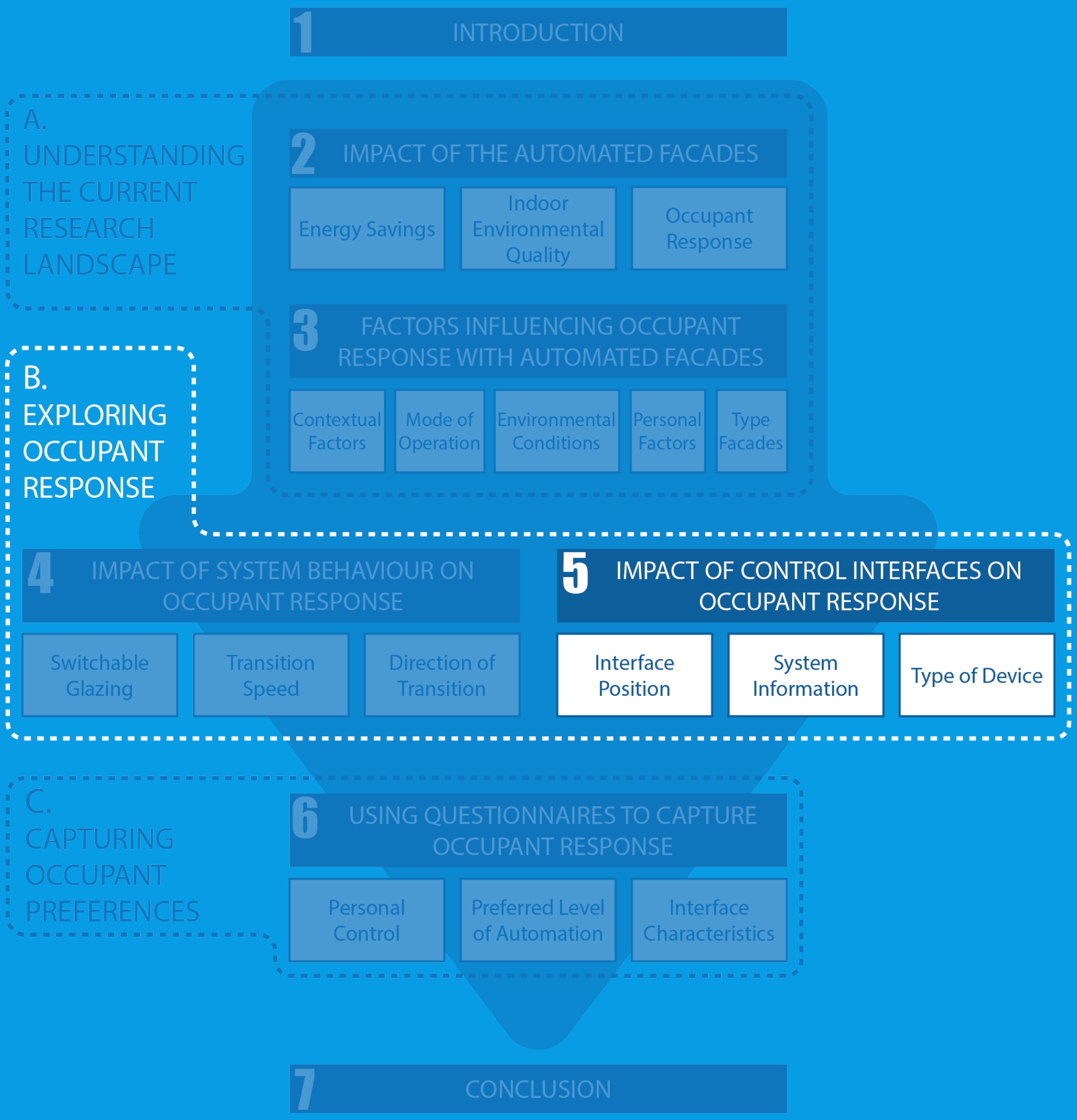
- Clustering analysis on participants' backgrounds and preferences has the potential to inform the distribution of certain behavioral drivers and perceptual responses when interacting with smart glazing, such as level of perception of glass changing state, distraction, annoyance, and satisfaction with the smart glazing operation.

This study has some limitations that merit investigation in future work. First, the participants were never exposed to glare conditions, which may have an effect on the satisfaction with the speed of switching. Participants tend to prefer swift automated controls when experiencing visual discomfort to promptly restore comfort levels. However, it is important to highlight that this study specifically focused on the transition rate during automated glazing operations. In these instances, the control of glazing to mitigate glare risk typically aims to anticipate discomfort (Luna-Navarro et al., 2023), posing more challenges in terms of acceptance.

Secondly, participants were positioned very close to the glazing and in a space with a large window-to-wall ratio. Therefore, the impact of the glazing transition rate could be larger than in real office environments, where occupants may be sitting further from the façade and exposed to a stronger artificially lit environment. It is also expected that the impact of the glazing transition rate can vary depending on the outside luminous conditions, so further assessments with larger daylight variance are recommended to expand the results beyond the overcast sky conditions.

Thirdly, this study tested only two transition rates, both of which were perceptible to the participants, as indicated by the FAUs. Further research on longer, potentially imperceptible transition times may be valuable, especially since longer transitions can be implemented without compromising building energy performance. This experiment focused on very fast transition times (1 second and 10 s), reflecting the capabilities of current glazing technologies and typical real-world applications. However, the ability to operate these technologies at such rapid rates raises an important question: what is the optimal balance between the shortest and most effective transition time to maintain both energy efficiency and occupant acceptance of the automated control action.

Finally, to evaluate the impact of additional factors on occupant response to changes in dynamic glazing, a larger group of people would have been required. The sample size was chosen on the basis of the main experimental scenarios but aggregating additional variables e.g. likelihood of overriding behavior and other personal attitudes, would require a larger sample size.



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5 Impact of Control Interfaces on Occupant Response

Interface design for lighting and shading controls: device type, position, and system cues influencing user preference and acceptance

This chapter is based on work published in 2025 in Building and Environment

This chapter investigates how control interface design—specifically type, position, and information—shapes occupant interaction, satisfaction, and acceptance of automated façades. Addressing the need for intuitive engagement identified in Chapter 3, a usability study was conducted in a controlled laboratory environment. Participants interacted with lighting and shading systems across six scenarios systematically varying interface modality (analog vs. digital), placement (wall vs. desk), and feedback levels. Data collected via the Post-Study System Usability Questionnaire (PSSUQ) and interviews quantify usability while elucidating the rationale behind occupant preferences and override behaviors. These findings identify critical usability drivers and preferred configurations, establishing the design requirements for the large-scale survey in Chapter 6 and bridging experimental insights with scalable application.

5.1 Introduction

Recent advancements in information technology have facilitated the integration of automation and building control systems in buildings, thereby improving occupant experience and energy efficiency [173]. Research in building control systems has demonstrated that automated controls often fail to align with occupants' preferences, particularly when the system's logic does not match individual environmental needs [17, 174]. While discussions around Human-Building Interaction (HBI) strategies have primarily focused on analyzing occupants' environmental preferences and behavior to develop personalized comfort models or behavioral models for energy simulations [25], research on control interfaces, especially concerning personal control of building services, has received less attention [46, 154].

Although limited, field studies on control interfaces, in particular for lighting, show that interface characteristics (e.g., type of device, position, and information) directly influence how occupants negotiate control in shared offices [175–177]. Lashina et al. [178] found that open-office occupants often adopt strategies that avoid conflicts (e.g., setting compromise values, waiting for others' reactions, or relying on automated actions) when sharing controls. Smartphone apps, wall-mounted devices, and hand-operated controls, such as curtain cords, lead to different patterns of individual versus collective use, influencing both individual satisfaction and social dynamics in shared-office environments. Beyond the interface itself, contextual constraints also play a role. Day et al. [179] observed that poor furniture layouts or the fear of disturbing co-occupants can limit people's access to controls, clearly demonstrating that both interface design and indoor spatial characteristics should be considered together when aiming to enhance satisfaction and energy efficiency.

Interfaces further affect the perceived level of personal control, which influences environmental satisfaction [43, 180] and acceptance of automation [181]. Empirical studies suggest that providing occupants with the means for personal lighting and shading controls can enhance satisfaction by giving occupants a sense of agency, while also reducing interpersonal conflicts in shared spaces. Similarly, Meerbeek et al. [149] demonstrated that providing occupants with feedback on system status and automated blinds actions improves trust and reduces the need for overrides, thereby increasing acceptance of automation.

A consistent finding across research is that usability is critical for building control systems. Perry et al. [182] demonstrated that thermostats and lighting interfaces must be efficient and straightforward, with web platforms enabling faster and more accurate adjustments. Amardeep et al. [183] reached similar conclusions, proposing touchscreen interfaces as intuitive and interactive ways to manage dimming and related lighting functions. Another key aspect is the importance of clear feedback and consistency (e.g. simple status, confirmation that input was received, or explanatory clues). Karjalainen & Koistinen [184], Lashina et al. [185], and Yilmaz et al. [186] showed that such feedback helps occupants understand how HVAC and lighting systems operate, reduces confusion during malfunctions, and strengthens perceived control. This is a meaningful finding given the current state of lighting control interfaces, as Someren et al. [187] found that they are often inconsistent and difficult to access, which undermines usability. Evidence from other building systems reinforces these insights. Large-scale evaluations of connected thermostats confirmed that usability dominates occupant concerns, far more than energy considerations [188]. Similarly, evaluations of web-based building management tools showed that clarity, reachability, and actionable feedback are essential for adoption by facility managers [189].

Despite this evidence, a standardized methodology for evaluating usability in building control interfaces has yet to be developed. Numerous models for measuring and benchmarking usability exist in the Human-Computer Interaction (HCI) field [190], but limited research has examined whether they effectively apply to control interfaces in buildings. Existing metrics, such as Sauro and Kindlund's usability metric (SUM), were designed for web and desktop applications and have not been extended to building controls [191]. Yet building interfaces present unique challenges: they are task-specific, used infrequently, and must compete for occupants' limited attention. As Murphy [192] observed, devices such as thermostats need to be simple enough for occasional use without training while still providing reliable functionality. Studies of programmable thermostats confirm that poor usability leads to incorrect use and wasted energy [182], while reviews of energy-saving behavior show that poorly designed interfaces can undermine efficiency, whereas simple nudges such as progressive dimming or clear feedback can deliver significant savings [193]. The lack of clear and consistent usability metrics has, therefore, hindered interface improvements, underlining the need for evaluation methods tailored to building systems.

This study aims to evaluate the effectiveness of usability testing as an innovative method for assessing building system control interfaces and occupant interaction with automation in the built environment. Specifically, it explores individual occupant preferences for interfaces that control visual quality, such as window shading and artificial lighting. We investigated the impact of factors such as interface "Position" (desk or wall), level of "System Cues" (level of information), and "Type of Device" (analog or digital) on occupant satisfaction in an experimental office setting involving 20 participants. Using an adapted Post-Study System Usability Questionnaire (PSSUQ), we evaluated satisfaction in terms of Ease of Use, Reachability, and Information. Our adaptation repurposes a standard HCI usability instrument for building control interfaces and adds items tailored to spatial reachability and system feedback for automation, dimensions that are rarely captured by the single-item comfort or satisfaction measures commonly used in built-environment studies.

5.2 Methodology

In this study, we aimed to investigate the impact of different interaction strategies on participants' perceived usability and preferences when controlling artificial lighting and window roller shades in an office environment. We conducted our experiment in a controlled laboratory designed as a simple office setting (the "office lab"), focusing on three key variables: the "Type of Device" (analog or digital), "System Cues" (no cues, basic system state cues, and system state with task completion cues), and "Position" (wall, desk, and split, i.e., controls distributed between wall and desk). Twenty participants took part in the experiments, which assessed their interaction with various control configurations. Through a combination of questionnaires and interviews about preferences, we collected both quantitative and qualitative data to gain insights into how the tested variables influence Ease of Use, satisfaction with Information, Reachability, and Overall Satisfaction with the control system interface. Below is a detailed description of the methodology, including the experimental setup, procedures, and data analysis techniques.

FIG. 5.1 The Office Lab at The Green Village, Delft University of Technology. (a) Interior view showing the seats of the participant and researcher; (b) Top-down schematic of the layout including systems, participant, researcher, and entrance; (c) Front view of the window with the roller shade set to the mid position; (d) Lighting system used in the experiment; and (e) Exterior view of the Office Lab.

The office lab is located at The Green Village, a living lab affiliated with Delft University of Technology in the Netherlands (Figure 5.1a). Measuring 2.45 x 2.95 meters, the office lab is southwest-facing and equipped with dimmable LED ceiling lights (Figure 5.1c) and a motorized roller shade (Figure 5.1d) on the outer side of the window. Both the lighting and roller shades were connected to a control system powered by the Home Assistant platform [194], which enabled integration with the interfaces being tested. Inside the room, we placed a desk with a computer to mimic an office environment. A separate table was positioned in the corner for the researcher, who was responsible for assisting participants as needed and noting any important observations (Figure 5.1b).

The participants were recruited via email and social media. In total, 20 participants took part in the experiment (9 females and 11 males; age range 23–40, mean = 30, SD = 4.48). Participants worked in technical fields other than building science. The experimental plan was reviewed and approved by the Human Research Ethics Committee of Delft University of Technology under ID 3752.

5.2.1 Experimental procedure

Figure 5.2 shows the timeline of the experimental procedure. First, participants received an introduction to the experiment and signed the consent form. The test started with a questionnaire and an interview about the participants' expectations for controlling artificial lighting and window roller shades in an office space. Participants then completed six randomly ordered scenarios, with the PSSUQ administered after each scenario. Upon completing all six scenarios, participants were interviewed and asked to complete a questionnaire about their experience with the interfaces. The entire usability test lasted approximately 60 minutes per participant. The experiment is explained in detail in the following sections.

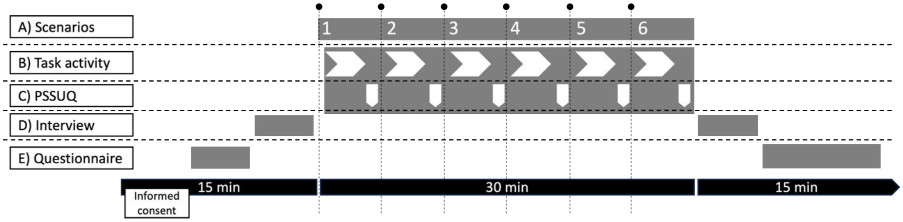


FIG. 5.2 Experimental procedure timeline.

5.2.1.1 Scenarios

We designed six scenarios to evaluate the impact of three key variables: “Type of Device” (analog switches vs. digital touchscreen), the interface “Position” (wall-mounted vs. desk-mounted, or split position), and the level of “System Cues” provided (no system cues, system state, or system state and cues for supporting the task completion). The split position consisted of positioning the lighting control interface on the wall in proximity of the entrance and the blind control interface on the wall in the proximity of the window. A detailed description of these scenarios is presented in Table 5.1. Each participant experienced the scenarios in a random order.

TABLE 5.1 Overview of the six scenarios, which considered different “Device Types”, “Positions”, and “System Cues”.

	Type of Device		Position		System Cues	
Scenario	Light	Roller shade	Light	Roller shade	Light	Roller shade
SC1	Analog	Analog	Wall/entrance	Wall/entrance	No cues	No cues
SC2	Analog	Analog	Desk	Desk	No cues	No cues
SC3	Analog	Analog	Wall/entrance	Wall/Window	No cues	No cues
SC4	Digital	Digital	Desk	Desk	No cues	No cues
SC5	Digital	Digital	Desk	Desk	System state	System state
SC6	Digital	Digital	Desk	Desk	System state + task completion	System state + task completion

We placed interfaces in three positions: on the wall next to the entrance (switches only), split across the wall next to the window and entrance (shading and lighting switches, respectively), and on the participant’s desk (either switches or a tablet). Figure 5.3 illustrates the control interface positions within the office lab.

The scenarios utilized two types of control devices: a switch as the analog interface (Figure 5.4a-b) and a tablet as the digital interface (Figure 5.4c). All three device types were capable of controlling artificial lighting and the window roller shade. The tablet featured three visual interfaces (Figure 5.5): one with no system cues (Figure 5.5a), one with system state cues (Figure 5.5b), and one with system state plus task completion cues (Figure 5.5c).

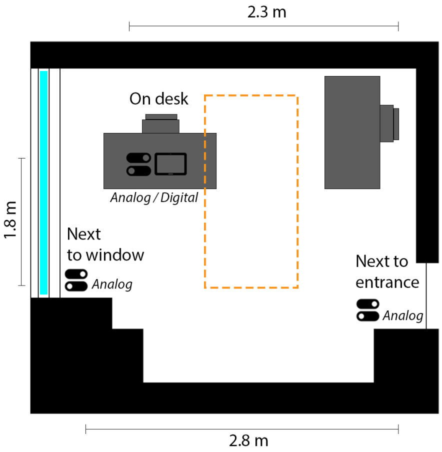


FIG. 5.3 Top view of the office lab indicating the positions where the interfaces were placed during the tested scenarios.

FIG. 5.4 Types of device interfaces used in the experiment: (a) analog light switch, (b) analog roller shade switch, and (c) tablet interface controlling both lights and roller shades.

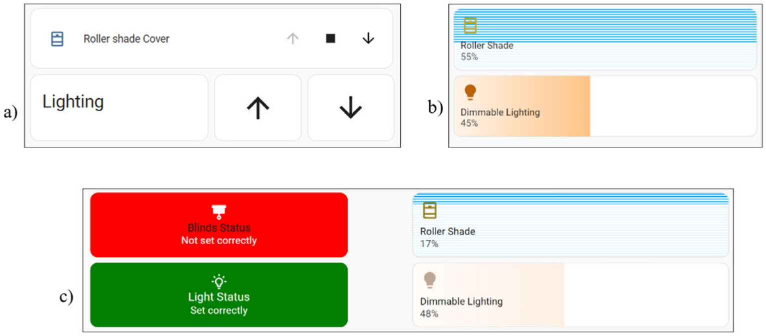


FIG. 5.5 Various types of digital control interfaces displayed on the tablet interface screen: (a) no system cues, (b) system state cues, and (c) with system state plus task completion.

5.2.1.2 Control Task Activity

The task activity in this study was designed to simulate realistic interactions with the different building control interfaces being tested. It ensured that participants engaged with the system, allowing us to evaluate how effectively the interfaces (analog switches and digital touchscreens) supported occupant interaction and control over the artificial lighting and window roller shade system. Additionally, the task tested participants' ability to regain control after an automated action was triggered. The task activity implemented in this experiment is described in the following steps:

a) Entering the Room and Initial Setup: Participants were asked to adjust the lighting to 50% brightness and set the roller shades to a halfway position using the control interface. This step evaluated how intuitively and effectively participants could interact with the system to achieve these specific settings.

b) Seated Work Simulation: After completing the initial setup, participants were instructed to sit at a desk and use a computer, simulating a typical work scenario. This setup established a context for the upcoming automated system actions.

c) Automated System Action: While participants were engaged in the computer-based task, an automated system action was triggered, causing the lights and roller shades to adjust automatically. This phase assessed how participants reacted to the system taking control and their comfort in the situation.

d) Recovering Control: Following the automated action, participants were instructed to reset the lights and roller shades to their original settings. This step tested their ability to quickly and accurately reassert control over the system.

e) Completion and Feedback: After the system was restored to its initial state, the task scenario concluded. Participants then completed the Post-Study System Usability Questionnaire (PSSUQ), providing feedback on their experience with the control interface.

5.2.1.3 Post-Study System Usability Questionnaire

To assess participants' satisfaction with their perceived personal control over the office environment, we employed the Post-Study System Usability Questionnaire (PSSUQ) as a psychometric instrument. Originally developed to evaluate occupants' satisfaction with computer systems and applications [195], the PSSUQ demonstrates strong reliability. All categories (system quality, information quality, and interface quality) report Cronbach's alpha values above 0.80, indicating good internal consistency and supporting its suitability as a measure of usability.

Although PSSUQ is often used for digital systems (e.g., websites or software), its focus on general usability categories makes it suitable for evaluating the control interfaces in this study. The main categories measured were:

a) System Usefulness: How well the system helps occupants achieve their goals.

b) Information Quality: Clarity and usefulness of the system's information.

c) Interface Satisfaction: Occupant's overall satisfaction with the system's design and interaction.

Since the standard PSSUQ does not cover the impact of interface reachability on occupant's satisfaction, we added four customized items addressing this aspect. The original statements were also modified to refer specifically to the control interfaces being tested (Table 5.2).

TABLE 5.2 Modified PSSUQ developed for testing building control interfaces. The items were adjusted to match the aim of this usability test, focusing on assessing Ease of Use, Reachability, and Information. "How strongly do you agree or disagree with the following items" – Strongly disagree (1) to Strongly agree (5).

Number	Item	Category
1	Overall, I am satisfied with how easy it is to use this control interface.	Ease of use
2	It was simple to use this control interface.	Ease of use
3	I was able to complete the tasks and scenarios quickly using this control interface.	Ease of use
4	I felt comfortable using this control interface.	Ease of use
5	It was easy to learn to use this control interface.	Ease of use
6	The control interface was pleasant to use.	Ease of use
7	I liked using this control interface.	Ease of use
8	This control interface has all the functions and capabilities I expect it to have.	Ease of use
9	The control interface provided information that helped me to use the light and roller shade.	Information
10	The information provided by this control interface was clear.	Information
11	The information on the control interface was effective in helping me complete the tasks.	Information
12	The organization of information on the control interface was clear.	Information
13	I found it easy to access the control interface in its current position.	Reachability
14	The position of the control interface was convenient for me.	Reachability
15	The control interface's position was appropriate for the tasks I needed to perform.	Reachability
16	The control interface's position allowed me to interact with it without causing discomfort.	Reachability
17	Overall, I am satisfied with the control interface (position, information, and type).	Overall Satisfaction

5.2.1.4 Interviews

We conducted two interviews during the experiment:

a) Pre-Experiment Interview: The first interview aimed at understanding participants' expectations regarding control interfaces in a typical office environment. Questions focused on preferences for "Type of Device" (analog vs. digital), interface "Position", the desired level of "System Cues", and acceptance of automation.

b) Post-Experiment Interview: After the experiment, participants provided feedback on the control interfaces they used during the six scenarios. The same topics were revisited, enabling a comparison between participants' initial expectations and their actual experiences.

5.2.1.5 Familiarity and Preferences Questionnaires

At the start of the experiment, participants completed a questionnaire to assess their familiarity with and experience of various devices, both at home and in the office, including smart roller shades, manual roller shades, dimmable lights, smart lights, analog control interfaces (e.g., switches, dials), and digital control interfaces (e.g., touch screens). Familiarity was rated on a Likert scale ranging from 1 (not at all familiar) to 7 (extremely familiar). Additionally, a multiple-choice format was used to determine which of these devices were present in their typical office environment.

At the end of the experiment, participants filled out a preference questionnaire consisting of three sections, each targeting different aspects of interface design for lighting and shading control. Section 1 focused on personal preferences in the office lab setting, using single-choice questions and one ranking task to assess preferences for the three interface characteristics tested in the study: "Position", "System Cues", and "Type of Device". Participants were asked to indicate where they preferred the interface to be located (e.g., on the desk or by the entrance), what type of feedback they found most helpful (e.g., system status), and whether they favored analog or digital controls. Section 2 explored how these preferences might change in a shared office context, using Likert-scale statements to evaluate trade-offs between convenience, occupant responsibility, and feedback clarity. Section 3 examined how these interface characteristics influenced the acceptability of automation, focusing on whether specific design elements, such as interface type, feedback, or placement, might make participants feel comfortable with automated lighting and shading systems. The structure and content of the questionnaire are summarized in Table 5.3.

TABLE 5.3 Structure and content of the post-experiment questionnaire assessing participants' preferences for interface characteristics related to lighting and shading control. The questionnaire was divided into three sections: (1) baseline preferences in a private office setting, (2) preference shifts in a shared office context, and (3) influence of interface characteristics on the acceptability of automation.

Section	Focus	Question type	Interface characteristics examined
Section 1: Personal Preferences in the Office Lab	Identifying preferences for control interface characteristics in a private office setup after the experiment	Single choice; ranking (attribute importance)	- Preferred location of the control interface for lighting and shading. - Preferred level of system feedback. - Preferred type of control device (analog/digital). - Relative importance of interface characteristics: position, system cues, and type of device.
Section 2: Preferences in Shared Office Context	Exploring how preferences shift in a shared office setting	5-point Likert-scale agreement (strongly disagree to strongly agree)	- Preferred location of controls in a shared office (desk, entrance, separate). - Preference for analog vs. digital controls. - Importance of system feedback. - Desire for simplicity vs. information-rich interfaces.
Section 3: Automation Acceptability and Interface Design	Assessing which interface features improve occupant acceptance of automation	5-point Likert-scale agreement (strongly disagree to strongly agree)	- Interface types that enhance comfort with automation (analog vs. digital). - Interface location (desk, door, distributed). - Degree and clarity of feedback from the automated system.

5.2.2 Data Analysis

Our data analysis consisted of seven steps: (1) summarizing participants' familiarity ratings; (2) validating the PSSUQ via exploratory factor analysis and Cronbach's α; (3) isolating interface effects with Bonferroni-adjusted pairwise tests; (4) modeling Overall Satisfaction using ordered logistic regression; (5) examining post-test preferences and automation acceptance; and (6) analyzing interview data to contrast initial expectations with actual experiences.

5.2.2.1 Level of familiarity distribution

We summarized participants' self-reported familiarity with manual and smart devices and control interfaces (1–7 Likert) by computing means, standard deviations, and interquartile ranges, and displayed as boxplots. Counts of device availability (e.g., manual, smart, and dimmable lighting) are presented to characterize the participants' prior exposure.

5.2.2.2 Suitability of the Post-Study System Usability Questionnaire

We tested the suitability of the PSSUQ questionnaire for our case study by conducting an Exploratory Factor Analysis (EFA) [196]. By performing this analysis, we aimed to identify the key factors for which the survey was designed: Ease of Use, Information, and Reachability. For a preliminary analysis, we checked the factorability of the sample using Bartlett's test of sphericity ($\chi^2 = 77.70$, $p < 0.001$) [197] and the Kaiser-Meyer-Olkin (KMO) measure of sampling adequacy (0.914) [197], both of which confirmed that the number of participants was appropriate for the factor analysis. After confirming the suitability of performing the EFA, we calculated the Kaiser's eigenvalues of the correlation matrix to determine the number of factors, selecting all eigenvalues greater than one [33]. Before selecting the rotation, we analyzed correlations to decide on the matrix rotation method. We opted for the Oblimin rotation [198], which is appropriate when factors are assumed to be correlated. We tested the internal consistency of the variables summarized in every factor [199] and calculated the factor scores using the refined method of regression, which maximizes validity [200]. Finally, we assessed the reliability of the obtained results by calculating Cronbach's alpha as described in Sauro and Lewis [195] and comparing their reported values with those derived from our modified PSSUQ questionnaire.

5.2.2.3 Usability Scores and Interface Characteristics Impact

We report usability scores for each factor identified, along with the Overall Usability score, calculated as the average of the first 16 modified PSSUQ items. To examine how usability factors varied across the six interface scenarios, we conducted Bonferroni-adjusted pairwise statistical comparisons of scenario ratings for Ease of Use, Reachability, and Information. These comparisons isolated the effect of each variable ("Type of Device", "Position", and "System Cues") while controlling for the others, enabling a clearer interpretation of their individual impacts. At the same time, the set of scenarios covered all three levels of each variable, allowing for group-level analysis across interface "Position", "Type of Device", and "System Cues" (Table 5.4).

TABLE 5.4 Pairwise comparisons by variable, controlling for other factors.

Variables	Level comparison	Scenario A	Scenario B	Constant variables
Interface Position	Wall vs. Desk	1 – Analog – Wall – No cues	2 – Analog – Desk – No cues	Analog, No cues
Interface Position	Wall vs. Split	1 – Analog – Wall – No cues	3 – Analog – Split – No cues	Analog, No cues
Interface Position	Desk vs. Split	2 – Analog – Desk – No cues	3 – Analog – Split – No cues	Analog, No cues
Type of Device	Analog vs. Digital	2 – Analog – Desk – No cues	4 – Digital – Desk – No cues	Desk, No cues
System Cues	No cues vs. State cues	4 – Digital – Desk – No cues	5 – Digital – Desk – System state	Digital, Desk
System Cues	State vs. Full cues	5 – Digital – Desk – System state	6 – Digital – Desk – Feedback	Digital, Desk
System Cues	No cues vs. Full cues	4 – Digital – Desk – No cues	6 – Digital – Desk – Feedback	Digital, Desk

5.2.2.4 Influence of Factors on Overall Satisfaction

We performed a regression analysis to assess the ability of the identified factors to predict the Overall Satisfaction with the interface, as measured by the item 17: “Overall, I am satisfied with the control interface (position, information, and type of device)". Since the dependent variable, Overall Satisfaction, was measured on a Likert scale (ordinal), we employed an Ordered Logistic Regression model [201].

5.2.2.5 Personal Interface Preferences After the Experiment

We summarized participants’ preferences for interface “Position”, “Type of Device”, and “System Cues” by reporting frequencies and percentages for each option within the office lab setup. To identify which pairwise differences in preference were statistically meaningful, we applied chi-square tests of independence with Bonferroni-adjusted post hoc comparisons (adjusted $\alpha = .05$), allowing us to isolate specific contrasts (e.g., desk vs. wall) while controlling the family-wise error rate.

To examine the consistency of preferences across contexts, we compared each participant’s selections in the office lab setup with their responses to a follow-up questionnaire describing a hypothetical shared office scenario. For each interface characteristic (“Position”, “Type of Device”, and “System Cues”), we defined a match as a participant choosing the same option in both contexts. We then calculated a match rate, expressed as the proportion of participants whose choices were consistent across the two contexts. This participant-level comparison provided a descriptive measure of context dependency, indicating how stable preferences remained when moving from a controlled, individual lab setting to an imagined, socially shared office environment.

For the automated lighting and shading acceptance questionnaire, we treated each interface characteristic rating (“Position”, “Type of Device”, “System Cues”) as a within-subject comparison of ordinal 5-point Likert scores. We first described this data using medians and interquartile ranges. We then conducted Wilcoxon signed-rank tests for all relevant within-subject pairings (α = .05) to determine whether median differences were unlikely under the null hypothesis of no preference. Finally, we tallied each participant’s single top-ranked attribute to complement these inferential analyzes with a measure of peak preference.

5.2.2.6 Interviews

We analyzed the interview data using structured data analysis. The analysis focused on participants’ expectations versus their actual experiences with interface positions, the type and level of system cues provided, interface preferences, and attitudes towards automation. We used a comparative approach to assess shifts in participants’ perceptions by contrasting participants’ initial expectations with their post-interaction experiences.

5.3 Results

5.3.1 Level of familiarity with lighting, shading and control interfaces

This section examines participants’ self-reported familiarity with manual and smart lighting, shading, and control interfaces. Figure 6 compares what participants know versus what they are experienced with in their office environments. Specifically, Figure 5.6a shows the responses of the participants in terms of the perceived familiarity with different types of lighting, shading and control interfaces in office spaces, while Figure 5.6b shows the number of participants reporting the presence of one or more of these items in their office space. The majority of participants (84%) reported being familiar with analog control interfaces and indicated having experience with them in their office space. In line with this, when asked specifically about manually controlled roller shades (typically operated through analog interfaces), participants also reported high familiarity and frequent availability in their office environments. Smart automated lights or manually controlled dimmable lights were less frequently available in the office spaces (5.3% and 10.5% of participants, respectively), even though participants reported being highly familiar with dimmable lights (implying exposure outside of their office environments). In the middle of the available options, smart automated roller shades were present in the office space of 37% of participants.

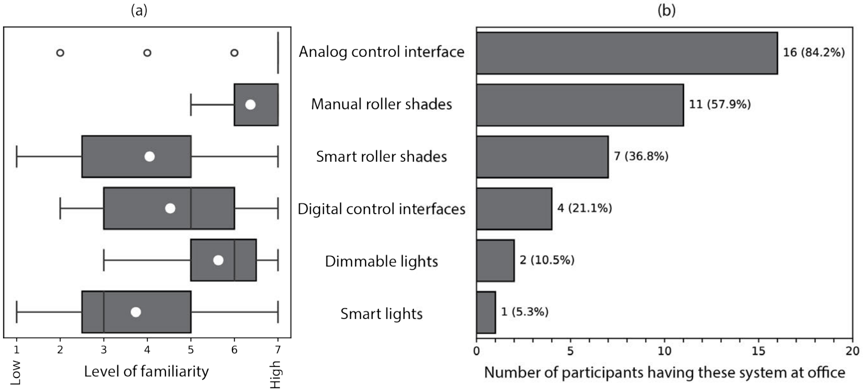


FIG. 5.6 Overview of participants' familiarity with and availability of different lighting, shading, and control interfaces in office spaces. (a) Participants' self-reported familiarity with manual and smart roller shades, dimmable and smart lighting, and analog or digital control interfaces. (b) Number of participants who reported having these systems in their office.

5.3.2 Suitability of the PSSUQ

This section examines the psychometric suitability of the modified PSSUQ for evaluating usability in lighting and shading control interfaces. After interacting with six interface scenarios, participants completed the questionnaire, providing quantitative measures of satisfaction across sixteen usability items. To verify whether the instrument reliably captured distinct aspects of participants' responses, we conducted factor analysis and reliability testing.

We performed a factor analysis of participants' responses to the 16 PSSUQ items, which resulted in three main factors: (1) Ease of Use, (2) Reachability, and (3) Information. These three factors collectively explained 80.01% of the variance in the dataset, indicating that those domains offer a good representation of the whole dataset of participants' responses, and exceed common thresholds for explained variance in scale development [199].

Table 5.5 reports the factor loading for each item, indicating their relative contribution to the identified factors. Factor 1 (Ease of use) clustered items related to satisfaction (item 1 = 0.70), simplicity (item 2 = 0.82), comfort (item 4 = 0.82), and ease of learning (item 5 = 0.70). It also included items addressing quickness (item 3 = 0.51), pleasantness (item 6 = 0.54), liking (item 7 = 0.66), and expectation of functionality (item 8 = 0.65), which showed weaker loadings (<0.70). Factor 2 (Reachability) was defined by items addressing the position and access to the interface, with particularly strong factor loadings for appropriateness of position (item 14 = 0.95), ease of access (item 13 = 0.88), and absence of discomfort (item 16 = 0.80). Factor 3 (Information) gathered items related to "System Cues", with high loadings for helpfulness (item 9 = 0.97), clarity (item 10 = 0.94), and organization (item 12 = 0.80). These results validate that the modified PSSUQ differentiates between Ease of Use, interface Reachability (or ease to access), and Information, thereby validating its structure for evaluating lighting and shading control systems in this study.

TABLE 5.5 Factor loadings for each item in the factor analysis. Factor 1 represents the items related to Ease of Use, Factor 2 to Reachability, and Factor 3 to Information.

Category	Num.	Item	Factor 1	Factor 2	Factor 3
Ease of use	1	Overall, I am satisfied with how easy it is to use this control interface.	0.70	0.17	0.05
Ease of use	2	It was simple to use this control interface.	0.82	-0.19	0.07
Ease of use	3	I was able to complete the tasks and scenarios quickly using this control interface.	0.51	0.35	0.15
Ease of use	4	I felt comfortable using this control interface.	0.82	0.11	-0.11
Ease of use	5	It was easy to learn to use this control interface.	0.70	-0.28	0.13
Ease of use	6	The control interface was pleasant to use.	0.54	0.35	0.12
Ease of use	7	I liked using this control interface.	0.66	0.19	0.08
Ease of use	8	This control interface has all the functions and capabilities I expect it to have.	0.65	0.28	0.00
Information	9	The control interface provided information that helped me to use the light and roller shade.	-0.05	0.00	0.97
Information	10	The information provided by this control interface was clear.	0.04	-0.08	0.94
Information	11	The information on the control interface was effective in helping me complete the tasks.	-0.02	0.17	0.85
Information	12	The organization of information on the control interface was clear.	0.09	0.00	0.80
Reachability	13	I found it easy to access the control interface in its current position.	0.08	0.88	-0.07
Reachability	14	The position of the control interface was convenient for me.	-0.01	0.95	0.06
Reachability	15	The control interface's position was appropriate for the tasks I needed to perform.	0.04	0.92	0.01
Reachability	16	The control interface's position allowed me to interact with it without causing discomfort.	0.06	0.80	0.14

To assess the reliability of the modified PSSUQ in measuring the underlying factors, we calculated Cronbach's alpha. We examined reliability across three models: (1) the original subscale structure of PSSUQ v3, (2) the modified version with equal weighting of items, and (3) the modified version incorporating factor loadings. As summarized in Table 5.6, the modified questionnaire achieved high internal consistency across all configurations, comparable to the original PSSUQ. The Overall factor showed excellent reliability in both the original and equal-weighted modified versions (α = 0.94), with a slight improvement when factor loadings were applied (α = 0.95). The Ease of Use factor, aligned with the original System Quality subscale, also showed high internal consistency, achieving α = 0.90 in the original and equal-weighted models, and α = 0.93 with factor loadings. The Information factor improved slightly in the modified versions (α = 0.95) compared to the original Information Quality subscale (α = 0.91), indicating enhanced coherence within this dimension. Finally, the newly introduced Reachabilityfactor demonstrated excellent reliability (α = 0.96), confirming it as a stable and meaningful construct in this study and supporting its inclusion as a distinct usability dimension for evaluating lighting and shading control interfaces.

TABLE 5.6 Comparison of Cronbach's alpha values between the original PSSUQ (version 3), the modified PSSUQ questionnaire with equal weighting across items, and the modified PSSUQ questionnaire incorporating factor loadings.

Subscales	Cronbach's α (PSSUQ v3)	Cronbach's α (Modified PSSUQ, equal item weights)	Cronbach's α (Modified PSSUQ, factor loadings)
Overall	0.94	0.94	0.95
System Quality (Ease of use in this study)	0.90	0.90	0.93
Information Quality	0.91	0.95	0.95
Interface Quality	0.83	(Not evaluated)	(Not evaluated)
Reachability (New factor in this study)	(Not applicable)	0.96	0.96

5.3.3 Usability Score per level of Reachability, Ease of Use, and Information

This section reports usability scores for each factor identified previously, along with the Overall Usability score, calculated as the average of all 16 items. We conduceted pairwise comparisons between scenarios to identify statistically significant differences. Figure 5.7 presents these results, displaying scores for Ease of Use (a), Reachability (b), Information (c), and the Overall Usability score (d).

As shown in Figure 5.7a, Ease of Use scores exhibited a rising trend from Scenario 1 (Analog, Wall, no cues) to Scenario 6 (Digital, Desk, System Cues). We found differences in Ease of Use between analog (Scenarios 1–3) versus digital (Scenarios 4–6) type of interfaces. For instance, Scenario 2 (Analog, Desk, No cues) and Scenario 4 (Digital, Desk, No cues) show the positive effect of switching to a digital interface, even when no additional cues were provided and the interface location was kept constant on the desk close to the participant.

When focusing on Reachability, as described in Figure 5.7b, participants rated wall-mounted (Scenario 1) and split-position interfaces (Scenario 3) lower than the desk-mounted scenarios (Scenarios 2, 4,5 and 6). A clear improvement was observed between Scenario 1 (Wall) and Scenario 2 (Desk), which represent the scenarios with analog interfaces and no system cues. High usability scores for desk-mounted interfaces were relatively consistent across both analog (Scenario 2) and digital scenarios (Scenarios 4, 5, 6), indicating that interface “Position” may have a stronger influence on Reachability than ease of use.

Usability scores for the Information factor increased as system cues were added (Figure 5.7c). Scenarios 1–4, which lacked cues, were consistently rated lower than Scenarios 5 and 6. This trend is clearly shown between Scenarios 4 and 5, where “Type of Device” and “Position” were kept the same, underscoring the positive effect of introducing feedback cues on occupant experience. However, no significant differences were noted between Scenario 5 (state cues) and Scenario 6 (state + task completion cues), showing that, once the required information level is provided to the occupant, a further increase in information level may not enhance the occupant experience.

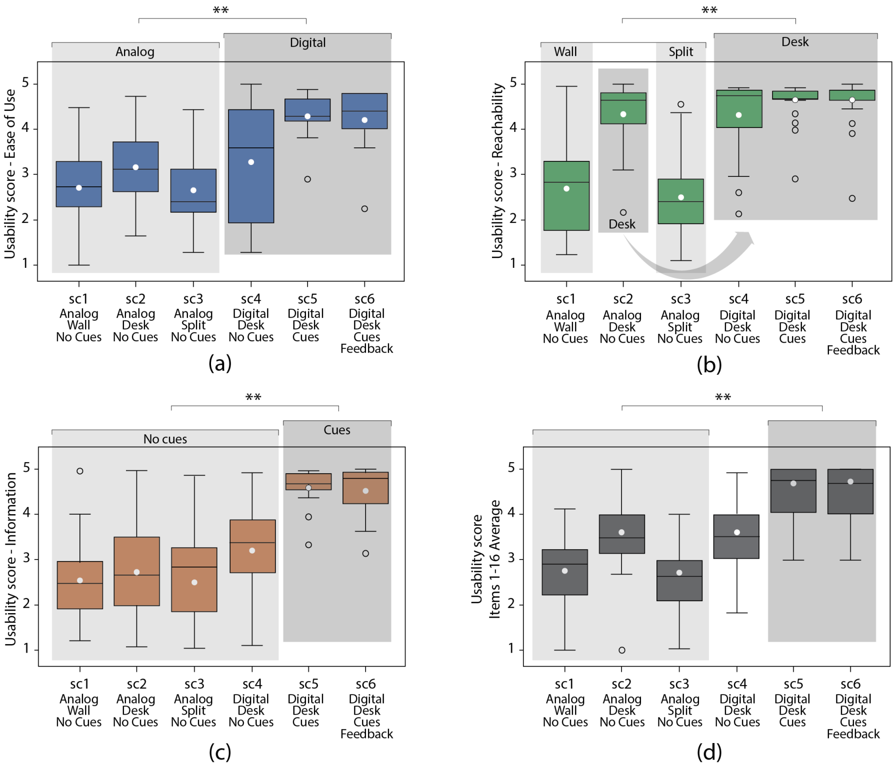


FIG. 5.7 Usability scores for Ease of Use (a), Reachability (b), Information (c), and Overall Usability score (d) across interface scenarios tested. ** = ($p < 0.01$).

Figure 5.7d presents the Overall Usability scores across the six interface scenarios. Pairwise comparisons revealed statistically significant differences ($p < 0.01$) for all contrasts between Scenarios 1-3 and Scenarios 5-6 (i.e., 1-5, 1-6, 2-5, 2-6, 3-5, 3-6). Scenarios 1 and 3, which used wall-mounted and split interfaces, respectively, scored the lowest. In contrast, Scenarios 5 and 6 used desk-mounted interfaces and received significantly higher satisfaction ratings. The analog interfaces in Scenarios 1 to 3 were consistently rated lower than the digital interfaces used in Scenarios 4 to 6, even when the position remained constant (e.g., Scenario 2 vs. 4). The evident differences emerged with the inclusion of system cues. Scenarios 5 and 6, which incorporated state and task completion cues, outperformed Scenarios 1 to 4, which lacked cues. The contrast between Scenario 4 (digital, desk, no cues) and Scenario 5 (digital, desk, state cues) isolates the strong positive effect of adding feedback cues.

5.3.4 Influence of Position, Ease of Use, and Information on Participants' Overall Satisfaction

In this section, we examine how the three usability factors relate to Overall Satisfaction, as measured by item 17 of the modified PSSUQ ("Overall, I am satisfied with the control interface - position, information, and type"). We do this to assess whether Ease of Use, Reachability, and Information also explain participants' overall satisfaction with the interfaces. As shown in Figure 5.8, we found strong and statistically significant positive correlations between all three factors and Overall Satisfaction (all $r > 0.65$, $p < 0.001$), with particularly high associations for Ease of Use ($r = 0.84$) and Reachability ($r = 0.80$). These results indicate that participants who rated these domains highly were more likely to report greater overall satisfaction with the control interfaces.

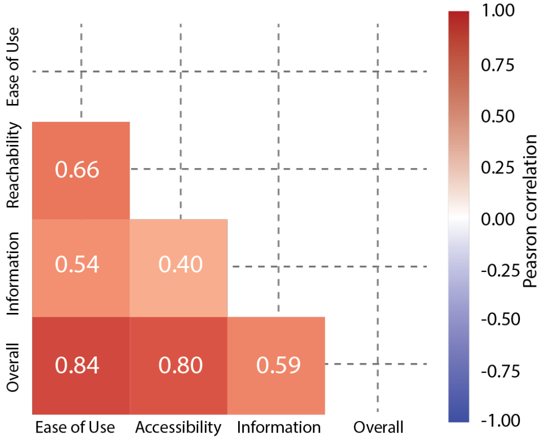


FIG. 5.8 Pearson correlation matrix showing relationships between the three usability domains, Ease of Use, Information, and Reachability, and Overall Satisfaction.

TABLE 5.7 Ordered logistic regression results for Overall Satisfaction. The rows represent the independent variables: Ease of Use, Reachability, and Information, as well as the threshold coefficients (1/2, 2/3, 3/4, and 4/5) indicating satisfaction category boundaries. The columns display the estimated coefficients (Estimate), standard errors (SD err), z-values (z), p-values (P>|z|), and 95% confidence intervals ([0.025, 0.975]).

Parameter	Estimate	SD err	z	p
Ease of use	1.831	0.430	4.26	$< .001$
Reachability	2.317	0.512	4.53	$< .001$
Information	0.597	0.256	2.33	0.020
1/2 threshold	6.944	1.435	4.84	$< .001$
2/3 threshold	1.668	0.225	7.41	$< .001$
3/4 threshold	1.702	0.207	8.21	$< .001$
4/5 threshold	1.260	0.207	6.10	$< .001$
Accuracy on test set: 0.722				

We then performed an ordered logistic regression model to examine the relationship between Ease of Use, Reachability, Information, and Overall Satisfaction(Item 17). The analysis indicates that Ease of Use (β = 1.831, p < 0.001) and Reachability (β = 2.317, p < 0.001) are significant predictors of Overall Satisfaction, while Information (β = 0.597, p = 0.020) had a comparatively smaller but still significant contribution. The full regression results are presented in Table 5.7.

5.3.5 Participant Preferences for Interface Variables After the Experiment

In this section, we report the results of the post-experiment questionnaire. After completing the usability test, participants answered a three-part questionnaire designed to capture different aspects of interface design for lighting and shading control (see Table 5.3). The questionnaire was divided in three section: (i) the first section captured baseline for laboratory setup preferences through single-choice questions and one ranking task, focusing on the three interface characteristics tested in the study: “Type of Device”, “Position”, and “System Cues”; (ii) the second section explored differences in preferences for interface characteristics for single and shared office setups, using Likert-scale statements to test trade-offs between convenience, occupant responsibility, and feedback clarity; (iii) the third section examined the influence of interface characteristics on acceptance of automation, asking whether specific features, such as “Type of Device”, “System Cues”, or “Position”, would make participants more comfortable with automated lighting and shading systems.

5.3.5.1 Laboratory setup preferences

Figure 5.9 presents participants' preferences for interface "Position", "System Cues", and "Type of Device". Regarding the preferred position for the lighting control interface (Figure 5.9a), the majority of participants (n = 12) favored having the interface on their desk, compared to the wall (n = 6), while no participants selected placement near the lighting fixture.

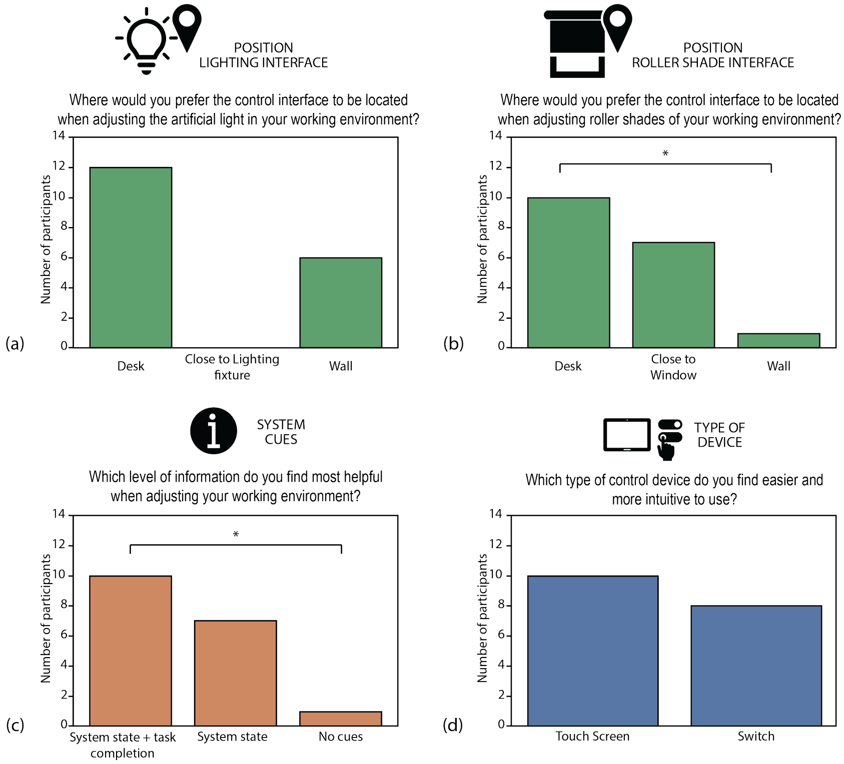


FIG. 5.9 Participant preferences for interface variables after the experiment. (a) Preferred position of the lighting control interface; (b) Preferred position of the shading control interface; (c) Preferred level of system feedback; (d) Preferred type of device. Bars indicate the number of participants; significance brackets represent Bonferroni-adjusted pairwise Chi-squared comparisons. * = ($p < 0.05$).

For shading controls (Figure 5.9b), preferences were more diverse. Although the desk remained the most preferred position (n = 10), close to the window was also selected (n = 7), and the wall was least preferred (n = 1). A pairwise comparison revealed a statistically significant preference for the desk over the wall for the roller shades interface ($p < 0.05$).

In terms of “System Cues” (Figure 5.9c), the most chosen configuration was system state with task completion feedback (n = 10), followed by system state only (n = 7). No cues configuration was least preferred (n = 1), and the difference between the most and least preferred options was statistically significant ($p < 0.05$).

Lastly, “Type of Device” preferences (Figure 5.9d) showed a relatively balanced distribution between touch screens (n = 10) and physical switches (n = 8), with no statistically significant difference.

Participants rated the importance of three interface attributes (“Position”, “System Cues”, and “Type of Device”) on a three-point scale (Not Important, Somewhat Important, Very Important). Figure 5.10 shows a bubble chart. Bubble size reflects the number of respondents at each attribute-by-importance cell, labels show counts (n), and colors indicate respondent groups that share the same ranking profile across attributes. The pattern concentrates at Very Important for “Position” (most participants placed it at the top), while “Type of Device” tilts toward lower importance (many chose Somewhat/Not Important and only a few marked it Very Important). “System Cues” sits between these extremes, with responses split mainly across Somewhat and Very Important. For context, in the underlying rankings, 14/18 participants placed “Position” first, 10/18 placed “Type of Device” last, and “System Cues” was divided (6/18 first, 6/18 second).

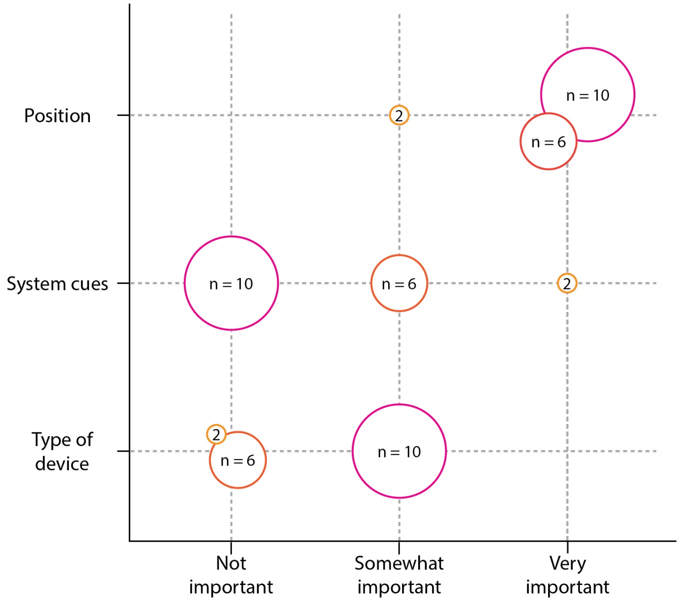


FIG. 5.10 Participant importance ratings for interface attributes. Bubbles show how many participants rated each attribute (Position, System cues, and type of device) at each importance level on the x-axis (Not important, Somewhat important, Very important). Bubble area is proportional to the number of respondents; labels show counts (n). Color encodes respondent groups that share the same importance ranking profile across attributes (equal ranks).

5.3.5.2 Differences in Preferences for Interface Characteristics for Single and Shared Office Setups

To further examine how participants' preferences might shift across different social contexts, the final questionnaire included items related to potential shifts in preferences when multiple occupants are present in the same office space. Figure 5.11 summarizes the distribution of preferred interface characteristics in the office lab setup (which mirrors a single office condition) and compares them to preferences expressed in a shared office context. Preferences are grouped by interface "Position", "Type of Device", and "System Cues", along with the percentage of participants whose selections matched across both contexts.

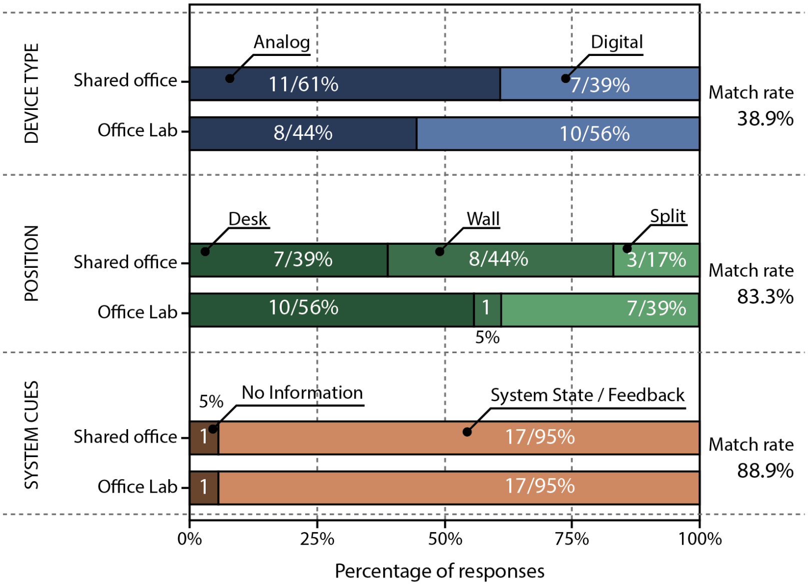


FIG. 5.11 Comparison of participants' interface preferences in office lab versus shared office settings across three attributes: "Position", "Type of Device", and "System Cues". The figure presents the number and percentage of participants who preferred each option in both settings (match rate).

For the interface "Position", most participants preferred a desk-mounted control in the single office setup (56%), whereas in a potential shared office context, preferences shifted toward wall-mounted interfaces (44%). The overall match rate for "Position" preferences was 38.9%, indicating that context significantly influenced participants' preferred interface "Position".

"Type of Device" preferences remained relatively consistent. Analog controls were selected by 44% of participants in the laboratory and increased to 61% in the shared office setup. Despite this shift, the match rate between contexts was high

(83.3%), suggesting that participants' preferences regarding the "Type of Device" (e.g., analog vs. digital) are less dependent on social context.

Preferences for "System Cues" were highly consistent: 95% of participants selected interfaces that provided system state and feedback cues in both the laboratory and shared office scenarios, while only one participant (5%) preferred no information. The resulting match rate of 88.9% reflects a strong and stable preference for "System Cues" across contexts.

5.3.5.3 Influence of Interface Characteristics on Acceptance of Automation

TABLE 5.8 Statements used in section 3 of the post-experiment questionnaire on automation acceptance. Participants rated their agreement on a 5-point Likert scale ranging from 1 (Strongly Disagree) to 5 (Strongly Agree).

Variables Tested for Their Impact on Automation Acceptance	Statements
Analog interface	I'd be less bothered by automation if it had a simple analog switch interface—like a familiar physical switch—giving quick, intuitive control of lights and roller shades without extra learning or mental effort.
Digital interface	I'd be less bothered by automation if it included a responsive touchscreen—enabling fluid interaction with lights and roller shades, and seamlessly integrating into the workspace.
Desk position	I'd feel less bothered by automation if lighting and roller shade controls were positioned on my desk within easy reach.
Wall position	I'd feel less bothered by automation if lighting and roller shade controls were mounted by the door, letting me set lights and roller shades as I enter the room.
Separated (split) position	I'd feel less bothered by automation if lighting and roller shade controls were separated—light switches by the door and shade controls by the windows—so I stay aware of each system throughout the room.
No information	I'd feel less bothered by automation if it were intuitive enough to need no status indicators or performance feedback for lighting and roller shades.
System information	I'd feel less bothered by automation if I could easily check its current state—like the shades' position or the lights' status.
System information and feedback	I'd feel less bothered by automation if it displayed its ongoing actions for lighting and roller shades and let me know once they're complete.

To assess which interface characteristics might promote a higher acceptance of automated lighting and roller shade controls, participants rated their agreement with statements shown in Table 5.8 about each characteristic on a 1–5 Likert scale (1 = strongly disagree, 5 = strongly agree). Figure 5.12 illustrates the distribution of these scores. Desk-mounted controls were viewed as most preferred, with a median of 4.0, whereas wall-mounted controls registered a median of 3.0, and the split layout (lighting at the entrance wall, shades by the window) scored lowest with a median of 2.0. In terms of “Type of Device”, both digital displays and analog dials achieved medians of 4.0, indicating equal overall acceptance. Finally, among system cues, system-state and feedback cues each reached a median of 4.0, while the no-info option stayed behind at 3.0. Altogether, these results suggest that occupants prefer interfaces that are within easy reach, employ familiar control formats, and provide clear system feedback.

To assess the likelihood that observed differences arose by chance, we applied Wilcoxon signed-rank tests to each within-subject pairing. Only the comparison between desk-mounted and split layouts reached statistical significance (W = 5.0, p = .039), confirming a reliable preference for desk placement over the split configuration. None of the other pairs, such as desk versus wall (p = .359), digital versus analog (p = .512), or any pairing among system-state readouts, generic feedback cues, and the no-info condition (all p > .37), attained the $\alpha = .05$ threshold.

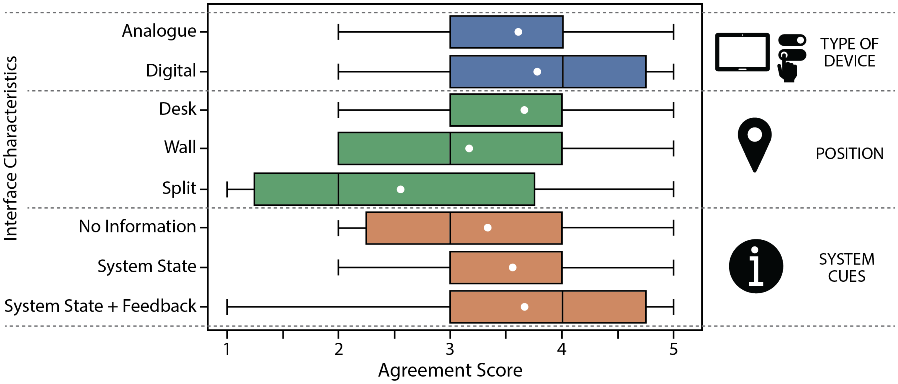


FIG. 5.12 Boxplots of 1–5 agreement scores for each interface feature (n = 18). Each panel shows the full distribution of participant ratings for (top to bottom) desk-, wall-, and split-mounted positions; digital versus analog devices; and system-state read-outs, feedback cues, or no information. Boxes show the interquartile range, whiskers the full range, and white circles the means.

5.3.6 Interview Results

This section presents qualitative insights from the pre- and post-experiment interviews, which provide context for and help validate the quantitative findings. The interviews explored participants’ expectations of control interfaces before the usability test and their perception after interacting with the six scenarios. By asking about the three interface variables tested through the experiment (“Type of Device”, “Position”, “System Cues”) the interviews showed how participants’ expectations changed through hands-on experience, offering explanations and nuances that complement the statistical results.

5.3.6.1 Type of Position

The examination of participants’ expectations versus experiences with control interfaces for lighting and roller shades reveals notable shifts in perception. Participants expected that the interfaces would be located near the entrance for lighting and close to the window for roller shades, with the expectation that these positions would significantly impact their satisfaction. One participant expressed this view, stating, “I would expect the switch next to the entrance for lights. The same for the shading, next to the entrance.” One participant mentioned this preference was related to convenience in reducing the number of items in the desk, “I like being closer to the door. I don’t think I need to interact regularly with the system. Having too many things on the desk is not convenient.” However, some participants also expressed that proximity to the interface was key for comfort and efficient interaction. For example, a participant noted that “…on the desk is the best position because of convenience. However, in a shared office, I would prefer the controls at the entrance.”

5.3.6.2 Level of Information

At the start of the experiments, participants expected minimal information on control interfaces, such as basic directional cues (e.g., up/down, increase/decrease brightness). One participant shared this expectation, stating, “I was expecting no information, only icons telling me what I am supposed to do. Maybe information about the system state, such as light brightness can be conveyed by the dial position easily.” However, their experience during the experiment demonstrated to a few of them that higher information levels and cues can enhance their overall experience. For instance, one participant noted, “I liked it when the system told me when I achieved the control task goal. I would like to have information on the impact of my behavior on the building performance.” Another participant supported this, saying, “I like the information about the system state. I feel I have more control if I have that information.”Additionally, some participants expressed a preference for further details on how their behavior influenced the building’s performance and indoor environment. As one participant commented, “I would prefer building performance information combined with my personal preferences.”

5.3.6.3 Type of Interface

Regarding the type of interface, participants preferred analog devices initially, such as switches and dials for lighting, and manual cords or switches for blinds. One participant reflected this preference, stating: “I would expect a blind controlled by a cord. If it is remotely controlled, I expect information on up and down state.” After using the interfaces during the experiment, a few participants reported preferring digital interfaces, because they offer interactive features and detailed feedback. As one participant commented, “I liked the percentages and the extra information about my task performance. With this information, I can set up my environment as I want.” Despite these comments, some participants continued to appreciate the simplicity of analog systems. One participant noted, “I liked the sliders, but I don’t like accuracy at that level. Every 10% of the adjustment option is better for me”. Furthermore, while simplicity was favored, participants found that having access to detailed information, despite its complexity, was beneficial. Another participant emphasized this, stating, “I liked having access to information. The better the information, the better my perception of control.” Overall, information is appreciated by occupants, but they also remarked several times that the level of information should be simple and useful, according to their expectations.

5.3.6.4 Acceptance of Automation

Concerns about automation were also noted, with participants seeking systems that were understandable and controllable. One participant expressed this clearly, stating, “Automation might be frustrating if I can’t understand it.”This underscores the need for interfaces that are both intuitive and integrative. Another participant highlighted the desire for control, remarking, “If I could understand the logic behind the automated control, I would accept it more.”Overall, the transition from expectation to experience demonstrated that while participants anticipated certain features, their actual satisfaction was significantly influenced by practical experience with the interfaces. One participant reflected this sentiment, saying, “I like the information. The better the info, the better my perception of the control.”

5.4 Discussion

This study demonstrates the applicability of the PSSUQ in the built environment domain by successfully adapting it to evaluate building control interfaces. The high internal consistency and robust factor structure, comprising Ease of Use, Reachability, and Information, indicates that usability in environmental control interfaces can be reliably measured using this approach. This aligns with earlier findings in human-computer interaction domains [195] while extending the utility of PSSUQ to a new application context.

During the experiment, we found a strong preference for control interfaces that provide clear system cues and are easily accessible, particularly those mounted on the desk. These interface characteristics achieved the highest satisfaction scores across all usability dimensions. Insights from the post-experiment interviews and questionnaires, however, suggest that while desk-mounted controls were preferred in the individual office lab setting, participants anticipated favoring wall-mounted configurations in shared offices. This reflects the influence of social norms, privacy considerations, and aversion to personal desk space. This context dependency, particularly regarding interface position, aligns with findings from previous studies that show spatial and social conditions shape interaction with building controls [178, 184, 187]. These results suggest that one-size-fits-all solutions may not be effective and highlight the need for adaptable or personalized control strategies. Although the information was not ranked as important as position (Figure 10), both the experimental results (Figure 7) and interview findings showed that information level supports a positive experience with the automation system when the information is relevant to the occupant's needs. However, occupants' perceived acceptance of automation did not appear to be influenced by the level of information provided. This finding should be verified through behavioral experiments that measure override behavior under varying levels of information, as there may be a discrepancy between perceived and actual acceptance. Other studies showed, for instance, that transparency and occupant understanding might mitigate the resistance often associated with automated building systems [178].

Regarding the type of device, participants showed a clear preference for the digital interface, primarily because it was the only option providing system-state information, as illustrated in Figure 7 (a). Notably, digital control interfaces that included such information were both preferred over analog interfaces without information and perceived as easier to use, particularly when equipped with explicit system-state cues. This finding reinforces previous research emphasizing the role of intuitive and informative interfaces in enhancing occupant satisfaction and facilitating behavior change [182, 186] . However, the preference for digital over analog controls also presents an important challenge. While digital or touch-based interfaces can deliver richer feedback, they may introduce accessibility barriers for certain occupant groups [202]. Hybrid solutions, combining physical elements (e.g., buttons or tactile feedback) with digital components providing system information, have been shown to improve both usability and inclusivity across domains [203]. It is important to note that these findings are specific to the controlled office-lab setting and may not directly generalize to real-world environments.

Participants' initial expectations for analog interfaces appeared to change over the course of the experiment. While they initially preferred simple analog controls, post-experiment feedback revealed a shift toward interfaces offering system feedback—hence, digital configurations. This evolution suggests that direct interaction with control interfaces can enhance understanding, perceived ease of use, and overall attitudes toward personal control and automation. Similar dynamics have been observed in previous studies, where hands-on testing or prolonged use prompted participants to revise their preferences toward more advanced, information-rich systems [204]. These results highlight the value of usability testing not only as an evaluation tool but also as a means of fostering occupant learning and managing expectations.

The diversity in participants’ ranking of interface characteristics, ranging from the importance of system feedback to a preference for simplicity, clearly indicates that participants’ needs are not uniform. This finding aligns with prior research showing that while some occupants value detailed system feedback and advanced control features [186, 204], others prefer simple, easy-to-use interfaces that minimize cognitive load [154]. These individual differences suggest that flexible or personalized control strategies may be necessary to accommodate varying occupant expectations and interaction styles.

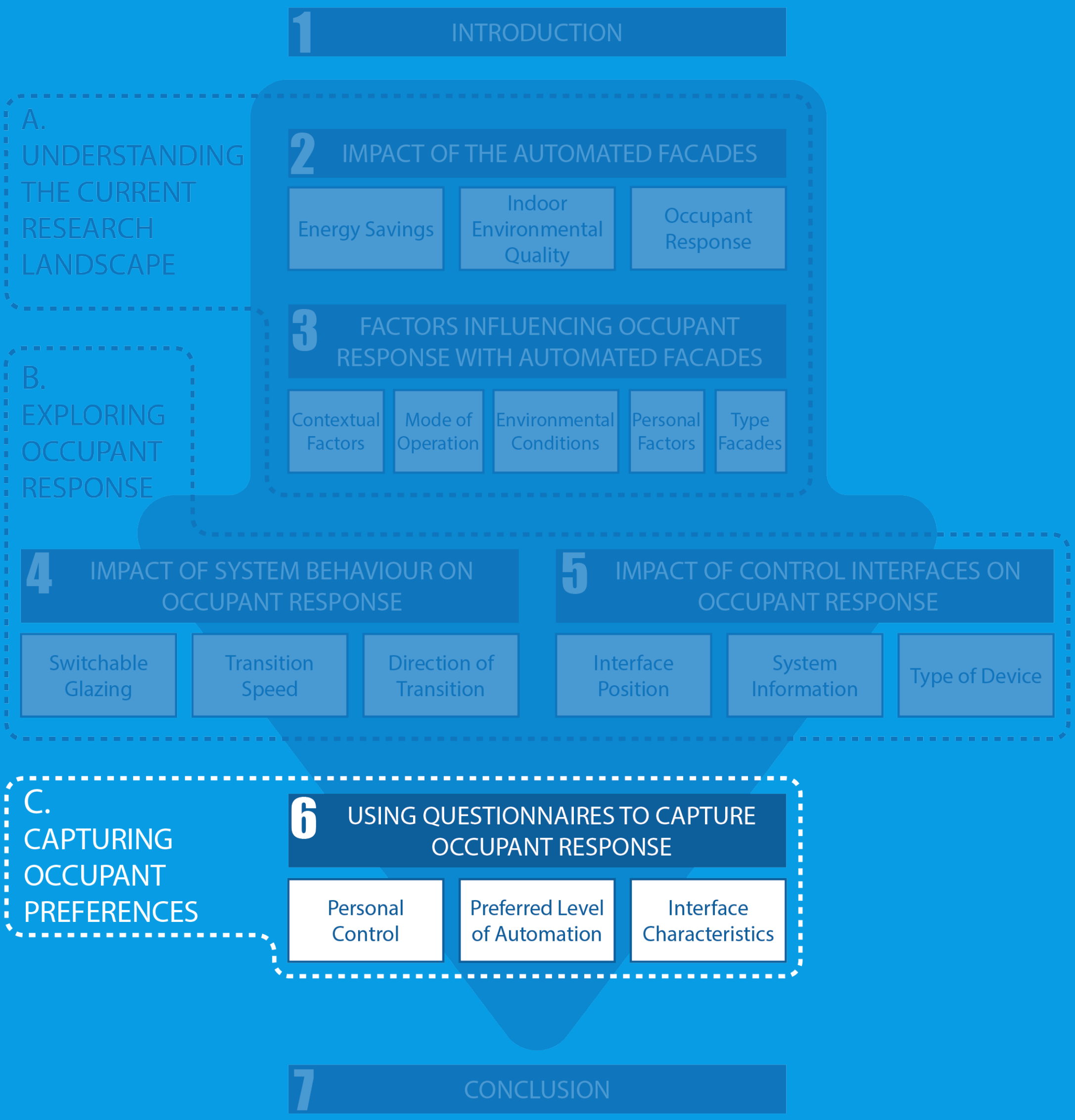
This study has several limitations. First, it was conducted in a single controlled office lab with 20 relatively young participants with technical expertise, which constrains the generalizability of the findings to other building types, occupant groups, and cultures. Second, the experiment focused on lighting and shading in a specific set of interface configurations, so the results may not extend to other building services or interface designs. Finally, preferences and acceptance of automation were measured using self-reported questionnaires in both the office lab and hypothetical shared-office scenarios, without observing long-term use or override behaviour in real shared spaces. Future research should therefore test similar interfaces in real multi-occupant offices, include more heterogeneous occupant groups, and combine usability ratings with behavioral measures of interaction and overrides over time.

5.5 Conclusion

In this study, we utilized the PSSUQ framework to investigate occupant experience with building control interfaces for lighting and shading, focusing on Overall Satisfaction related to “Type of Device”, “Position”, and “System Cues”. We first validated the PSSUQ’s suitability for this context, involving interaction strategies for lighting and shading in an office environment. This study represents a novel application of the PSSUQ, extending its use beyond traditional settings. Compared to other methods for evaluating building control strategies, our approach provided more detailed insights into participant requirements for Ease of Use,Reachability, and Information. The effectiveness of the methodology implemented in the office lab was due in part to its ability to encourage meaningful interaction with the interfaces during task-based scenarios. This resulted in more informed and consistent responses across participants. The alignment between quantitative findings and qualitative interview insights further strengthens the validity of the results and supports the robustness of the usability testing framework in this application.

The results showed higher preferences for desk-mounted, digital interfaces that provided clear system-state cues. These characteristics consistently received the highest usability scores across all dimensions and played a central role in participants' acceptance of automated building systems. Preferences for control interfaces varied based on contextual factors, such as whether the setting was private or shared, and individual characteristics, such as attitudes toward automation and expectations of simplicity. These findings underscore the importance of context-aware control strategies rather than one-size-fits-all solutions. Additionally, participants' expectations changed after interacting with the control interfaces during the experiment. Initial preferences for analog and simple solutions moved towards digital, information-rich systems. This shift highlights the role of empirical experience in influencing occupant preferences towards control interfaces.

Future work should further explore the influence of contextual variables (e.g., shared vs. individual space) and personal factors (e.g., familiarity, cognitive style) on occupant interface preferences. Moreover, research should investigate how different types and levels of system information impact occupant engagement with automation, comfort, and control in everyday use. These findings could inform the development of tailored HBI strategies that align with diverse occupant needs and support both indoor environmental quality and building performance.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6 Using Questionnaires to Capture Occupant Response

What Should Be Automated in Offices? Occupants' Preferences for Automation Levels from a Large Survey in Spain and the Netherlands

This chapter corresponds to a manuscript currently under review at Energy and Buildings.

This chapter operationalizes the dissertation's findings to address the overarching research question regarding occupant requirements and automation acceptance. Building on the problem space defined in Chapters 2 and 3 and the experimental evidence on interaction dynamics from Chapters 4 and 5, this study deploys a large-scale questionnaire to quantify occupant preferences. It assesses preferred automation levels across distinct workday phases, characterizes control desires for specific building services, and identifies concrete interaction requirements regarding interface type, position, and information. By translating experimental factors into measurable variables, this chapter provides population-level evidence on the consistency of occupant needs, validating generalizable requirements to inform future façade control strategies.

6.1 Introduction

Reducing operational energy use while maintaining acceptable indoor environmental quality (IEQ) remains a challenge for the building sector and a key pathway for climate-change mitigation [205]. In office buildings, where thermal conditions, ventilation, lighting, solar control, acoustics, and view/privacy jointly shape comfort and productivity, performance depends not only on technical system capabilities but also on how building services are operated in everyday use [206–208]. Research has progressively shifted toward occupant-centered building design and operation, in which energy and comfort outcomes depend on alignment between building controls, indoor environmental requirements, and occupants' preferences [17, 209]. Persistent discrepancies between predicted and measured building energy performance further reinforce the need to understand how occupants prefer building services to be controlled and what interaction conditions enable effective operation in practice [12, 154]. Accordingly, evidence on occupants' control preferences is essential for strategies that deliver both energy efficiency and acceptable user experience [147].

Advanced building control strategies, such as occupancy-based control, predictive control, and adaptive algorithms, are studied and, in many cases, deployed in building automation systems, shaping when, how, and by whom control decisions are made [21, 77, 135, 210, 211]. These strategies do more than control building services, they define the occupant's role in the control loop. Human-factors research on levels of automation conceptualizes automation as a spectrum of human involvement across information acquisition, interpretation, decision-making, and action, and shows that outcomes depend not only on the type of automated control strategy but also on feedback and the ability to intervene or override when needed [212]. In buildings, this implies that the same system described as automated can be experienced differently depending on whether the system communicates status and intent (e.g., cues, explanations, recommendations), whether it requests confirmation, and whether override is accessible and reliable [149, 209]. Consequently, developing a building control strategy requires clear specification of both the level of automation and the interaction mechanisms through which occupants remain informed and can influence outcomes, an issue central to occupant-centric design [17, 147, 154, 212].

Empirical studies on occupants' preferences for building automated control indicate that acceptance depends on two conditions. Automation should preserve meaningful occupant agency (e.g., the ability to intervene) and provide sufficient transparency for occupants to understand system state and actions [149, 213, 214]. Occupants often report annoyance of extremes control strategies (fully manual or fully automated) and instead preferring intermediate arrangements in which the system provides support (e.g., recommendations or automated actions) while maintaining confirmation and/or override opportunities [149, 213, 214]. In office settings, studies of automated blinds and façades frequently report deactivation of fully automated modes and identify perceived loss of control as a recurring barrier to acceptance [89, 90, 215]. Experimental work further shows that clearer feedback about system state and actions can improve satisfaction and support energy efficient operation, underscoring the role of transparency in automated building services acceptance [149]. A recent review of occupant-centric controls similarly emphasizes that successful implementation depends on interaction mechanisms that support comprehension and accessible intervention when automation conflicts with occupant needs [216]. Therefore, automated building services are more likely to be accepted when occupants can interpret system status and intent, anticipate automated actions, and intervene via straightforward override or adjustment when automated decisions do not match their requirements [89, 147, 149, 154].

A further implication of occupant-centered control is that preferred levels of automation are unlikely to be uniform across services or stable across time. Building services differ in how quickly they affect comfort, how noticeable their effects are, how reversible actions are perceived, and how disruptive automation may be during everyday work, which can influence whether occupants accept automation or prefer manual control [217]. Consistent with this, prior work shows that preferences for automated controls vary across occupants and across control contexts and systems, suggesting that a single automation level is unlikely to suit all situations [213, 214]. In offices, perceived personal control is linked to satisfaction and comfort, but varies across buildings and user groups, indicating that personal control is not experienced consistently in practice [215, 218, 219]. At the service level, studies comparing manual and automated strategies for blinds and lighting report differences in discomfort and acceptability, illustrating that the same automation policy can be experienced differently depending on the system and context [89, 90, 149]. In addition, field studies show that interactions with controls can cluster around workday-phases, with some actions (e.g., manual window opening) occurring frequently at the start of the day, suggesting that control needs are shaped by routines as well as discomfort [220]. Office studies also report workday-phases use of heating-related personal controls (e.g., thermostat/TRV interactions and setpoint-related actions) and building control concepts often operationalize occupancy transitions through preheating and setback periods [21, 23, 210]. A systematic review of user-centered lighting controls also highlights that variability in working hours and occupant routines is often poorly represented by fixed schedules and default control logics [221]. However, this evidence remains fragmented across single services and heterogeneous constructs, and rarely captures the stated preferences for automation levels across multiple services and workday phases using a consistent scale, limiting practical guidance for offices on what to automate, to what extent, and when occupants want to be involved [89, 149, 154, 213, 214].

Even when buildings provide manual control or override, these features may not enable effective interaction if controls are difficult to reach, unclear, or provide limited feedback about system state. A review of building control interfaces reports recurring usability problems across windows, blinds, thermostats, and lighting (poor labeling, inconvenient placement, ambiguous control–effect mapping, and weak system-state cues) often leading to under-use, misuse, and workarounds that can undermine comfort and energy performance [154]. Field monitoring and test in offices confirm that the interface through which occupants interact influences control behavior for lighting and shading [212, 222]. Thermostat research similarly shows that interface complexity and poor information constrain understanding and contribute to ineffective use of control features [223, 224], while work on operable windows highlights the value of direct, immediate agency for comfort regulation [225]. Large post-occupancy datasets further indicate that dissatisfaction frequently co-occurs with perceptions of limited personal control, suggesting that control can be experienced as absent even when options exist [215, 218, 226–228]. Interface design also conditions automation acceptance. Studies of automated blinds show higher acceptance when automation is intelligible and straightforward to intervene in, and when explicit feedback is provided about system state and actions [23, 149]. Office lighting research likewise emphasizes that user-centered control concepts only succeed when implemented through interaction mechanisms that fit office routines and constraints [187, 221, 229]. These findings indicate that interface characteristics are central to whether automation and manual control policies are usable and acceptable in practice [149, 154, 187, 212, 221].

However, despite the growing emphasis on occupant-centered control, research still lacks a coherent, comparable evidence base on how office occupants prefer different building services to be automated and on the interaction requirements that make automation workable in everyday office routines. Existing studies provide valuable insights into specific systems and contexts, but they rarely compare explicit levels of automation across a broad set of building services using a consistent assessment scale, test whether preferred automation varies across workday phases, and jointly assess interface preferences that shape how easily occupants can understand and intervene in automated operation [89, 149, 154, 213–216, 218]. In practice, these gaps leave human–building interaction strategies under-specified. Control algorithms may be technically sophisticated yet misaligned with occupants' preferred role in control, while inadequate interface design can make feedback and override difficult to access and thereby undermine the mechanisms that support trust and acceptance [25, 147, 149, 154].

This study addresses these gaps using a large-scale questionnaire of office occupants in the Netherlands and Spain. We map preferred levels of automation across three workday phases (arrival, while working, leaving) and ten building services using a five-point ordered response scale ranging from fully manual control to recommendation-based support and automated control with varying notification and override conditions. We also assess the preferred interface characteristics (device type, interface position, and information level) to identify interaction requirements that support acceptable automation and practical intervention. The aim is to provide evidence for office automated control strategies that reflect service- and workday phase-specific preferences and can be implemented through usable, informative, and accessible interfaces.

6.2 Methodology

6.2.1 Study design and recruitment

This study is based on responses to an online questionnaire distributed to office workers in the Netherlands and Spain. Participants were recruited through a Dutch online survey sampling provider. Eligibility was restricted to adults who reported working in an office environment. Quality control procedures included minimum completion-time thresholds, attention-check items, and consistency checks using repeated questions at different points in the questionnaire. Only respondents who passed all checks were retained. In total, 3,504 respondents provided valid responses and country information (NL = 1,870; ES = 1,634). Participation was voluntary and respondents could withdraw at any point by closing the browser.

The study protocol, including the questionnaire and procedures, was approved by the Human Research Ethics Committee of Delft University of Technology (ID 3515). Participants gave their informed consent by ticking an agreement box before accessing the first survey page.

TABLE 6.1 Overview of questionnaire sections, main constructs, and response formats.

Section	Main constructs	Response format
Demographics	Age, Sex, Education, Country of residency	Single-choice
Office context	Location, work frequency (days/hours), desk type (fixed/flex)	Multiple-choice & numeric
Environmental context	Floor level, layout, window proximity, noise/view satisfaction	5-point Likert & descriptive
Current building services	Availability of 10 services (HVAC, lighting, etc.) and current automation level	Binary (Yes/No) & multi-selection
Automation preferences by workday phase	Desired control during arrival, while working, and leaving	5-level automation scale (manual to full auto)
Automation preferences by building service	Desired control level for 10 specific building services	5-level automation scale (manual to full auto)
Interface preferences	Preferred type (analog/digital), position, and information level	Single-choice

6.2.2 Questionnaire structure and content

The questionnaire covered five domains: (i) Demographics, (ii) office context, (iii) environmental context, (iv) current building services, (v) automation preferences by workday-phase, (vi) automation preferences by building service, and (vii) interface characteristics preferences. Table 6.1 summarizes the main constructs and response formats. The distributed questionnaire is provided in Appendix B.

6.2.3 Statistical analysis

6.2.3.1 Descriptive statistics

We first summarized automation preferences across workday phases, building services, and interface characteristics using absolute frequencies and row-normalized percentages (i.e., percentages summing to 100% within each category), complemented by data visualizations.

6.2.3.2 Workday-phase shifts in preferred automation

To test whether the same respondents expressed different automation preferences across workday phases ("arrival" vs. "while working"; "while working" vs. "leaving"), we treated responses as paired (within-respondent) categorical data. For each adjacent phase pair, we constructed a square contingency table that cross-tabulates automation levels at phase 1 (rows) against phase 2 (columns). These tables (i) provide a complete summary of transitions between categories (e.g., from "manual" to "automated-with-override") and (ii) serve as the standard input for paired multi-category tests and agreement metrics [230]. To visualize these within-person transitions across the three-phase sequence, we plotted an alluvial diagram in which bar segments show marginal distributions at each workday-phase and flows represent respondents moving between automation levels from one phase to the next.

We quantified within-respondent stability using weighted Cohen's kappa (κ), which measures agreement beyond chance while accounting for the ordinal nature of the five-level scale (disagreements of one step within the scale are treated as smaller than disagreements of several steps) [231]. To test whether changes show a systematic direction on the ordered scale, we recoded the five response options as ordinal scores from "fully manual" to "fully automated" and applied Wilcoxon signed-rank tests to paired phase responses. This non-parametric test is appropriate for ordinal outcomes and paired observations and evaluates whether responses tend to shift upward (toward more automation) or downward (toward more manual control) [232, 233]. We report effect size as $r = Z/\sqrt{N}$, where Z is the standardized Wilcoxon statistic and N is the number of paired observations.

As complementary, distribution-based checks that do not require ordinal scoring, we applied (i) the Stuart–Maxwell test of marginal homogeneity to assess whether the overall distribution of automation levels differs between two phases for the same respondents [234], and (ii) Bowker's test of symmetry to assess whether transitions are directionally balanced (e.g., whether from "manual" to "automated" control transitions occur as often as the reverse) [235].

6.2.3.3 Service-specific preferences for automation

For each of the ten building services, we summarized the distribution of preferred automation levels. To test whether the same individuals expressed different preferences for conceptually related services (e.g., heating vs. air-conditioning; indoor vs. outdoor shading), we conducted within-respondent pairwise comparisons using the Stuart-Maxwell test applied to square contingency tables [234], adjusting p-values for multiple comparisons using Holm's method [236]. These paired tests isolate service effects from between-respondent differences in the sample.

To characterize cross-service heterogeneity, we derived respondent-level profiles based on each respondent's pattern across the ten services: Manual (only manual-type levels), Automated (only automated-type levels), and Mixed control (a combination of manual and automated levels). To interpret the Mixed control profile, we decomposed preferences within this subgroup by calculating, for each service, the percentage distribution across the five automation levels.

6.2.3.4 Predictors of preferring higher automation

To identify factors associated with preferring higher automation, we estimated proportional-odds ordinal logistic regression models [237]. The outcome is the five-level automation preference scale, ordered from "fully manual" to "fully automated." Separate models by phase and by service allow associations to differ depending on when (workday phase) and what (building service) is being automated.

Model results are reported as odds ratios (OR) with 95% confidence intervals (CI). In this study, ORs indicate whether a predictor is associated with a greater tendency to select higher automation categories (OR> 1) or lower (more manual) categories (OR< 1), holding other variables constant. We checked the proportional-odds assumption using standard diagnostics [238]; where minor deviations were observed, we interpret ORs as average effects across thresholds.

6.2.3.5 Associations among interface attributes and interface type

To examine whether interface attributes are chosen independently, we tested associations among preferred interface type ("digital" vs. "analog"), position ("close to entrance"/"on the desk"/"close to the system"), and information level (ordered cue options). We first quantified overall pairwise associations between attributes using χ^2 tests of independence and report Cramér's V as effect size [230].

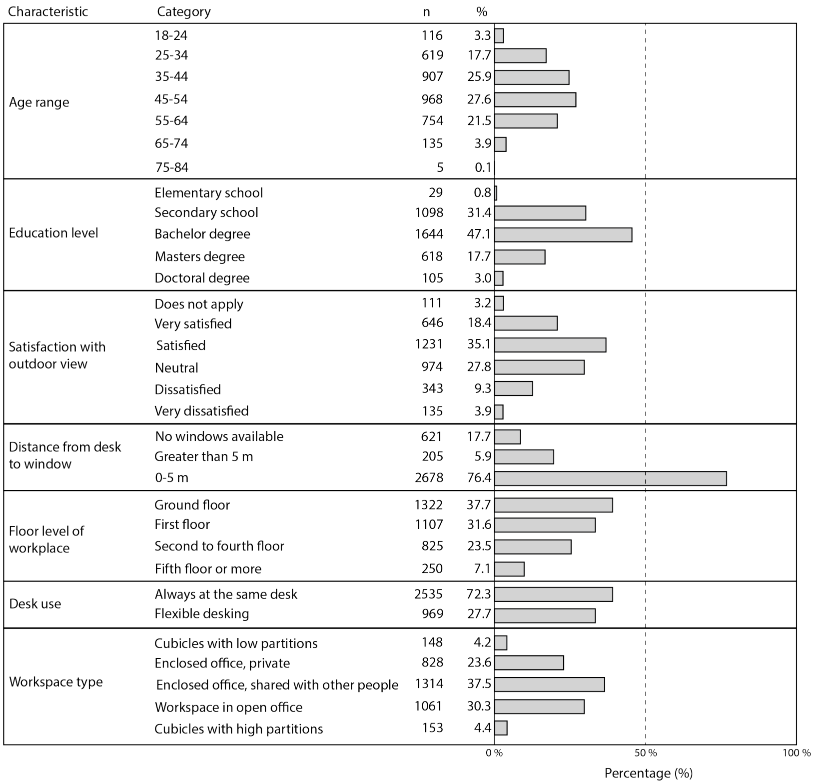
To identify which specific combinations drive these global associations, each attribute level was recoded as a binary indicator (selected vs. not selected), and we tested all level-by-level pairings across attributes using 2×2 contingency tables, reporting the signed ϕ coefficient as effect size [230]. P-values for these multiple level-by-level tests were adjusted using a Bonferroni correction [236].

To quantify how information level and position jointly relate to choosing a "digital" interface, we estimated a binary logistic regression with interface type as the outcome ("digital" = 1; "analog" = 0), excluding "no preference" responses [230]. Information level was entered as an ordered predictor and interface position as a categorical predictor (reference = "close to entrance"). Coefficients were exponentiated to ORs with 95% CIs. For interpretability, we also plotted the observed proportion choosing a digital interface across information levels, stratified by interface position.

Finally, to test whether respondents who prefer higher automation also tend to prefer different interface designs, we assessed associations between preferred automation level ("while working") and each interface characteristic (type, position, information level) using χ^2 tests with Cramér's V effect sizes, excluding "no preference" responses [230].

6.3 Results

6.3.1 Respondent characteristics and workspace context



Characteristic	Category	n	%
Age range	18-24	116	3.3
	25-34	619	17.7
	35-44	907	25.9
	45-54	968	27.6
	55-64	754	21.5
	65-74	135	3.9
	75-84	5	0.1
Education level	Elementary school	29	0.8
	Secondary school	1098	31.4
	Bachelor degree	1644	47.1
	Masters degree	618	17.7
	Doctoral degree	105	3.0
Satisfaction with outdoor view	Does not apply	111	3.2
	Very satisfied	646	18.4
	Satisfied	1231	35.1
	Neutral	974	27.8
	Dissatisfied	343	9.3
	Very dissatisfied	135	3.9
Distance from desk to window	No windows available	621	17.7
	Greater than 5 m	205	5.9
	0-5 m	2678	76.4
Floor level of workplace	Ground floor	1322	37.7
	First floor	1107	31.6
	Second to fourth floor	825	23.5
	Fifth floor or more	250	7.1
Desk use	Always at the same desk	2535	72.3
	Flexible desking	969	27.7
Workspace type	Cubicles with low partitions	148	4.2
	Enclosed office, private	828	23.6
	Enclosed office, shared with other people	1314	37.5
	Workspace in open office	1061	30.3
	Cubicles with high partitions	153	4.4

FIG. 6.1 Sample and workspace characteristics of the respondent population. Data is grouped by variable (age range, education level, satisfaction with the outdoor view, distance from desk to window, floor level of workplace, desk use, and workspace type), with categories listed within each group.

On average, respondents worked 3.5 days per week in the office and 7 hours per day at the workplace. The sample was broadly balanced by sex assigned at birth (female $n = 1{,}795$; male $n = 1{,}680$; prefer not to say $n = 16$). As shown in Figure 6.1, most of the respondents were middle-aged adults (predominantly 35-54 years) most had at least secondary education and nearly half reported a bachelor's degree. Satisfaction with the outdoor view was generally moderate to high, and most respondents sat relatively close to a window (76.4%), typically on the lower floors (ground floor = 37.7%; first floor = 31.6%). the workspace configurations were oriented toward fixed and shared settings: 72.3% reported working at the same desk (vs. 27.7% flexible desking), and 76.4% worked in enclosed shared offices or open-plan desk areas (vs. 23.6% private offices or cubicles).

Figure 6.2 provides the baseline context for what respondents can actually control in practice. Heating, air-conditioning, and lighting were the most widely available services (reported as available by 76% for heating and 72% for air-conditioning and lighting). For heating and air-conditioning, current control was split across "manual", "semi-automated", and "fully automated" control modes, indicating that respondents are exposed to heterogeneous control strategies even for the same service. Lighting was more often "manual" (45%), although a large number reported "automated" lighting (21%). Mechanical ventilation was frequently not available or not perceived as an available system (76% "not available"). When present, mechanical ventilation was predominantly "automated". In contrast, openable windows were available to 56% of respondents and were almost exclusively "manual" (52%), suggesting that window opening remains the main occupant-driven means to affect fresh air and thermal conditions. Shading was comparatively scarce (indoor shades available to 29%; outdoor shades to 35%) and, when available, tended to be "manual". Personal devices were rare (task lights 19%, personal fans 12%, personal heaters 7%) and predominantly "manual". Overall, several occupants report limited access to shading and personal devices, implying fewer opportunities to fine-tune comfort beyond a small set of simple manual actions (e.g., switching lights, opening windows).

	☐ Not available	🟧 Manual	🟩 Semi	🟥 Auto
Heating	23.9 %	27.9 %	20.0 %	28.3 %
Air-conditioning	27.9 %	30.0 %	16.0 %	26.1 %
Mechanical ventilation	76.3 %	3.3 %	2.9 %	17.5 %
Openable window	43.7 %	52.2 %	1.5 %	2.7 %
Indoor shadings	71.0 %	14.4 %	5.1 %	9.4 %
Outdoor shadings	64.6 %	29.8 %	2.5 %	3.0 %
Artificial lighting	27.9 %	44.9 %	6.1 %	21.0 %
Task lights	81.4 %	16.1 %	0.8 %	1.8 %
Personal fans	87.8 %	10.8 %	0.5 %	0.9 %
Personal heaters	93.4 %	5.9 %	0.4 %	0.4 %

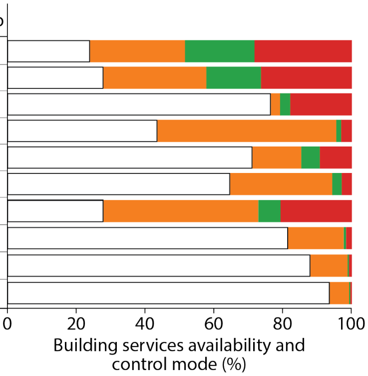


FIG. 6.2 Availability and current control mode of building services in respondents' workplaces. Rows list building services, and stacked bars show the share of respondents for whom each service is not available, manually controlled, semi-automated, or fully automated.

6.3.2 Preferred level of automation across workday phases and predictors

Figure 6.3 summarizes (i) the distribution of preferred automation levels at "arrival", "while working", and "leaving", and (ii) within-respondent changes between workday phases. At "arrival", respondents were evenly split between "manual" and "automated" control options (50% vs. 50%). The share preferring some form of automation increased slightly "while working" (52%) and was highest at "leaving" (54%). This shift is concentrated within the automated response options: "automated-no override" increased from 10% at "arrival" to 20% at "leaving", while "fully manual" decreased from 44% to 41% and "manual with notifications" from 6% to 5%.

The transitions represented in Figure 6.3 show that most respondents retained the same preference across workday phases on the five-point automation scale (ranging from fully manual to automated control with varying notification and override conditions), while a minority changed. However, Wilcoxon signed-rank tests indicate systematic within-respondent shifts toward higher automation from "arrival" to "while working" ($p = 2.34 \times 10^{-7}$, $r = 0.17$) and from "while working" to "leaving" ($p = 1.30 \times 10^{-10}$, $r = 0.27$). From arrival to while working, 15.1% moved at least one step toward higher level of automation and 10.9% moved toward lower automation (net +4.2%). From "while working to leaving", 19.2% moved toward higher level of automation and 10.4% moved toward lower automation (net +8.8%). Agreement between adjacent phases remained high (weighted $\kappa = 0.782$ and 0.718), indicating that preferences are largely stable overall. Nonetheless, when respondents do change, shifts occur more often toward higher automation later in the workday.

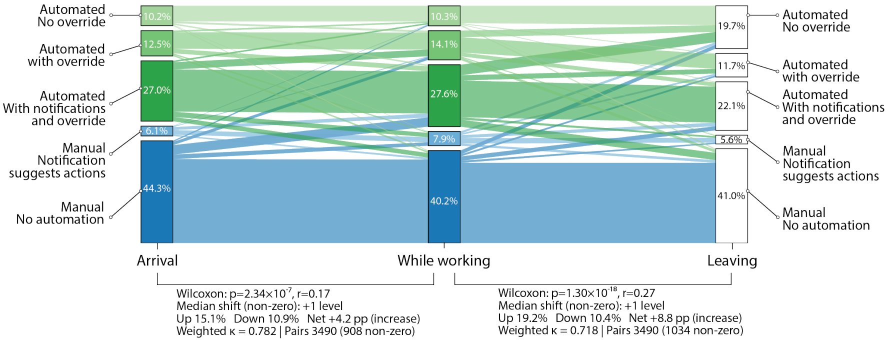


FIG. 6.3 Preferred automation levels at three workday phases (arrival, while working, and leaving). Bar segments show the share of respondents selecting each automation level, while the connecting streams represent individual transitions between stages (upward flows indicate moves toward more automation, downward flows toward more manual control). Summary statistics beneath each pair of stages report Wilcoxon signed-rank tests, effect sizes, proportions moving up or down the scale, and weighted agreement (κ) between stages.

Building on Figure 6.3, Figure 6.4 classifies respondents into workday-phase preference profiles: Manual (the same manual-type option at all three phases), Automated (the same automated-type option at all three phases), and Mixed control (any change across phases). Most respondents exhibited stable phase-to-phase preferences: 78.3% were classified as Manual (37.9%) or Automated (40.4%), while 21.7% were classified as Mixed control. In particular, 35.4% preferred "fully manual" control at every workday phase. Within the Automated profile, choices that preserved occupant agency (override and/or feedback) were most common, whereas "fully automated" control with no override represented the smallest automated subgroup (9.9%).

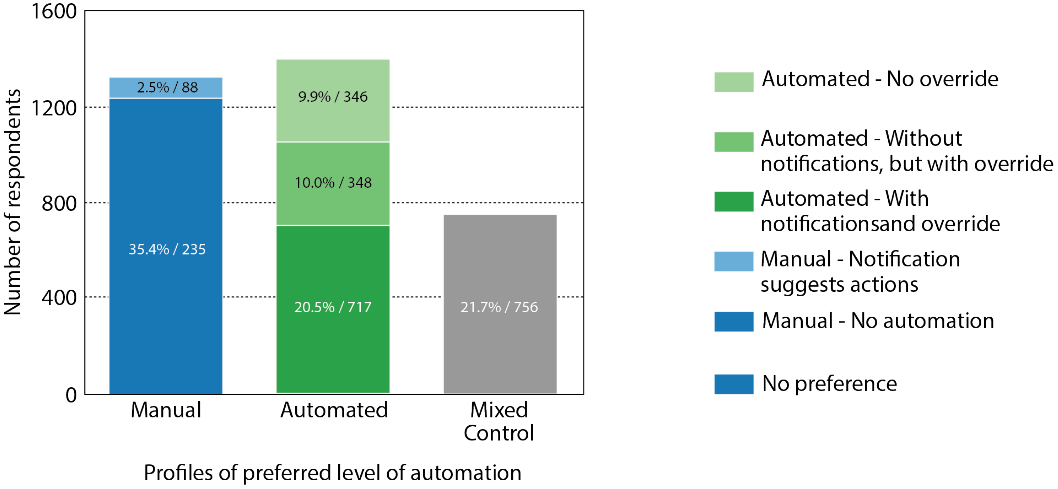


FIG. 6.4 Number of respondents per preference profile: (i) Manual (manual at all workday phases), (ii) Automated (automated at all stages), and (iii) Mixed (preferences vary across workday phases).

To examine which factors are associated with preferring higher automation at each phase, Figure 6.5 reports odds ratios (ORs) from ordinal logistic regression models estimated separately for "arrival", "while working", and "leaving" (OR > 1 indicates higher odds of selecting a more automated control option; OR < 1 indicates higher odds of selecting a more manual control option). Across workday phases, prior experience with automated services is consistently associated with higher odds of preferring automation (ORs typically > 1), whereas prior experience with manual control is associated with lower odds (ORs typically < 1). Workspace characteristics show smaller but systematic associations: private offices tend to reduce automation preference, while shared offices and flexible desking tend to increase it, particularly during "while working" and "leaving". Demographic effects (e.g., country, gender) tend to fall near the "small-effect" band, indicating limited practical impact relative to experience- and workspace-related predictors. Overall, familiarity with automated controls emerges as the most consistent correlated parameter of preferring automation across the day.

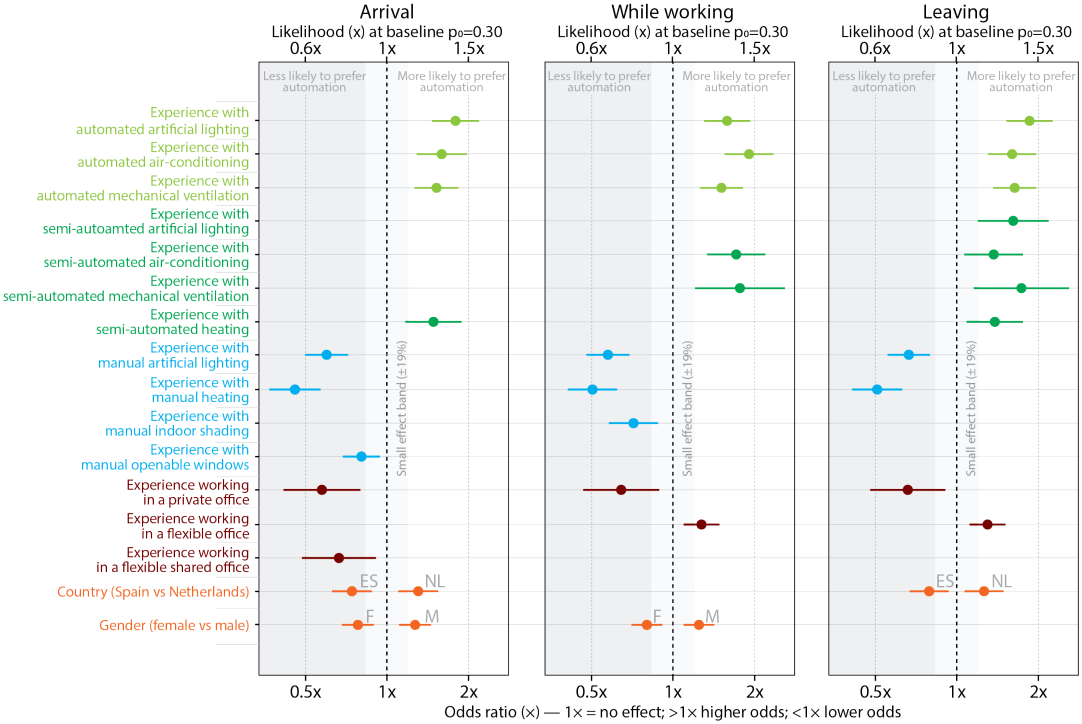


FIG. 6.5 Predictors of preferred automation across workday phases. Odds ratios (OR; points) with 95% confidence intervals (bars) from ordinal logistic regression models estimated separately for the Arrival, While working, and Leaving workday phases. OR values > 1 indicate higher odds of selecting a higher automation level (i.e., preferring more automated options), whereas OR values < 1 indicate lower odds (i.e., a shift toward more manual options), relative to the reference category while holding other predictors constant. The grey band denotes an approximate small-effect region around OR $= 1$ (about ± 5 percentage points in predicted probability at the baseline probability $p_0 = 0.30$). Predictors are color-grouped by domain: prior automated experience (green), prior manual experience (blue), workspace characteristics (dark red), and demographics (orange).

6.3.3 Preferred level of automation by building services and predictors

Figure 6.6 shows that preferred automation levels vary by building service, describing a clear gradient from HVAC to personalized environmental control systems. Personalized environmental control systems (task lights, personal fans, personal heaters, and openable windows) exhibit the strongest preference for "fully manual" control: 67% for task lights, 70% for personal fans, 69% for personal heaters, and 68% for openable windows. Shading and lighting occupy an intermediate position, with "fully manual" control still dominant but with substantial number of respondents preferring automation when override and/or notifications are available. In contrast, HVAC services show the preferred choice as "automated" control. For heating and air-conditioning, "fully manual" control accounts for 39% and 41%, respectively, and the most common automated choice is "automated with notification and override" (29% and 28%). Mechanical ventilation stands out as the building services preferred mostly automated, with the lowest "fully manual"share (35%) and the highest "fully automated" share (19%). Pairwise comparisons (horizontal brackets) confirm that these differences are not only visual. Most service pairs differ significantly in how preferences are distributed across the five control levels ($p < 0.05$), with non-significant results mainly occurring between closely related services (e.g., heating vs. air-conditioning). Across services, "notification suggests manual actions" remains a small minority (approximately 5–7%).

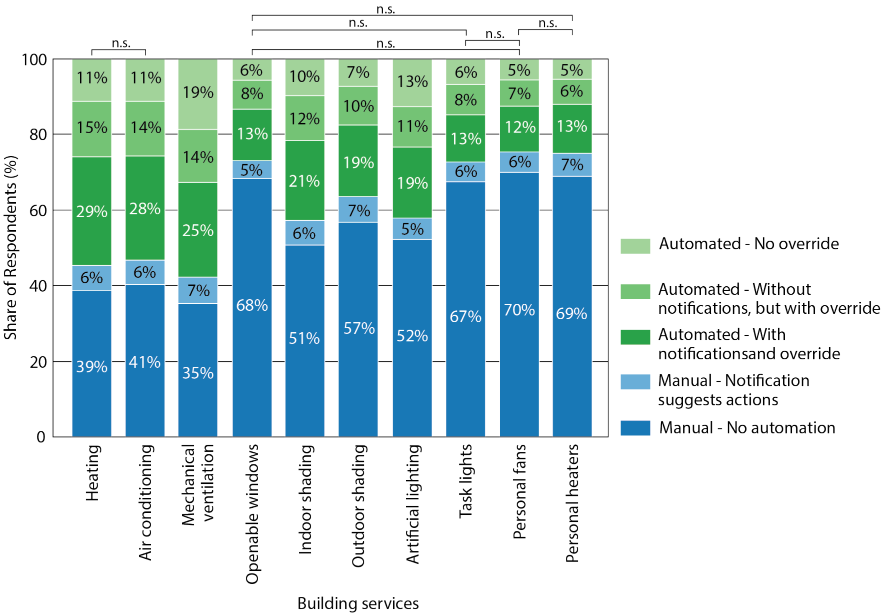


FIG. 6.6 Preferred level of automation by building service. Horizontal brackets indicate pairwise comparisons of the distributions across services; "n.s." denotes no statistically significant differences ($p \geq 0.05$), whereas no brackets indicate statistically significant differences ($p < 0.05$).

Figure 6.7(i) shows the profiles of respondents across building services: Manual (same manual option for all services), Automated (same automated option for all services), and Mixed control (preferences vary by service). The Mixed control profile is the largest group (61.5%, $n = 2{,}241$), while consistent Manual profiles (27.3%, $n = 994$) are more common than consistent Automated profiles (11.2%, $n = 410$). Figure 6.7(ii) decomposes the Mixed control profile by building service. Even among respondents who vary their preferences across services, HVAC remains mainly preferred "automated" (mechanical ventilation: 78% selecting an automated control option; heating: 72%; air-conditioning: 69%). Shading and lighting sit in the middle (indoor shading: 49% "manual" vs. 51% "automated"; lighting: 51% "manual" vs. 49% "automated"), while outdoor shading remains predominantly "manual" (60% "manual"). Personal devices and operable elements remain strongly "manual" within this mixed group (task lights: 77% "manual"; openable windows: 79%; personal heaters: 81%; personal fans: 82%).

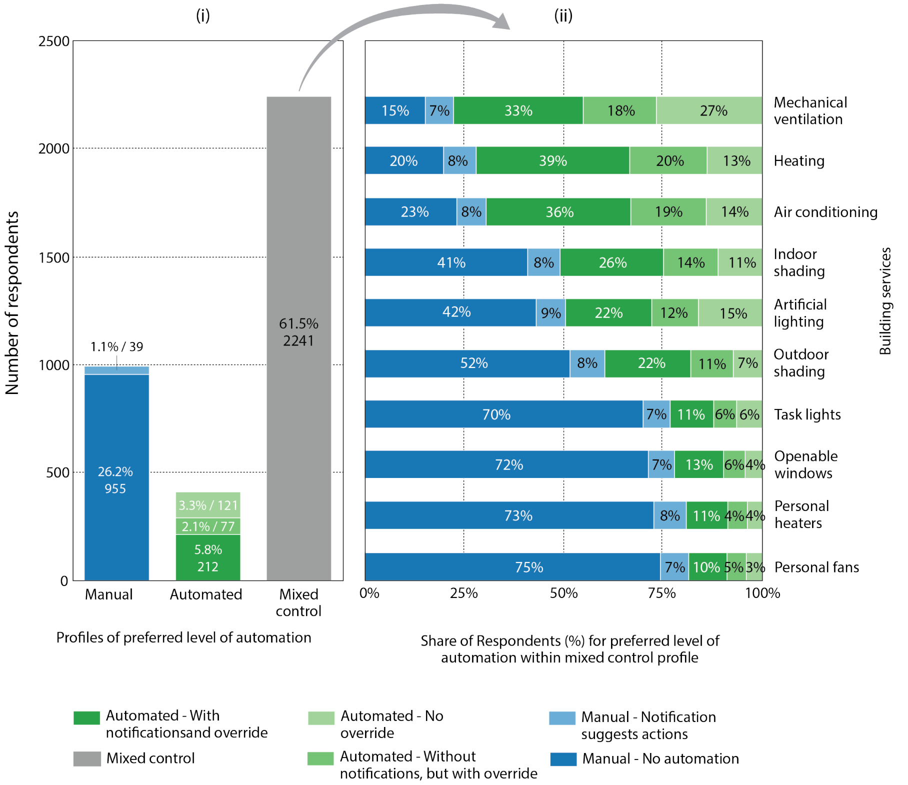


FIG. 6.7 Profiles of preferred automation and decomposition of mixed-control preferences by building service. (i) classifies respondents according to whether they choose the same automation level for all services ("Manual" or "Automated") or vary their choice across services (Mixed control). (ii) Decomposition of "Mixed" profile by building service.

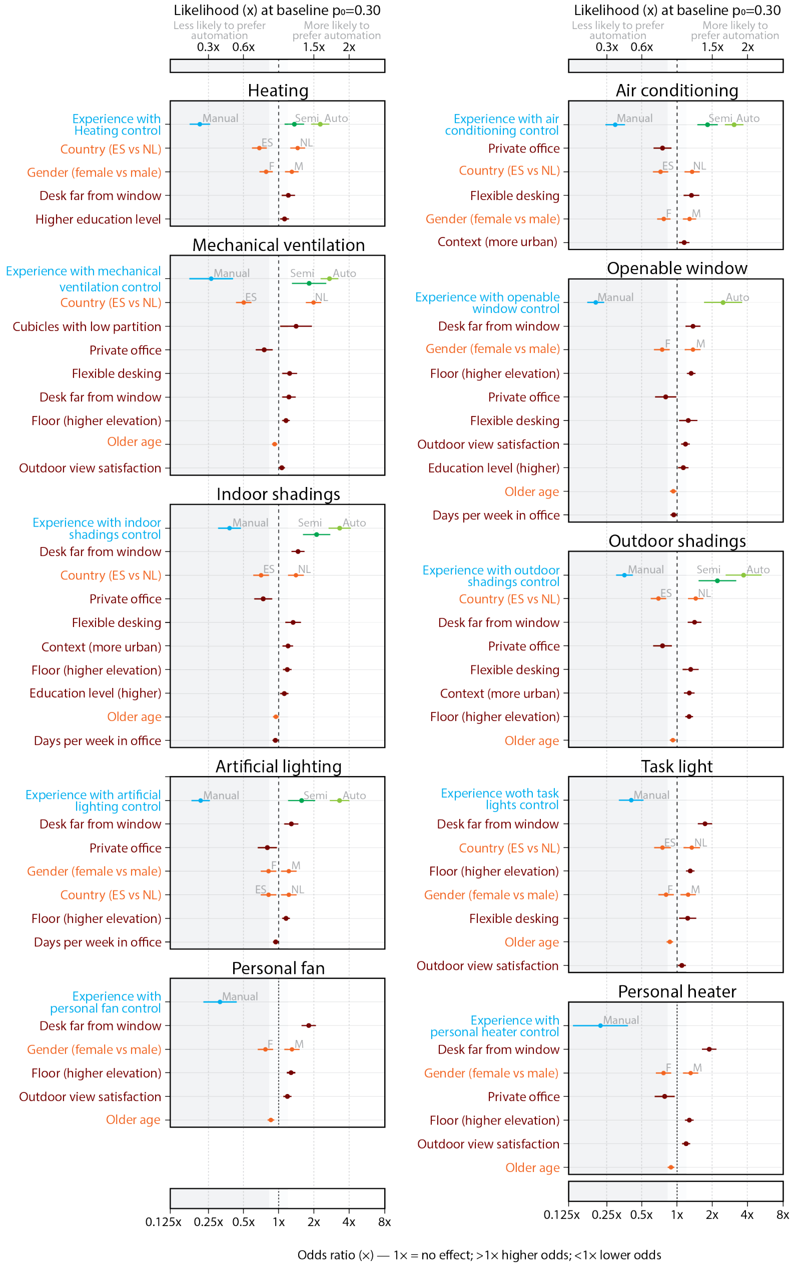


FIG. 6.8 Building service–specific predictors of preferring higher automation. Odds ratios (points; 95% confidence intervals, bars) from ordinal logistic models estimated separately for each service. The dashed vertical line marks no effect (OR = 1 ×). The top scale shows the corresponding change in likelihood at a baseline probability $p_0 = 0.30$. Colors group predictors: prior experience with the same service (blue = manual, green = semi- or fully automated), workspace characteristics (dark red), and demographics (orange). Values to the right of 1 × indicate higher odds of choosing a more automated option, and values to the left indicate lower odds.

To examine why automation preferences differ by building service, we fitted separate ordinal logistic regression models for each service (Figure 6.8). ORs summarize whether a factor is associated with a greater tendency to select higher automated control levels (OR > 1) or more manual options (OR < 1). Across building services, prior control experience shows the most consistent association. Predominantly prior manual control experience is linked to lower odds of preferring higher automated control, while prior semi-/automated experience is linked to higher odds, with the strongest effects for HVAC and clear patterns also for openable windows. Workspace characteristics show smaller associations (private offices generally lower automated control preference; flexible/shared desking higher), and desk distance to the window is most relevant for façade-proximate services (openable windows and shading), where greater distance corresponds to higher odds of preferring automation. Demographic effects are modest. Spain (vs. the Netherlands) typically shows ORs below 1 (often excluding 1), and when gender effects appear they indicate slightly lower automated control preference among women.

6.3.4 Preference for control interface characteristics

Figure 6.9 summarizes respondents' preferred interface characteristics. For interface type, respondents leaned toward "digital devices" (43%), followed by "analog devices" (33%), with 25% reporting "no preference". For interface position, the most common preference was "next to the entrance" (37%), followed by "on the desk" (28%). Fewer respondents preferred controls "close to the system" (19%) or reported "no preference" (17%). For information level, preferences concentrated on providing some feedback. "Basic cues" (27%) and "system status" (24%) were most frequent, whereas richer information options were less common ("status+suggestions" = 14%; "status+suggestions+feedback" = 10%). "No cues" (13%) and "no preference" (12%) were least selected.

To test whether these interface attributes are chosen independently, we assessed pairwise associations among type, position, and information level using χ^2 tests with Cramér's V effect sizes ($N = 2{,}322$). Interface type showed the strongest association with information level ($\chi^2(4) = 340.2$, $p < .001$, $V = 0.38$), followed by a moderate association with position ($\chi^2(2) = 99.3$, $p < .001$, $V = 0.21$). The association between position and information was weaker ($\chi^2(8) = 117.3$, $p < .001$, $V = 0.16$).

Figure 6.10 decomposes the overall associations among interface type, position, and information level into level-by-level relationships using signed ϕ coefficients (cell-wise association strength and direction; stars indicate significance). The strongest and most coherent pattern links digital interfaces with desk-reachable and information-rich designs. "Digital" co-occurs with "on the desk" position ($\phi = +0.16^{***}$) and with higher information levels, particularly "status+suggestion+feedback" ($\phi = +0.18^{***}$). In contrast, analog interfaces show

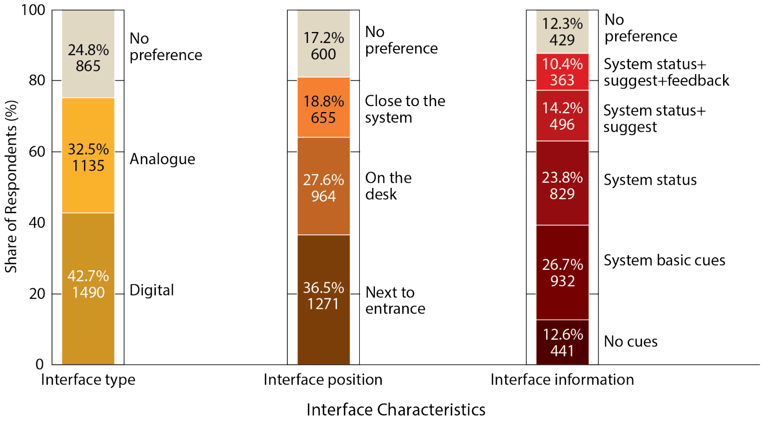


FIG. 6.9 Number of respondents' preferences for interface type ("digital", "analog", "no preference"), interface position ("next to the entrance", "on the desk", "close to the system", "no preference"), and interface information level ("no cues", "basic cues", "system status", "status + suggestions", "status + suggestions + feedback", "no preference").

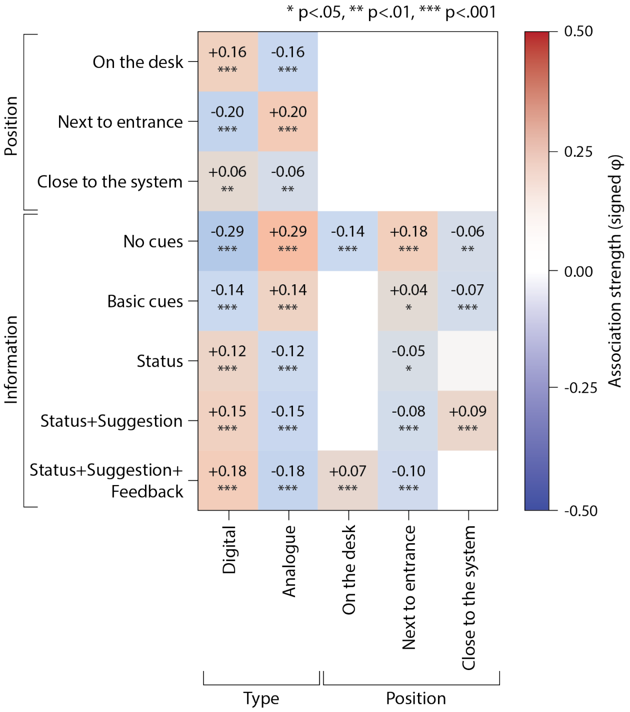
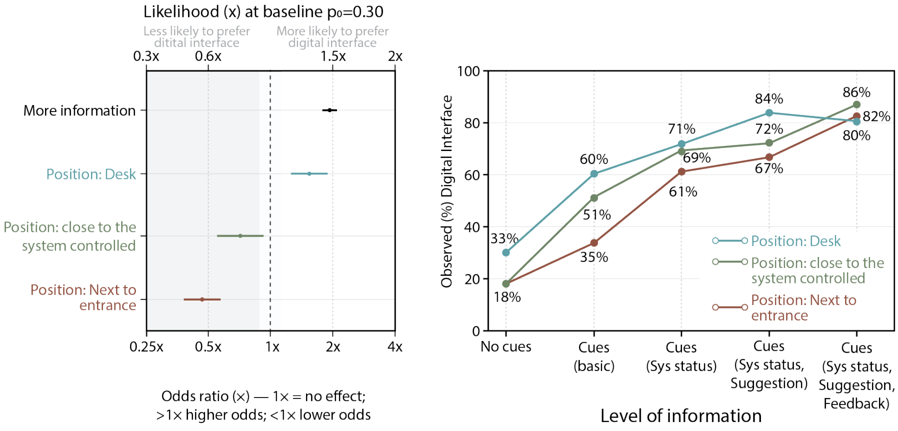


FIG. 6.10 Level-by-level associations between interface type, position, and information. Cells show signed ϕ coefficients from 2×2 contingency tables (N = 2,322), with positive values (red) indicating that two levels co-occur more often than expected by chance and negative values (blue) indicating under-representation. Asterisks denote statistical significance (* $p < .05$, ** $p < .01$, *** $p < .001$).

the complementary configuration, co-occurring with "next to entrance" position ($\phi = +0.20^{***}$) and with minimal information (in particular "no cues", $\phi = +0.29^{***}$). Position-information associations are generally smaller, but remain directionally consistent with these configurations (e.g., "no cues" with "next to entrance", $\phi = +0.18^{***}$; "status+suggestion" with "close to the system", $\phi = +0.09^{***}$). Overall, the heatmap indicates two coherent interface configurations: (i) digital-desk-information and (ii) analog-entrance-basic cues.

Figure 6.11 examines predictors of choosing a "digital" (vs. "analog") interface, consistent with the patterns suggested by the association matrix. Figure 6.11(i) reports odds ratios from a logistic regression model. Two effects stand out. First, higher level information is strongly associated with choosing "digital" interfaces (OR > 1), indicating that respondents tend to pair digital devices with interfaces that display system status, suggestions, and feedback. Second, interface position differentiates "digital" versus "analog" choices: desk-mounted controls are associated with higher odds of choosing "digital", whereas entrance-mounted controls are associated with lower odds (i.e., a shift toward analog).

Figure 6.11(ii) shows the observed proportions and illustrates the joint pattern across positions. The share selecting a digital interface increases with higher level of information for all three positions, and remains highest for desk-mounted interfaces (33% for "no cues" increasing to 82% for "system status, suggestion, feedback"), followed by interfaces close to the controlled system (18% to 86%), and lowest for entrance-mounted interfaces (18% to 80%). Taken together, these results reinforce a coherent "digital-reachable-information" configuration, while analog choices associate with entrance-mounted and basic information options.



(i) (ii)

FIG. 6.11 Predictors of choosing a digital interface. Left: Odds ratios (points; 95 % CIs) from a logistic model predicting digital vs analog as a function of information richness and interface position; the dashed line marks OR=1× and the header notes the baseline probability $p_0 = 0.30$. Right: Observed share choosing digital (%) by information level, stratified by position (Desk, Close to the system, Next to entrance). Digital preference increases with information and is highest for on-desk placement, intermediate near the system, and lowest at the entrance.

6.3.5 Associations between preferred automation level and interface characteristics

We examined whether interface preferences are associated with respondents' preferred automation level during the "while working" phase, which we use as the primary indicator of preference for automated control. Responses of "no preference" for interface characteristics were excluded. Figure 6.12 presents three plots showing, for each automation level, the share of respondents selecting each option for (i) interface type, (ii) interface position, and (iii) information level; Cramér's V summarizes the strength of the χ^2 association in each plot.

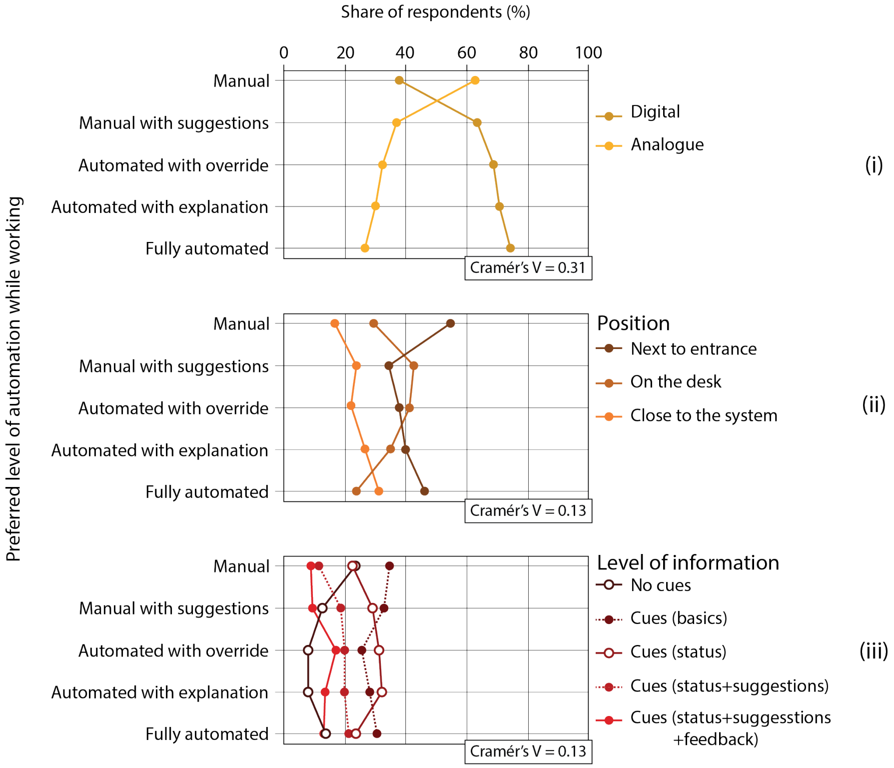


FIG. 6.12 Distribution of preferred interface options within each preferred automation level during the "while working" phase ("no preference" responses excluded). Points/lines represent observed shares of respondents selecting each interface option across automation levels. For each panel, Cramér's V summarizes the overall strength of association between automation preference and the corresponding interface characteristic (effect size from the χ^2 test of independence; $V = 0$ indicates no association and larger values indicate stronger association).

For interface type, Figure 6.12(i) shows a clear shift toward "digital" interfaces as respondents prefer higher levels of automation. Among those preferring "fully manual" control, 38% prefer "digital" interfaces and 62% prefer "analog" devices, whereas among those preferring "fully automated" control, 74% prefer "digital" and

26% prefer "analog". This pattern corresponds to a moderate association between automation preference and interface type (Cramér's $V = 0.31$).

For interface position, Figure 6.12(ii) shows smaller differences across automation levels. Among respondents preferring "manual" control, 54% prefer controls "next to the entrance", 30% "on the desk", and 16% "close to the system". For automation with override, preferences are more evenly distributed (38%, 41%, and 22%, respectively), and for "fully automated" control they are 46%, 23%, and 31%. Because entrance-mounted controls remain common across all automation levels and shifts across positions are modest, the association is weak (Cramér's $V = 0.13$).

For information level, Figure 6.12 also indicates a weak association. "Manual" control preferences are more often paired with minimal feedback (23% "no cues"; 35% "basic cues"), whereas automation with override is more often paired with higher level information (36% "status+suggestions+feedback"). However, the distributions overlap substantially across automation levels, so the overall association, while statistically significant, remains weak (Cramér's $V = 0.13$).

6.4 Discussion

Overall, our findings challenge the idea that office occupants have a single, stable preference for automation. When preferences are considered jointly across workday phases and building services, most respondents fall into a "mixed-control" profile, indicating that an acceptable control strategy depends on what is being controlled and when control decisions take place. This aligns with occupant-centered automation research showing that preferences and acceptance are context- and task-dependent rather than fixed individual characteristics [14, 22, 239, 240], and it provides quantitative support for control designs that differentiate across services and routines.

With respect to workday phases, most respondents selected the same automation level at "arrival", "while working", and "leaving", indicating substantial within-respondent stability. However, among the minority who changed their preference, shifts toward more automated options were more common than shifts toward more manual options from "arrival" to "leaving", yielding a tendency toward higher automation at the end of the workday. This should not be interpreted as a continuous increase in preference over time. Rather, it indicates that the distribution of preferred automation levels differs across workday phases. This phase dependence is consistent with previous evidence showing that occupant interactions with building services are structured by office routines and occupancy transitions, and it suggests that automated control strategies may need to account for workday phases (e.g., different support at arrival vs. active work vs. leaving) instead of relying on a single default interaction and control strategy [25, 241–243].

Preferences also differ strongly by building service. HVAC-related services (especially mechanical ventilation, followed by heating and air-conditioning) show the highest number of respondents preferring automated control, whereas personal devices and directly operable elements (task lights, personal fans/heaters, and openable windows) are predominantly preferred as "fully manual". Shading and artificial lighting occupy an intermediate position: many respondents still prefer manual control, but a substantial number accepts automation when it preserves agency through override and/or provides clear notification. Together, these results indicate that automated control strategy should be treated as a service-specific design decision rather than a single global "manual" versus "automated" policy, consistent with earlier evidence on service-dependent perceptions of responsibility and control [23, 109, 154].

Across services, prior control experience shows the most consistent association with preferring higher automation levels. Respondents who have previously experienced a service operating in a semi-/automated control mode are more likely to prefer automated control for that service, whereas those familiarized to manual control tend to prefer manual control strategies. This pattern is strongest for HVAC (heating, cooling, and ventilation) and is also evident for openable windows and lighting. This supports an interpretation of automation preference as partly experience-based: preferences for different levels of automation may reflect learned expectations about whether automation is reliable and useful for a particular service, and whether manual interaction is effective and worth retaining. This aligns with evidence from automation and smart-home research linking prior experience with automated systems to greater trust, acceptance, and willingness to use automation again [14, 214, 244].

Finally, results on preference for interface highlight that occupants do not perceive interface characteristics independently. Instead, respondents tend to select coherent interface configurations, in particular "digital + desk + information-rich" configuration and a complementary "analog + entrance + low-information" configuration. Moreover, interface preferences relate systematically to preferences for automation: respondents who prefer higher automation more often select digital and information-rich interfaces, whereas respondents that prefer manual control more often select analog and low-information configurations. This suggests that increasing automation without improving the interface may be counterproductive: as occupants rely more on system automated control logic, accessible controls and clear information become essential to support transparency and preserve personal environmental control. Conversely, for services that occupants prefer to keep manual, simple and robust interfaces may be sufficient. These findings reinforce that occupant-centric automation is not only about control logics, but also about providing interaction mechanisms (reachability, ease of use, and system cues) that make automation acceptable within everyday office routines [109, 149, 154, 214]. This pattern further supports the role of perceived control as a central factor in automation acceptance. Interface configurations that provide clear system cues and low-effort access to control may not only improve usability, but also reinforce occupants' sense of being able to influence outcomes when needed. In this sense, perceived control functions as a bridge between interface design and acceptance of automated operation, helping explain why similar control strategies can be experienced differently depending on how interaction is structured.

An important consideration when interpreting these findings is the distinction between stated preferences and actual behavior. While the survey captures how occupants report wanting to interact with automated systems, experimental evidence in this dissertation (Chapters 4 and 5) shows that real-time responses to automated actions can differ, particularly under conditions of perceived loss of control or disruption. For example, occupants may express acceptance of automation in abstract terms, yet still intervene when system behavior conflicts with immediate needs or expectations. Therefore, the results of this chapter should be interpreted as indicative of preferred interaction conditions rather than direct predictions of in-situ behavior, reinforcing the importance of combining survey-based and experimental approaches in occupant-centered control research.

This study has limitations. It is based on stated preferences collected in a cross-sectional survey, and actual in-situ behavior (particularly overrides under real discomfort, glare, noise, or social constraints) may differ. While we distinguished workday phases, we did not track individuals longitudinally or link preferences to measured indoor conditions, control actions, or energy outcomes. The sample is limited to office workers in two European countries and may not represent other cultural or building contexts. Finally, the reported relationships are associative rather than causal.

6.5 Conclusion

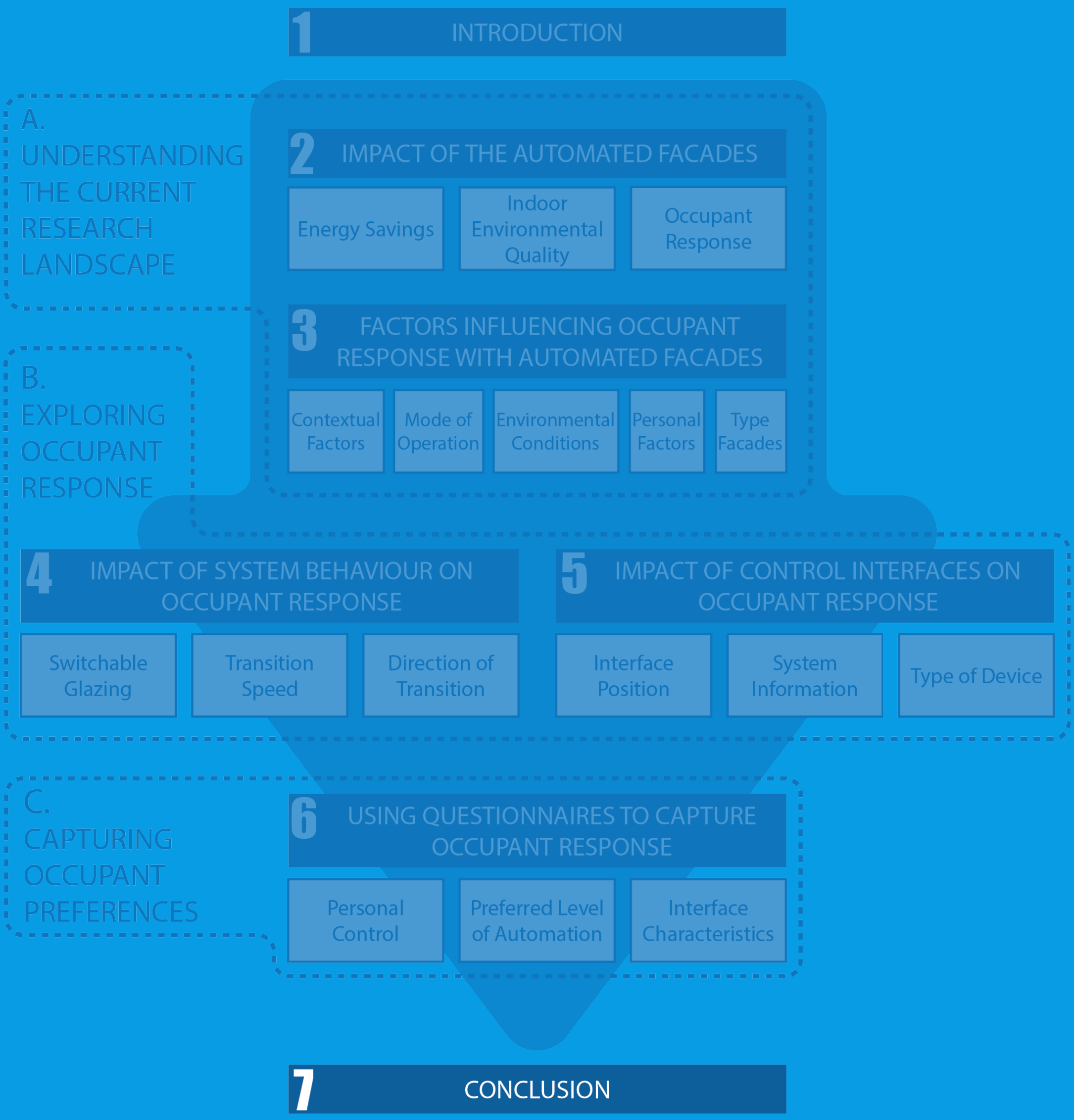
Using an online questionnaire with 3,504 office workers in the Netherlands and Spain, this study quantified preferred automation levels for ten building services across three workday phases and examined how these preferences relate to interface type, interface location, and information provision. The results show that automation preferences in offices are not random, they are structured, context-dependent, and actionable for both design and building operation.

Three patterns stand out. First, preferences shift modestly over the workday phases, with highest preference for automation during the "leaving" phase, suggesting that predictable transitions are moments when occupants are most willing to delegate control. Second, preferences are strongly service-specific. Background services such as mechanical ventilation and heating are widely preferred as automated, especially when occupants can override. Directly reachable and highly personal systems, including openable windows, task lights, and personal heaters and fans, are strongly preferred manual. Third, most respondents display a “mixed” profile, varying their preferred automation by both phase and service rather than consistently choosing “manual” or “automated.” This indicates that heterogeneity is a key signal to design for, not noise to average out.

Individual experience and workspace context further shape these preferences. Familiarity with automated control of a given service is consistently associated with a higher willingness to preferred automation again, while habitual manual operation aligns with a desire to keep that service manual. Workspace arrangements also matter. Private offices tend to be associated with lower preference for automation, whereas shared and flexible desk environments show greater tolerance for delegating control, pointing to social and organizational influences on comfort management. Interface preferences are similarly patterned. Respondents tend to select coherent configurations, in particular a “digital, desk-reachable, information-rich” combination, over an “analog, entrance-located, low-information” combination, and stronger automation preference is associated with choosing digital, information-rich, desk-reachable controls.

These findings argue against one-size-fits-all automation policies. In practice, occupant-centered control strategies should be phase-specific and service-specific, and they should explicitly accommodate mixed user profiles. A practical translation is to prioritize automated modes with transparent override for room-level services that occupants are willing to delegate (particularly ventilation and thermal conditioning) while keeping control of openable windows, personal heaters, personal fans, and task lighting in occupants’ hands. Automation support can be increased during predictable transitions (e.g., preparing to leave) when willingness to delegate is highest. Finally, control interfaces should be aligned with these interaction expectations. Placing information-rich digital interfaces within easy reach at the desk is consistent with automated operation that still preserves meaningful intervention through accessible override and clear system-state cues. For both new-build and retrofit projects, such differentiated strategies are more likely to support energy goals while reducing conflict and preserving perceived agency.

Future work should therefore move from stated preference to field validation and mechanism testing. Two directions are particularly promising. First, longitudinal field studies that log control actions and overrides, alongside indoor environmental conditions and energy use, can test how workday phase- and service-specific preferences translate into real behavior and performance. Second, the individual drivers identified here can be extended with psychological constructs (such as personality traits, perceived agency, trust in automation, and control beliefs) to explain why some occupants accept delegation while others resist it, and how interface cues and transparency moderate that relationship. Together, these steps would support the development of adaptive control strategies that learn from interaction, tailor automation by service and context, and deliver energy benefits without sacrificing comfort or occupant personal control.



1 INTRODUCTION

A. UNDERSTANDING THE CURRENT RESEARCH LANDSCAPE

2 IMPACT OF THE AUTOMATED FACADES

- Energy Savings
- Indoor Environmental Quality
- Occupant Response

3 FACTORS INFLUENCING OCCUPANT RESPONSE WITH AUTOMATED FACADES

- Contextual Factors
- Mode of Operation
- Environmental Conditions
- Personal Factors
- Type Facades

B. EXPLORING OCCUPANT RESPONSE

4 IMPACT OF SYSTEM BEHAVIOUR ON OCCUPANT RESPONSE

- Switchable Glazing
- Transition Speed
- Direction of Transition

5 IMPACT OF CONTROL INTERFACES ON OCCUPANT RESPONSE

- Interface Position
- System Information
- Type of Device

C. CAPTURING OCCUPANT PREFERENCES

6 USING QUESTIONNAIRES TO CAPTURE OCCUPANT RESPONSE

- Personal Control
- Preferred Level of Automation
- Interface Characteristics

7 CONCLUSION

7 Conclusion

7.1 Introduction

This dissertation examined why automated façades frequently fail to achieve their technical potential in actual buildings and proposed that a key constraint lies in the design of interaction strategies, referring to how automated control logic operates over time and how occupant needs are translated into operation that is understandable, open to negotiation, and capable of adaptation. Based on two systematic reviews, controlled experiments, and a large-scale survey, the dissertation demonstrated that automated façades can reduce energy demand and provide IEQ benefits. However, the evidence showed that achieving these benefits depends on whether automated control supports collaborative occupant–automation control, rather than being experienced as disruptive, opaque, or poorly aligned with work requirements, conditions that trigger dissatisfaction, manual overrides, and contribute to the performance gap. Figure 7.1 illustrates how this dissertation addresses the main research question by depicting how interaction strategies shape occupant responses and, in turn, influence operational energy use and IEQ outcomes.

First, this dissertation examined existing evidence on automated façade performance by synthesizing reported energy savings, indoor environmental quality (IEQ) outcomes, and occupant response, showing that energy benefits are not uniform across studies. Lighting savings are the most consistently reported because daylight-responsive shading can directly reduce electric lighting demand. Cooling savings are generally positive because limiting solar gains typically reduces cooling loads, but results vary with climate, orientation, and control settings. Heating impacts are mixed, partly because automation can also reduce beneficial solar gains. Reported IEQ benefits most often concern visual and thermal conditions, while multi-domain assessment remains uncommon. Trade-offs between glare protection, daylight, view, privacy, and thermal objectives recur, yet are rarely evaluated

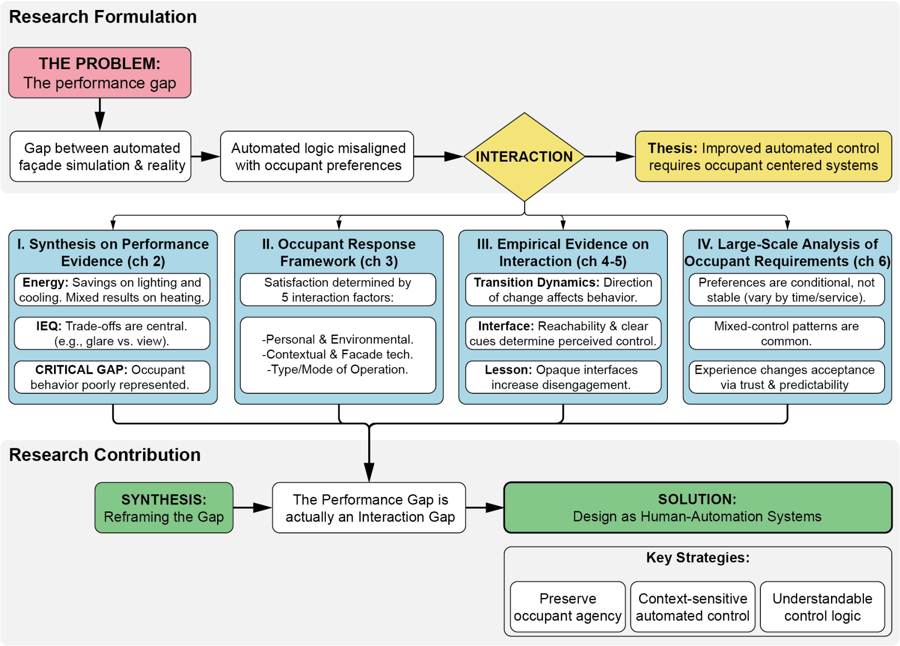


FIG. 7.1 Reframing the performance gap through interaction. The figure synthesizes the dissertation's argument that underperformance in automated façades is often linked to interaction mechanisms (e.g., opaque operation and limited support for occupant agency). Evidence across four research components motivates occupant-centered interaction strategies that support collaborative occupant–automation control through legible operation, context sensitivity, and low-effort override.

together. Critically, occupant behavior is widely acknowledged but often insufficiently represented in performance evaluations, contributing to the gap between simulated potential and operational outcomes.

An important implication of this evidence is that interaction requirements differ across IEQ domains. Visual conditions, such as daylight, glare, and view, are highly dynamic, immediately perceptible, and often directly linked to façade actions, which can trigger fast occupant responses. Thermal conditions typically evolve more slowly and are less directly attributable to a single control action, which may lead to delayed or less frequent interventions. Indoor air quality is often less directly perceivable, making feedback and system transparency especially important for trust. Acoustic conditions, when affected by façade operation, can produce immediate dissatisfaction, but are less commonly addressed through direct façade interaction. These differences suggest that occupant response should not be generalized across IEQ domains and that automated façade strategies require domain-specific interaction approaches.

Building on this performance evidence, this dissertation showed that satisfaction, acceptance, and interaction behavior are shaped by five interacting factor groups: personal factors, environmental conditions, contextual factors, façade technology, and type and mode of operation. This framework clarifies why the same automated action can be welcomed in one situation and rejected in another. Context and environmental dynamics determine how challenging the control problem is, personal factors shape what “good” means for an occupant, and system operation determines whether automation remains predictable, understandable, and easy to override when it does not align with occupant requirements.

The experimental evidence demonstrated that parameters often treated as purely technical should also be understood as interaction strategy design decisions. Transition dynamics, particularly direction of change (toward a darker versus toward a clearer state), alter occupant response primarily through behavioral and attentional mechanisms, including the likelihood of override. Complementary evidence on control interfaces showed that reachability, ease of use, and clear system cues are important for perceived control and satisfaction. Interfaces that are easy to access and provide understandable feedback support automated control being perceived as safe and reversible, whereas disruptive or opaque interaction strategies increase frustration and reduce acceptance of automated control.

Finally, the large-scale survey evidence confirmed that occupant requirements are context-dependent rather than a single stable preference. Preferences vary by workday phase and by building service, and mixed level of automated control patterns are common, with many occupants preferring automation for some services while preferring manual or semi-automated arrangements for others. Acceptance shifts toward higher levels of automation from arrival to while working and increases further from while working to leaving, and prior experience with automation is associated with greater acceptance. Together, these findings reinforce that interaction strategies can shape acceptance by building trust through predictable operation, transparency, and low-effort override.

Taken together, this dissertation shows that the performance gap of automated façades is not only a control problem but also an interaction problem. Energy and IEQ benefits are achievable, yet they depend on whether automation remains predictable, understandable, and easy to override when it does not match occupant needs. Occupant response is shaped by interacting personal, contextual, environmental, technological, and operational factors, which explains why the same automated action can be acceptable in one situation and rejected in another. Seemingly technical choices such as transition dynamics, as well as interface reachability and the quality of system cues, function as interaction design decisions that influence attention, overrides, satisfaction, and acceptance. Finally, occupant requirements are context-dependent and service-specific, with mixed-control preferences being common, implying that effective automation should support flexible, differentiated interaction rather than a single uniform level of automation.

In the next section, the dissertation’s five sub-research questions are addressed in sequence. Sub-question 1 synthesizes evidence on energy savings, indoor environmental quality (IEQ) outcomes, and occupant response associated with automated façades. Sub-question 2 consolidates the factors that influence occupant response and explains how these factors shape satisfaction and acceptance. Sub-question 3 examines how transition dynamics—specifically speed and direction of change—influence occupant response. Sub-question 4 examines how interface information, position, and type influence satisfaction, acceptance, and interaction. Sub-question 5 characterizes how occupant requirements vary with personal factors, building service type, and context, establishing the context-dependent nature of automation preferences. The chapter then addresses the main research question, **How do interaction strategies influence occupant response to automated façades?**, and concludes with the limitations of this work and directions for future research.

7.2 Addressing Sub-research Questions

7.2.1 Sub-question 1. What is the impact of automated façades on energy savings, IEQ, and occupant response? (Chapter 2)

The systematic review in Chapter 2 showed that automated façades can reduce energy demand, but the strength and consistency of evidence differed by end use and by study type. Evidence was most consistent for lighting energy savings and generally positive, though more variable, for cooling, while heating results were mixed. For cooling, simulation studies commonly reported reductions in the range of 0–40% (with climate- and orientation-dependent outliers such as 85% and 93%), whereas empirical studies tended to show more modest reductions (12–28%) and, in some cases, increases in energy consumption (for example, +10% cooling for automated roller shades). For heating, reported impacts ranged from large increases (up to +103%) to large reductions (such as 77% and 42%), with many cases showing only small changes (around 5%), partly because automated control can reduce beneficial solar gains. Lighting showed the most consistent savings: simulations reported 31–81%, and laboratory and real-building studies reported up to 68% for electrochromic glazing, 75% for roller shades, and 86% for venetian blinds. However, higher savings were often reported under conditions where occupants could not intervene; when overrides were allowed, lighting savings could drop substantially (for example, to 10% for venetian blinds and 25% for roller shades).

For IEQ, the reviewed evidence supported improvements primarily in the visual and thermal domains through daylight regulation, glare mitigation, and thermal balancing. At the same time, the literature did not cover all IEQ domains equally, and multi-domain assessment remained limited. Many studies relied on rule-based control strategies (for example, illuminance thresholds, DGP, indoor air temperature, solar irradiance), while indoor air quality was addressed only occasionally (for example, window opening triggered when CO exceeded 1250 ppm). Across studies, trade-offs between competing goals were repeatedly observed: glare prevention could reduce daylight and view, and thermal optimization could conflict with visual or privacy needs, particularly for east and west orientations where competing demands were hardest to balance.

Regarding occupant response, Chapter 2 showed that occupant behavior was widely acknowledged as influential but was often not integrated into automated façade performance evaluation. When occupant-related outcomes were assessed, satisfaction and acceptance tended to improve when systems provided transparency, feedback, and intuitive override opportunities, and tended to worsen when automation was disruptive or misaligned with expectations—often reflected in more frequent overrides and lower satisfaction. Overall, the chapter indicated that part of the gap between simulated potential and observed outcomes was linked to how interaction was represented: benchmarks and study designs that omitted or constrained occupant intervention often described technical potential rather than operational performance in real use.

7.2.2 Sub-question 2. What factors influence occupant response with automated façades, and how do these factors impact satisfaction and acceptance? (Chapter 3)

The systematic review in Chapter 3 synthesized empirical evidence on occupant response to automated façades and grouped influencing factors into five categories: personal factors, environmental conditions, contextual factors, façade technology, and type and mode of operation. Across the reviewed studies, occupant response was most frequently captured through comfort, satisfaction, and behavior/interaction, while acceptance was assessed less often. Satisfaction and acceptance were commonly examined alongside behavioral indicators such as override actions, which helped connect subjective evaluation to observable interaction.

Environmental and contextual factors influenced satisfaction and acceptance by determining how difficult it was for the façade system to meet occupant requirements under changing conditions. Orientation and sky conditions shaped the magnitude and dynamics of solar penetration and glare risk. East and west exposures often produced rapid changes, while south and west-facing conditions could intensify both cooling and glare reduction demands, creating persistent conflicts between glare protection, daylight availability, view preservation, and thermal load reduction. Seasonal change and intermittent cloud cover could further amplify variability and increase the likelihood of frequent façade adjustments, which could be perceived as disruptive. Task context moderated these effects: during screen-based work or meetings, occupants tended to prioritize glare avoidance and well-balanced light, while during other activities they could tolerate more variability in exchange for daylight and view.

Personal factors explained why the same automated action could be acceptable for one occupant and unacceptable for another. The review highlighted substantial inter-individual variability in priorities, such as valuing view and daylight versus valuing glare control or stable illuminance, which made one-size-fits-all automation unreliable in practice. At the same time, the evidence base often under-specified deeper attitudinal drivers, which limited predictive understanding of acceptance across diverse occupants.

Technological and operational factors—particularly type and mode of operation and the interaction and control logic—most directly affected satisfaction and acceptance because they shaped perceived control, predictability, and alignment with occupant expectations. Systems were more likely to be accepted when they provided easy override and transparent feedback that enabled occupants to understand and correct the system when needed. Conversely, dissatisfaction was repeatedly associated with mismatch between automated actions and occupant needs, lack of information about why changes occurred, and disruptive operation. Façade technology characteristics also influenced acceptance by changing how intrusive automation was perceived; visible and audible operation of shading devices could be disruptive, and transition frequency, speed, and direction could increase distraction and annoyance. Overall, Chapter 3 indicated that satisfaction and acceptance depended most consistently on whether automated actions matched contextual and personal requirements under competing visual–thermal demands, and whether automation remained predictable and easy to intervene in, supported by legible feedback and straightforward override.

This also indicates that perceived control should be treated as more than a secondary satisfaction outcome. Occupants may accept automated operation when they feel able to understand, influence, or reverse system actions, even if the system does not always match their immediate preference. Conversely, dissatisfaction may arise even under acceptable environmental conditions when occupants perceive that control has been removed or made difficult. Therefore, perceived control functions as a mediating variable between automated operation and acceptance, linking system transparency, override possibility, and occupant trust.

7.2.3 Sub-question 3. How do speed and direction of change in automated façades influence occupant satisfaction, acceptance, and response? (Chapter 4)

Chapter 4 showed that transition dynamics in automated façade operation—particularly speed and direction—shaped occupant response primarily through behavioral and attentional mechanisms, while their impact on overall satisfaction was more limited under the tested conditions. Speed and direction mattered because they changed how noticeable and interpretable automated actions were, and therefore how likely occupants were to look toward the façade, become distracted, or intervene. Direction was particularly influential for interaction: transitions toward a darker state (clear-to-dark) were more likely to be interpreted as a loss of openness, daylight, and view, and they elicited more frequent intervention than transitions toward a clearer state (dark-to-clear), which were more often interpreted as restoring openness. Speed could increase the salience of change, but in this chapter its effects were clearer in occupant behavior than in broad satisfaction ratings.

These effects did not occur in isolation. Chapter 4 reinforced that occupant response was also shaped by how the control logic triggered transitions, including timing and stability. Transitions perceived as poorly timed or inconsistent could reduce tolerance and increase override behavior, even if the final state was acceptable. The chapter also emphasized heterogeneity: some occupants were considerably more sensitive to automated transitions than others. For that reason, parameters such as transition speed, direction, thresholds, and timing should be treated as interaction design decisions that can either preserve acceptance or trigger patterns of intervention that undermine automated operation.

7.2.4 Sub-question 4. How do information, position, and type of control interface influence occupant satisfaction, acceptance, and response with automated façades? (Chapter 5)

Chapter 5 showed that the control interface influenced occupant response because it determined two conditions central to satisfaction and acceptance: perceived ease of intervention (perceived agency) and the extent to which automated actions were understandable (system legibility). Across the tested interface concepts, these conditions were explained by interface characteristics related to device type (analogue versus digital), interface position (desk versus wall/entrance, including split-location configurations), and the information cues provided by the interface (from no cues to clear system-state and outcome cues).

Reachability was a dominant driver of perceived control and satisfaction. When the interface was easy to access, occupants reported higher satisfaction and were more willing to accept automated operation because intervening felt low-effort and reliable. When access was inconvenient or inconsistent—such as when control was split across locations—acceptance and satisfaction decreased. Ease of use reduced frustration and misalignment during interaction: intuitive interfaces made it easier for occupants to correct the system quickly when needed, which supported tolerance for automated actions. Information cues improved trust and acceptance when they provided clear and useful insight into system state and the consequences of actions. Importantly, the benefit arose from clarity and usefulness rather than from adding more information; once cues were sufficient to interpret state and outcomes, additional information yielded diminishing returns. A key nuance was that device type primarily affected usability, while acceptance was more consistently explained by reachability and system cues. In other words, occupants could accept different device types when control was reachable and automated actions were legible and easy to override.

7.2.5 Sub-question 5. Do occupants have different requirements for interaction with automation depending on personal factors, type of service, and context? (Chapter 6)

Chapter 6 demonstrated that occupant requirements for interaction with automated building services were conditional rather than fixed. Preferences varied systematically by workday phase, by service type, and by occupant profile, which implied that "automation preference" was not a single stable trait. Across the workday, preferences shifted toward higher automation from arrival to while working and further from while working to leaving, indicating that acceptance of automated operation became stronger as occupants transitioned away from actively shaping their immediate conditions. This phase dependence meant that an interaction strategy that was acceptable at one moment could be perceived as disruptive at another, particularly during high-attention work.

Preferences were also strongly service-specific. Room-level services such as heating, mechanical ventilation, and cooling were generally more acceptable as automated regulation—especially when occupants retained an easy override option—because they were often experienced as background conditioning. In contrast, services with immediate and perceptible impacts such as shading, lighting, and openable windows tended to produce more divided preferences, with many occupants favoring manual or semi-automated arrangements. Personal devices (such as task lights, personal fans, and personal heaters) showed the strongest association with manual preferences, consistent with their role as individualized, local self-regulation tools. Importantly, many occupants exhibited mixed-control patterns, preferring automation for some services and manual control for others. This supported the dissertation's argument that design should not reduce occupants to two extremes, but should instead support conditional, service-specific preferences as the dominant reality. Prior experience with automation also mattered: occupants who had interacted with automated building services were more likely to accept higher levels of automation, suggesting that acceptance can be supported through predictable operation, clear cues, and easy override that make delegating control feel safe and reversible.

7.3 General Conclusion

The primary goal of this research was to understand how interaction strategies shape occupant responses to automated façades, and how this, in turn, affects the ability of automated façade systems to deliver their intended indoor environmental quality (IEQ) and energy outcomes. This work focused on the premise that façade automation is not only a technical control problem, but also an interaction problem: occupants interpret, tolerate, and respond to automated actions in ways that can reinforce or undermine operational performance. However, a recurring challenge in both research and practice is that automated façades often underperform in real operation relative to their technical potential, in part because occupant requirements and behavioral responses are insufficiently represented in control design and evaluation.

To address this challenge, this study was structured around one main research question and divided into five research activities, explored across the dissertation chapters.

Main research question. How do interaction strategies influence occupant response to automated façades?

This dissertation showed that interaction strategies influence occupant response by determining how well automated façade objectives align with occupant requirements in real operation. Interaction was not an added “usability layer” placed on top of control logic; rather, interaction strategies were a fundamental determinant of whether automated façades achieved their intended IEQ and energy outcomes. When interaction strategies were well designed, occupants were more likely to experience automated operation as supportive and cooperative; when interaction strategies were poorly designed, automation was more likely to be experienced as disruptive, opaque, and imposed, triggering overrides and dissatisfaction that undermined operational performance. Interaction strategies shaped occupant response by defining the control logic as experienced in use, not only the environmental states the façade achieved. Evidence from the experimental and survey components provides a consistent account of how these interaction effects operate across scales.

Chapters 4 and 5 showed that specific interaction features directly influence occupant interpretation and intervention. Transition characteristics such as direction and speed functioned as interaction-relevant parameters because they affected noticeability, interpretability, and the likelihood of intervention. In particular, transitions toward a darker state were more likely to be interpreted negatively and to elicit intervention, highlighting that automation dynamics can influence behavior even when effects on overall satisfaction are limited under certain test conditions. This underscores that timing, stability, and transition design are not purely technical details; they are interaction design decisions that shape tolerance and trust. At the same time, interface characteristics played a central role in balancing understanding and perceived control. Chapter 5 demonstrated that reachability, ease of use, and clear system cues made automated operation legible and protected perceived control. When the interface was reachable and cues clearly communicated system state and outcomes, occupants could intervene confidently with low effort, supporting acceptance even when automated actions occasionally diverged from preferences. When interaction was inconvenient or opaque, uncertainty and frustration increased, and automated operation was more likely to be rejected.

The survey results in Chapter 6 extend these findings by showing that these interaction principles remain consistent at a broader scale, while also revealing how they vary with context. Acceptance differed across workday phases and building services, indicating that effective interaction strategies cannot be static. As occupant priorities shift over the day and differ across services, strategies must support differentiated modes that preserve stability and clear intervention opportunities during high-attention work, while enabling appropriate delegation when convenience becomes more relevant.

Across both experimental observations and survey responses, a consistent pattern emerges: occupants are more willing to accept automation when it remains understandable, predictable, and easy to override. At the same time, differences between observed behavior and stated preferences indicate that survey responses should be interpreted as expressions of desired interaction conditions rather than direct predictions of behavior in real buildings.

Finally, interaction strategies must accommodate diverse occupant profiles. Chapter 3 established that personal factors and preferences create substantial inter-individual variation, and Chapter 6 confirmed that mixed-control patterns are common at population scale. As a result, interaction strategies cannot be optimized as a single global automation level; they must support flexible, service-specific, and context-sensitive modes that allow occupants with different requirements to coexist within the same building operation.

Taken together, these findings showed that interaction strategies determine whether automated façades and occupants form a coordinated shared-control system or enter a conflict loop. Coordination emerged when automated actions were context-appropriate, predictable, legible, and easy to override, reducing unnecessary interventions and supporting both satisfaction and stable operation. Conflict emerged when automation was disruptive or opaque and intervention was difficult, prompting overrides and disengagement that eroded energy and IEQ performance and contributed to the gap between technical potential and operational outcomes. These conclusions should be interpreted relative to the empirical scope of this dissertation. The experimental studies focused on specific façade technologies and office-lab conditions, while the survey focused on office workers in Spain and the Netherlands. Therefore, the proposed interaction principles should be understood as empirically grounded design directions rather than universal prescriptions. Further validation is needed across different building types, climates, façade technologies, organizational settings, and long-term operational conditions.

7.4 Limitations and Future Research

This dissertation combined evidence from systematic reviews (Chapters 2–3), controlled laboratory studies (Chapters 4–5), and a large-scale survey (Chapter 6) to examine how interaction strategies shape occupant response to automated façades. While this mixed-evidence approach strengthens convergence of evidence, each component has limitations that constrain generalization. The following subsections summarize these limitations and propose future research directions to increase ecological validity, comparability, and operational applicability.

7.4.1 Evidence-base heterogeneity and limited comparability (Chapters 2–3)

A primary limitation identified in the reviews is the heterogeneity of the evidence base. Façade technologies, control objectives, climates, thresholds, benchmarks, and evaluation methods vary widely across studies. This reduces direct comparability and makes it difficult to attribute differences in energy, IEQ, or satisfaction outcomes to specific interaction or control-design choices with high certainty. The review also highlights that empirical studies with human participants remain relatively scarce, limiting validation of occupant-response claims in real use conditions. Future research should address this by developing more consistent metrics and benchmark scenarios (e.g., comparable baselines and thresholds) and by increasing the number of empirical studies in real offices that explicitly capture occupant behavior and override patterns.

7.4.2 Under-representation of occupant interaction in performance evaluation (Chapters 2–3)

Across the reviewed studies, occupant behavior is widely acknowledged as influential, yet interaction is often under-represented or simplified (e.g., constrained assumptions about intervention and overrides). This limits the ability to explain the performance gap and can bias conclusions about “optimal” automation, particularly when energy savings are reported under conditions where occupants cannot intervene. Future work should prioritize study designs that treat interaction as part of performance, including explicit modeling and measurement of interventions, and should build datasets that connect automated actions, overrides, and evolving preferences.

7.4.3 Limited multi-domain IEQ assessment and persistent trade-offs (Chapters 2–3)

The reviews show that IEQ benefits are most consistently reported for visual and thermal domains, while multi-domain assessment remains limited and trade-offs are repeatedly observed (e.g., glare prevention versus daylight and view; thermal optimization versus view/privacy needs). As a result, studies may report "improvement" in one domain while shifting discomfort to another, making it difficult to determine which strategies deliver robust, occupant-acceptable performance. Future research should advance multi-domain evaluation approaches and apply multi-criteria decision logic to make trade-offs explicit (including which parameters should be prioritized under different building contexts and occupant needs).

7.4.4 Boundary conditions of the glazing-transition experiment (Chapter 4)

The glazing-transition experiment (Ch.4) strengthens causal inference on how speed and direction affect noticeability and intervention, but its findings are bounded by several conditions. Participants were not exposed to glare, the sky condition was overcast, and participants were seated very close to the glazing in a high window-to-wall-ratio setting, which may amplify perceived transition effects compared with many offices. The study also tested only two fast, perceptible transition rates, and the sample size was designed for the main scenarios, limiting the ability to test a larger set of moderators (e.g., additional personal attitudes) with adequate power. Future work should therefore extend these tests to settings with greater daylight variance, varied seat-to-façade distances, and conditions that include glare/discomfort contexts, while exploring longer and potentially imperceptible transition profiles and using larger samples when adding behavioral and personal moderators.

7.4.5 Boundary conditions of the interface-usability experiment (Chapter 5)

The usability experiment (Ch.5) provides evidence that reachability, ease of use, and clear system cues are key drivers of interface satisfaction in the tested lighting and shading scenarios. However, this study was conducted in a single controlled office-lab, with 20 relatively young participants with technical expertise, focusing on a specific set of interface configurations and two services (lighting and shading). In addition, preferences and automation acceptance were measured largely through self-reported questionnaires and hypothetical shared-office scenarios, without observing long-term use or real multi-occupant override behavior. Future research should test similar interface configurations in real multi-occupant offices, include more heterogeneous occupant groups, extend the approach to other building services, and combine usability ratings with behavioral measures of interaction and overrides over time.

7.4.6 Survey limits: stated preferences, cross-sectional design, and missing links to measured conditions (Chapter 6)

The large-scale survey (Ch.6) provides population-level evidence that automation preferences are workday-phase-specific and building-service-specific, and that interface requirements cluster into coherent configurations. Yet, the evidence is based on stated preferences from a cross-sectional survey, so actual in-situ behavior under real discomfort (e.g., glare, noise) or social dynamics may differ. Additionally, the analysis did not follow individuals longitudinally or link preferences to measured indoor conditions or energy use. Future research should therefore conduct longitudinal field validation that integrates objective system logs (automated control logics and overrides), multi-domain IEQ measurements, and repeated occupant feedback, enabling direct tests of learning/adaptation and preference stability under real operational constraints.

7.4.7 Operationalizing occupant-centered interaction strategies in real buildings

A recurring gap in the field is that research has largely focused on identifying what occupants prefer or need, while offering limited guidance on how to operationalize these requirements in real control strategies that are stable, transparent, and acceptable in everyday use. Future work should therefore develop and test occupant-centered control approaches that adapt to override patterns and contextual cues without undermining predictability, clarity, and perceived control.

Implementing these strategies in real buildings also requires attention to practical constraints beyond control logic itself. Occupant-centered automation must be integrated with building management systems, commissioning procedures, facility management routines, maintenance requirements, and user communication. For example, adaptive control that learns from override behavior may improve alignment with occupant needs, but only if the resulting system behavior remains legible and does not create uncertainty about what the system will do next. Similarly, interfaces and feedback mechanisms must be simple enough to support everyday use while still providing sufficient information for occupants to understand system state, intent, and consequences.

In particular, adaptive logic should be evaluated not only for energy and IEQ performance, but also for whether it remains trustworthy over time. Future field studies should therefore examine how occupants respond to learning systems across weeks or months, whether interaction frequency decreases as trust develops, and whether occupant-centered strategies can reduce unnecessary overrides without reducing perceived agency.

7.4.8 System coordination beyond the façade

A further gap is that façade interaction strategies are often studied in isolation, even though occupants experience indoor climate, lighting, and shading as a single, integrated system. When façade, lighting, and HVAC controls are not coordinated, occupants can be confronted with fragmented or even contradictory system behavior, and trade-offs may be “solved” by shifting discomfort from one domain to another rather than resolving it. Future research should therefore develop and test coordinated control strategies across façade–HVAC–lighting, evaluating whether integration reduces recurring intervention cycles, improves multi-domain IEQ outcomes, and supports sustained acceptance of automated controls over time.

References

[1] IPCC, “Climate Change 2022: Mitigation of Climate Change. Contribution of Working Group III to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change,” The Intergovernmental Panel on Climate Change (IPCC), Tech. Rep., 2022.

[2] A. Leaman and B. Bordass, “Productivity in buildings: the ‘killer’ variables,” https://doi.org/10.1080/096132199369615, vol. 27, no. 1, pp. 4–19, 2010. [Online]. Available: https://www.tandfonline.com/doi/abs/10.1080/096132199369615

[3] ASHRAE, “ANSI/ASHRAE Standard 55: Thermal Environmental Conditions for Human Occupancy,” Atlanta, GA, USA, Tech. Rep., 2023.

[4] IEA (2023), “World Energy Outlook 2023, IEA,” 10 2023.

[5] M. Konstantoglou and A. Tsangrassoulis, “Dynamic operation of daylighting and shading systems: A literature review,” Renewable and Sustainable Energy Reviews, vol. 60, pp. 268–283, 7 2016.

[6] A. Shafaghat and A. Keyvanfar, “Dynamic façades design typologies, technologies, measurement techniques, and physical performances across thermal, optical, ventilation, and electricity generation outlooks,” Renewable and Sustainable Energy Reviews, vol. 167, p. 112647, 10 2022.

[7] M. Barozzi, J. Lienhard, A. Zanelli, and C. Monticelli, “The Sustainability of Adaptive Envelopes: Developments of Kinetic Architecture,” pp. 275–284, 1 2016.

[8] ——, “The Sustainability of Adaptive Envelopes: Developments of Kinetic Architecture,” Procedia Engineering, vol. 155, pp. 275–284, 1 2016.

[9] D. Khraisat, N. Taib, C. H. Y. Sern, and M. Al-Ruwaishedi, “Application of Kinetic Facades and Its Impact on Daylighting Performance: A Systematic Literature Review,” Civil Engineering and Architecture, vol. 12, no. 4, 2024.

[10] J. K. Day, B. Futrell, R. Cox, and S. N. Ruiz, “Blinded by the light: Occupant perceptions and visual comfort assessments of three dynamic daylight control systems and shading strategies,” Building and Environment, vol. 154, pp. 107–121, 5 2019.

[11] L. G. Bakker, E. C. Hoes-van Oeffelen, R. C. Loonen, and J. L. Hensen, “User satisfaction and interaction with automated dynamic facades: A pilot study,” Building and Environment, vol. 78, pp. 44–52, 8 2014.

[12] P. De Wilde, “The gap between predicted and measured energy performance of buildings: A framework for investigation,” Automation in Construction, vol. 41, pp. 40–49, 5 2014.

[13] H. Burak Gunay, W. O’Brien, and I. Beausoleil-Morrison, “Development of an occupancy learning algorithm for terminal heating and cooling units,” Building and Environment, vol. 93, no. P2, pp. 71–85, 11 2015. [Online]. Available: https://www.sciencedirect.com/science/article/pii/S0360132315300238

[14] K. A. Hoff and M. Bashir, “Trust in Automation,” Human Factors, vol. 57, no. 3, pp. 407–434, 5 2015. [Online]. Available: https://journals.sagepub.com/doi/10.1177/0018720814547570

[15] EU, “Directive (EU) 2024/1275 of the European Parliament and of the Council of 24 April 2024 on the energy performance of buildings,” Official Journal of the European Union, vol. 1275, 2024.

[16] European Commission, “Commission Implementing Regulation (EU) 2020/2156 of 14 October 2020 detailing the technical modalities for the effective implementation of an optional common Union scheme for rating the smart readiness of buildings ,” pp. 25–29, 12 2020.

[17] W. O’Brien, A. Wagner, M. Schweiker, A. Mahdavi, J. Day, M. B. Kjærgaard, S. Carlucci, B. Dong, F. Tahmasebi, D. Yan, T. Hong, H. B. Gunay, Z. Nagy, C. Miller, and C. Berger, “Introducing IEA EBC annex 79: Key challenges and opportunities in the field of occupant-centric building design and operation,” Building and Environment, vol. 178, p. 106738, 7 2020.

[18] C. F. Reinhart and K. Voss, “Monitoring manual control of electric lighting and blinds,” Lighting Research and Technology, vol. 35, no. 3, pp. 243–258, 2003.

[19] P. Boyce, C. Hunter, and O. Howlett, “The Benefits of Daylight through Windows Sponsored by: Capturing the Daylight Dividend Program,” 2003.

[20] A. Rabbani and S. Keshav, “The SPOT personal thermal comfort system,” in Proceedings of the 3rd ACM Conference on Systems for Energy-Efficient Built Environments, BuildSys 2016, 2016.

[21] M. Killian and M. Kozek, “Ten questions concerning model predictive control for energy efficient buildings,” Building and Environment, vol. 105, pp. 403–412, 8 2016.

[22] D. B. Kaber and M. R. Endsley, “The effects of level of automation and adaptive automation on human performance, situation awareness and workload in a dynamic control task,” Theoretical Issues in Ergonomics Science, vol. 5, no. 2, pp. 113–153, 2004. [Online]. Available: https://www.tandfonline.com/doi/abs/10.1080/1463922021000054335

[23] B. Meerbeek, M. te Kulve, T. Gritti, M. Aarts, E. van Loenen, and E. Aarts, “Building automation and perceived control: A field study on motorized exterior blinds in Dutch offices,” Building and Environment, vol. 79, pp. 66–77, 9 2014.

[24] A. Boerstra, T. Beuker, M. Loomans, and J. Hensen, “Impact of available and perceived control on comfort and health in European offices,” https://doi.org/10.1080/00038628.2012.744298, vol. 56, no. 1, pp. 30–41, 2 2013. [Online]. Available: https://www.tandfonline.com/doi/abs/10.1080/00038628.2012.744298

[25] B. Becerik-Gerber, G. Lucas, A. Aryal, M. Awada, M. Bergés, S. L. Billington, O. Boric-Lubecke, A. Ghahramani, A. Heydarian, F. Jazizadeh, R. Liu, R. Zhu, F. Marks, S. Roll, M. Seyedrezaei, J. E. Taylor, C. Höelscher, A. Khan, J. Langevin, M. L. Mauriello, E. Murnane, H. Noh, M. Pritoni, D. Schaumann, and J. Zhao, “Ten questions concerning human-building interaction research for improving the quality of life,” Building and Environment, vol. 226, p. 109681, 12 2022.

[26] S. Bianchi, C. Andriotis, T. Klein, and M. Overend, “Multi-criteria design methods in façade engineering: State-of-the-art and future trends,” Building and Environment, vol. 250, p. 111184, 2 2024. [Online]. Available: https://www.sciencedirect.com/science/article/pii/S036013232400026X

[27] D. S. Noaman, S. A. Moneer, N. A. Megahed, and S. A. El-Ghafour, “Integration of active solar cooling technology into passively designed facade in hot climates,” Journal of Building Engineering, vol. 56, p. 104658, 9 2022.

[28] S. Babu, J. Zhou, M. P. Wan, A. S. Lamano, J. N. Sarvaiya, Z. Zhang, D. E. Kumar, C. p. Gao, S. Valliappan, A. Goh, and A. Seoh, “Investigation of an integrated automated blinds and dimmable lighting system for tropical climate in a rotatable testbed facility,” Energy and Buildings, vol. 183, pp. 356–376, 1 2019.

[29] W. H. Ko, M. G. Kent, S. Schiavon, B. Levitt, and G. Betti, “A Window View Quality Assessment Framework,” LEUKOS, vol. 18, no. 3, pp. 268–293, 7 2022. [Online]. Available: https://www.tandfonline.com/doi/abs/10.1080/15502724.2021.1965889

[30] R. Sullivan, E. S. Lee, K. Papamichael, M. Rubin, and S. E. Selkowitz, “Effect of switching control strategies on the energy performance of electrochromic windows,” Optical Materials Technology for Energy Efficiency and Solar Energy Conversion XIII, vol. 2255, no. 9, pp. 443–455, 9 1994. [Online]. Available: https://www.spiedigitallibrary.org/conference-proceedings-of-spie/2255/0000/Effect-of-switching-control-strategies-on-the-energy-performance-of/10.1117/12.185387.fullhttps://www.spiedigitallibrary.org/conference-proceedings-of-spie/2255/0000/Effect-of-switching-control-strategies-on-the-energy-performance-of/10.1117/12.185387.short

[31] A. Tzempelikos and A. K. Athienitis, “The impact of shading design and control on building cooling and lighting demand,” Solar Energy, vol. 81, no. 3, pp. 369–382, 3 2007.

[32] F. Stazi, F. Naspi, G. Ulpiani, and C. Di Perna, “Indoor air quality and thermal comfort optimization in classrooms developing an automatic system for windows opening and closing,” Energy and Buildings, vol. 139, pp. 732–746, 2017.

[33] J. H. Kim, Y. J. Park, M. S. Yeo, and K. W. Kim, “An experimental study on the environmental performance of the automated blind in summer,” Building and Environment, vol. 44, no. 7, pp. 1517–1527, 7 2009.

[34] R. D. Clear, V. Inkarojrit, and E. S. Lee, “Subject responses to electrochromic windows,” Energy and Buildings, vol. 38, no. 7, pp. 758–779, 7 2006.

[35] E. Bilgen, “Experimental study of thermal performance of automated venetian blind window systems,” Solar Energy, vol. 52, no. 1, pp. 3–7, 1 1994.

[36] E. Vine, E. Lee, R. Clear, D. DiBartolomeo, and S. Selkowitz, “Office worker response to an automated venetian blind and electric lighting system: A pilot study,” 3 1998. [Online]. Available: http://www.osti.gov/servlets/purl/658295-UJcY2n/webviewable/

[37] E. S. Lee, D. L. DiBartolomeo, and S. E. Selkowitz, “Thermal and daylighting performance of an automated venetian blind and lighting system in a full-scale private office,” Energy and Buildings, vol. 29, no. 1, pp. 47–63, 12 1998.

[38] E. Kızılörenli and F. Maden, “Modular responsive facade proposals based on semi-regular and demi-regular tessellation: daylighting and visual comfort,” Frontiers of Architectural Research, vol. 12, no. 4, pp. 601–612, 8 2023.

[39] C. T. Do and Y. C. Chan, “Evaluation of the effectiveness of a multi-sectional facade with Venetian blinds and roller shades with automated shading control strategies,” Solar Energy, vol. 212, pp. 241–257, 12 2020.

[40] J. Xie and A. O. Sawyer, “Simulation-assisted data-driven method for glare control with automated shading systems in office buildings,” Building and Environment, vol. 196, p. 107801, 6 2021.

[41] A. Tabadkani, A. Roetzel, H. X. Li, and A. Tsangrassoulis, “Simulation-based personalized real-time control of adaptive facades in shared office spaces,” Automation in Construction, vol. 138, p. 104246, 6 2022.

[42] R. C. Loonen, F. Favoino, J. L. Hensen, and M. Overend, “Review of current status, requirements and opportunities for building performance simulation of adaptive facades†,” Journal of Building

Performance Simulation, vol. 10, no. 2, pp. 205–223, 3 2017. [Online]. Available: https://www.tandfonline.com/doi/pdf/10.1080/19401493.2016.1152303

[43] A. C. Boerstra, M. t. Kulve, J. Toftum, M. G. Loomans, B. W. Olesen, and J. L. Hensen, “Comfort and performance impact of personal control over thermal environment in summer: Results from a laboratory study,” Building and Environment, vol. 87, pp. 315–326, 5 2015.

[44] A. Luna-Navarro, G. R. Hunt, and M. Overend, “Dynamic façades – An exploratory campaign to assess occupant multi-domain environmental satisfaction and façade interaction,” Building and Environment, vol. 211, 2022.

[45] G. R. Newsham and C. Arsenault, “A camera as a sensor for lighting and shading control,” http://dx.doi.org/10.1177/1477153508099889, vol. 41, no. 2, pp. 143–160, 5 2009.

[46] A. Luna-Navarro, R. Loonen, M. Juaristi, A. Monge-Barrio, S. Attia, and M. Overend, “Occupant-Facade interaction: a review and classification scheme,” Building and Environment, vol. 177, p. 106880, 6 2020.

[47] A. Guillemin and N. Morel, “EXPERIMENTAL RESULTS OF A SELF-ADAPTIVE INTEGRATED CONTROL SYSTEM IN BUILDINGS: A PILOT STUDY †,” vol. 72, no. 5, pp. 397–403, 2002. [Online]. Available: www.elsevier.com/locate/solener

[48] A. Monteleone, G. Rodonò, A. Gagliano, and V. Sapienza, “SLICE: An Innovative Photovoltaic Solution for Adaptive Envelope Prototyping and Testing in a Relevant Environment,” Sustainability 2021, Vol. 13, Page 8701, vol. 13, no. 16, p. 8701, 8 2021. [Online]. Available: https://www.mdpi.com/2071-1050/13/16/8701/htmhttps://www.mdpi.com/2071-1050/13/16/8701

[49] S. Vanage, H. Dong, and K. Cetin, “Visual comfort and energy use reduction comparison for different shading and lighting control strategies in a small office building,” Solar Energy, vol. 265, p. 112086, 11 2023.

[50] N. Aste, J. Compostella, and M. Mazzon, “Comparative energy and economic performance analysis of an electrochromic window and automated external venetian blind,” Energy Procedia, vol. 30, pp. 404–413, 1 2012.

[51] M. V. Nielsen, S. Svendsen, and L. B. Jensen, “Quantifying the potential of automated dynamic solar shading in office buildings through integrated simulations of energy and daylight,” Solar Energy, vol. 85, no. 5, pp. 757–768, 5 2011.

[52] C. Gehbauer, E. S. Lee, and T. Wang, “An evaluation of the demand response potential of integrated dynamic window and HVAC systems,” Energy and Buildings, vol. 298, p. 113481, 11 2023. [Online]. Available: https://www.sciencedirect.com/science/article/pii/S0378778823007119

[53] S. Yeon, B. Yu, B. Seo, Y. Yoon, and K. H. Lee, “ANN based automatic slat angle control of venetian blind for minimized total load in an office building,” Solar Energy, vol. 180, pp. 133–145, 3 2019. [Online]. Available: https://www.sciencedirect.com/science/article/pii/S0038092X19300362

[54] A. Frattolillo, G. Loddo, C. C. Mastino, and R. Baccoli, “Heating and cooling loads with electrochromic glazing in Mediterranean climate,” Energy and Buildings, vol. 201, pp. 174–182, 10 2019. [Online]. Available: https://www.sciencedirect.com/science/article/pii/S0378778819308254#fig0002

[55] A. Norouziasas, A. Tabadkani, R. Rahif, M. Amer, D. van Dijk, H. Lamy, and S. Attia, “Implementation of ISO/DIS 52016-3 for adaptive façades: A case study of an office building,” Building and Environment, vol. 235, p. 110195, 5 2023.

[56] P. F. Tavares, A. R. Gaspar, A. G. Martins, and F. Frontini, “Evaluation of electrochromic windows impact in the energy performance of buildings in Mediterranean climates,” Energy Policy, vol. 67, pp. 68–81, 4 2014.

[57] A. Mesloub, A. Ghosh, M. Touahmia, G. A. Albaqawy, B. M. Alsolami, and A. Ahriz, “Assessment of the overall energy performance of an SPD smart window in a hot desert climate,” Energy, vol. 252, p. 124073, 8 2022.

[58] J. F. Flor, D. Liu, Y. Sun, P. Beccarelli, J. Chilton, and Y. Wu, “Optical aspects and energy performance of switchable ethylene-tetrafluoroethylene (ETFE) foil cushions,” Applied Energy, vol. 229, pp. 335–351, 11 2018.

[59] E. S. Lee, D. L. Dibartolomeo, E. L. Vine, and S. E. Selkowitz, “Integrated Performance of an Automated Venetian BlindlElectric Lighting System in a Full-Scale Private Office,” 9 1998.

[60] E. Lee, D. DiBartolomeo, J. Klems, R. Clear, K. Konis, M. Yazdanian, and B.-C. Park, “Field Measurements of Innovative Indoor Shading Systems in a Full-Scale Office Testbed,” ASHRAE Transactions, vol. 115, no. 2, 2009.

[61] D. R. Hax, R. K. Leitzke, A. C. S. B. da Silva, and E. G. da Cunha, “Influence of user behavior on energy consumption in a university building versus automation costs,” Energy and Buildings, vol. 256, p. 111730, 2 2022.

[62] D. K. Bui, T. N. Nguyen, A. Ghazlan, N. T. Ngo, and T. D. Ngo, “Enhancing building energy efficiency by adaptive façade: A computational optimization approach,” Applied Energy, vol. 265, p. 114797, 5 2020.

[63] A. Tzempelikos and H. Shen, “Comparative control strategies for roller shades with respect to daylighting and energy performance,” Building and Environment, vol. 67, pp. 179–192, 9 2013.

[64] S. Hong, A. Choi, and M. Sung, “Impact of bi-directional PV blind control method on lighting, heating and cooling energy consumption in mock-up rooms,” Energy and Buildings, vol. 176, pp. 1–16, 10 2018.

[65] E. S. Lee, C. Gehbauer, B. E. Coffey, A. McNeil, M. Stadler, and C. Marnay, “Integrated control of dynamic facades and distributed energy resources for energy cost minimization in commercial buildings,” Solar Energy, vol. 122, pp. 1384–1397, 12 2015.

[66] R. Tällberg, B. P. Jelle, R. Loonen, T. Gao, and M. Hamdy, “Comparison of the energy saving potential of adaptive and controllable smart windows: A state-of-the-art review and simulation studies of thermochromic, photochromic and electrochromic technologies,” Solar Energy Materials and Solar Cells, vol. 200, p. 109828, 9 2019.
[67] E. S. Lee, D. L. DiBartolomeo, S. E. Selkowitz, E. S. Lee, D. L. DiBartolomeo, and S. E. Selkowitz, “Electrochromic windows for commercial buildings: Monitored results from a full-scale testbed,” in 2000 ACEEE Summer Study on Energy Efficiency in Buildings, 4 2000, pp. 1–16.
[68] E. H. Suzuki, F. C. Lofrano, F. A. Kurokawa, R. T. Prado, and B. C. Leite, “Decision-making process for thermal comfort and energy efficiency optimization coupling smart-window and natural ventilation in the warm and hot climates,” Energy and Buildings, vol. 266, p. 112110, 7 2022. [Online]. Available: https://www.sciencedirect.com/science/article/pii/S037877882200281X
[69] E. S. Lee, D. L. Dibartolomeo, and S. E. Selkowitz, “Daylighting control performance of a thin-film ceramic electrochromic window: Field study results,” Energy and Buildings, vol. 38, no. 1, pp. 30–44, 1 2006.
[70] E. Lee, D. DiBartolomeo, and S. Selkowitz, “The Effect of Venetian Blinds on Daylight Photoelectric Control Performance,” Journal of the Illuminating Engineering Society, vol. 28, 1998.
[71] H. Shen and A. Tzempelikos, “Daylight-linked synchronized shading operation using simplified model-based control,” Energy and Buildings, vol. 145, pp. 200–212, 6 2017.
[72] S. G. Colaco, C. P. Kurian, V. I. George, and A. M. Colaco, “Integrated design and real-time implementation of an adaptive, predictive light controller,” Lighting Research and Technology, vol. 44, no. 4, pp. 459–476, 6 2012.
[73] N. Kunwar, K. S. Cetin, U. Passe, X. Zhou, and Y. Li, “Energy savings and daylighting evaluation of dynamic venetian blinds and lighting through full-scale experimental testing,” Energy, vol. 197, p. 117190, 4 2020.
[74] H. Bülow-Hübe, “Daylight in glazed office buildings: A comparative study of daylight availability, luminance and illumince distribution for an office room with three different glass areas,” Ph.D. dissertation, Lund University, Lund, Sweden, 2008. [Online]. Available: https://www.ebd.lth.se/fileadmin/energi_byggnadsdesign/images/Publikationer/Report_EBD_R_08_17_dagsljus.pdf
[75] G. Newsham, S. Mancini, J. Veitch, R. Marchand, W. Lei, K. Charles, and C. Arsenault, “Control strategies for lighting and ventilation in offices: effects on energy and occupants,” Intelligent Buildings International, vol. 1, no. 2, pp. 101–121, 2009. [Online]. Available: https://www.tandfonline.com/doi/abs/10.3763/inbi.2009.0004
[76] A. D. Galasiu, M. R. Atif, and R. A. MacDonald, “Impact of window blinds on daylight-linked dimming and automatic on/off lighting controls,” Solar Energy, vol. 76, no. 5, pp. 523–544, 5 2004.
[77] H. B. Gunay, W. O’Brien, I. Beausoleil-Morrison, and S. Gilani, “Development and implementation of an adaptive lighting and blinds control algorithm,” Building and Environment, vol. 113, pp. 185–199, 2 2017.
[78] G. Chiesa, S. Pizzuti, and M. Zinzi, “A new approach to assess the building energy performance gap: Achieving accuracy through field measurements and input data analysis,” Journal of Building Engineering, vol. 102, p. 111941, 5 2025.
[79] K. Jens, A. Das, M. B. Kjaergaard, and J. S. Gregg, “Human-centered Information for Decision-Making Processes of Future Space Designs,” in 2020 IEEE International Conference on Pervasive Computing and Communications Workshops, PerCom Workshops 2020. Institute of Electrical and Electronics Engineers Inc., 3 2020.
[80] Y. Wu, J. H. Kämpf, and J. L. Scartezzini, “Automated ‘Eye-sight’ Venetian blinds based on an embedded photometric device with real-time daylighting computing,” Applied Energy, vol. 252, p. 113317, 10 2019.
[81] X. Hong, M. K. Leung, and W. He, “Effective use of venetian blind in Trombe wall for solar space conditioning control,” Applied Energy, vol. 250, pp. 452–460, 9 2019. [Online]. Available: https://www.sciencedirect.com/science/article/pii/S030626191930772X
[82] B. Paule, E. Sok, S. Pantet, and J. Boutiller, “Electrochromic glazings: dynamic simulation of both daylight and thermal performance,” Energy Procedia, vol. 122, pp. 199–204, 9 2017. [Online]. Available: https://www.sciencedirect.com/science/article/pii/S1876610217329491
[83] Y. Sun, Y. Wu, R. Wilson, and S. Lu, “Experimental measurement and numerical simulation of the thermal performance of a double glazing system with an interstitial Venetian blind,” Building and Environment, vol. 103, pp. 111–122, 7 2016. [Online]. Available: https://www.sciencedirect.com/science/article/pii/S0360132316301111
[84] Y. Fang and P. C. Eames, “Thermal performance of an electrochromic vacuum glazing,” Energy Conversion and Management, vol. 47, no. 20, pp. 3602–3610, 12 2006. [Online]. Available: https://www.sciencedirect.com/science/article/pii/S0196890406000768#fig6
[85] A. L. Navarro, J. D. B. Cadena, F. Favoino, M. Donato, T. Poli, M. Perino, and M. Overend, “Occupant-Centred Control strategies for Adaptive Facades: A preliminary study of the impact of shortwave solar radiation on thermal comfort,” BUILDING SIMULATION CONFERENCE PROCEEDINGS, vol. 7, pp. 4910–4917, 2020.
[86] A. Motamed, L. Deschamps, and J. L. Scartezzini, “On-site monitoring and subjective comfort assessment of a sun shadings and electric lighting controller based on novel High Dynamic Range vision sensors,” Energy and Buildings, vol. 149, pp. 58–72, 8 2017.

[87] E. S. Lee and S. E. Selkowitz, “The New York Times Headquarters daylighting mockup: Monitored performance of the daylighting control system,” Energy and Buildings, vol. 38, no. 7, pp. 914–929, 2006.
[88] A. Guillemin and N. Morel, “An innovative lighting controller integrated in a self-adaptive building control system,” Energy and Buildings, vol. 33, no. 5, pp. 477–487, 5 2001.
[89] N. Lolli, A. Nocente, J. Brozovsky, R. Woods, and S. Grynning, “Automatic vs Manual Control Strategy for Window Blinds and Ceiling Lights: Consequences to Perceived Visual and Thermal Discomfort,” Journal of Daylighting, Vol. 6, Issue 2, pp. 112-123, vol. 6, no. 2, pp. 112–123, 11 2019. [Online]. Available: http://www.solarlits.com/jd/6-112http://solarlits.com/jd/6-112
[90] N. Lolli, A. Nocente, and S. Grynning, “Perceived Control in an Office Test Cell, a Case Study,” Buildings 2020, Vol. 10, Page 82, vol. 10, no. 5, p. 82, 4 2020.
[91] A. Luna-Navarro, G. Lori, D. Callewaert, and M. Overend, “Semi-automated vs manually controlled dynamic facades: assessment through a field study on multi-domain occupant satisfaction,” Energy and Buildings, vol. 286, p. 112912, 5 2023.
[92] B. Bueno, J. M. Cejudo Lopez, A. Katsifaraki, and H. R. Wilson, “A systematic workflow for retrofitting office façades with large window-to-wall ratios based on automatic control and building simulations,” Building and Environment, vol. 132, pp. 104–113, 3 2018.
[93] J. Xiong and A. Tzempelikos, “Model-based shading and lighting controls considering visual comfort and energy use,” Solar Energy, vol. 134, pp. 416–428, 9 2016.
[94] S. Yang, M. P. Wan, B. F. Ng, S. Dubey, G. P. Henze, W. Chen, and K. Baskaran, “Model predictive control for integrated control of air-conditioning and mechanical ventilation, lighting and shading systems,” Applied Energy, vol. 297, p. 117112, 9 2021.
[95] Z. Luo, C. Sun, and Q. Dong, “A daylight-linked shading strategy for automated blinds based on model-based control and Radial Basis Function (RBF) optimization,” Building and Environment, vol. 177, p. 106854, 6 2020.
[96] I. Konstantzos, A. Tzempelikos, and Y. C. Chan, “Experimental and simulation analysis of daylight glare probability inoffices with dynamic window shades,” Building and Environment, vol. 87, pp. 244–254, 5 2015.
[97] E. S. Lee, D. L. DiBartolomeo, J. Klems, M. Yazdanian, S. E. Selkowitz, E. S. Lee, D. L. DiBartolomeo, J. Klems, M. Yazdanian, and S. E. Selkowitz, “Monitored Energy Performance of Electrochromic Windows Controlled for Daylight and Visual Comfort Permalink https://escholarship.org/uc/item/76z069h7 Publication Date Monitored Energy Performance of Electrochromic Windows Controlled for Daylight and Visua,” 6 2006.
[98] E. S. Lee and D. L. DiBartolomeo, “Application issues for large-area electrochromic windows in commercial buildings,” Solar Energy Materials and Solar Cells, vol. 71, no. 4, pp. 465–491, 3 2002.
[99] N. Kunwar, K. S. Cetin, U. Passe, X. Zhou, and Y. Li, “Full-scale experimental testing of integrated dynamically-operated roller shades and lighting in perimeter office spaces,” Solar Energy, vol. 186, pp. 17–28, 7 2019.
[100] C. Goovaerts, F. Descamps, and V. A. Jacobs, “Shading control strategy to avoid visual discomfort by using a low-cost camera: A field study of two cases,” Building and Environment, vol. 125, pp. 26–38, 11 2017.
[101] P. La Roche and M. Milne, “EFFECTS OF COMBINING SMART SHADING AND VENTILATION ON THERMAL COMFORT.”
[102] Z. Luo, C. Sun, Q. Dong, and J. Yu, “An innovative shading controller for blinds in an open-plan office using machine learning,” Building and Environment, vol. 189, p. 107529, 2 2021.
[103] E. Shen, J. Hu, and M. Patel, “Energy and visual comfort analysis of lighting and daylight control strategies,” Building and Environment, vol. 78, pp. 155–170, 8 2014.
[104] H. Shen and A. Tzempelikos, “Daylighting and energy analysis of private offices with automated interior roller shades,” Solar Energy, vol. 86, no. 2, pp. 681–704, 2 2012.
[105] C. D. Corbin, G. P. Henze, and P. May-Ostendorp, “A model predictive control optimization environment for real-time commercial building application,” http://dx.doi.org/10.1080/19401493.2011.648343, vol. 6, no. 3, pp. 159–174, 5 2013.
[106] Z. Cheng, Q. Zhao, F. Wang, Y. Jiang, L. Xia, and J. Ding, “Satisfaction based Q-learning for integrated lighting and blind control,” Energy and Buildings, vol. 127, pp. 43–55, 9 2016.
[107] S. B. de Vries, R. C. Loonen, and J. L. Hensen, “Multi-state vertical-blinds solar shading – Performance assessment and recommended development directions,” Journal of Building Engineering, vol. 40, p. 102743, 8 2021.
[108] J. H. Choi, V. Loftness, D. Nou, B. Tinianov, and D. Yeom, “Multi-Season Assessment of Occupant Responses to Manual Shading and Dynamic Glass in a Workplace Environment,” Energies 2020, Vol. 13, Page 60, vol. 13, no. 1, p. 60, 12 2019. [Online]. Available: https://www.mdpi.com/1996-1073/13/1/60htmhttps://www.mdpi.com/1996-1073/13/1/60
[109] S. A. Sadeghi, P. Karava, I. Konstantzos, and A. Tzempelikos, “Occupant interactions with shading and lighting systems using different control interfaces: A pilot field study,” Building and Environment, vol. 97, pp. 177–195, 2 2016.
[110] L. Karlsen, P. Heiselberg, and I. Bryn, “Occupant satisfaction with two blind control strategies: Slats closed and slats in cut-off position,” Solar Energy, vol. 115, pp. 166–179, 5 2015.

[111] E. S. Lee, E. S. Claybaugh, and M. Lafrance, “End user impacts of automated electrochromic windows in a pilot retrofit application,” Energy and Buildings, vol. 47, pp. 267–284, 4 2012.
[112] S. S. Korsavi, R. V. Jones, and A. Fuertes, “The gap between automated building management system and office occupants’ manual window operations: Towards personalised algorithms,” Automation in Construction, vol. 132, p. 103960, 12 2021.
[113] L. Giovannini, F. Favoino, A. Pellegrino, V. R. M. Lo Verso, V. Serra, and M. Zinzi, “Thermochromic glazing performance: From component experimental characterisation to whole building performance evaluation,” Applied Energy, vol. 251, p. 113335, 10 2019.
[114] L. Karlsen, P. Heiselberg, I. Bryn, and H. Johra, “Solar shading control strategy for office buildings in cold climate,” Energy and Buildings, vol. 118, pp. 316–328, 4 2016.
[115] M. Rabani, H. Bayera Madessa, and N. Nord, “Achieving zero-energy building performance with thermal and visual comfort enhancement through optimization of fenestration, envelope, shading device, and energy supply system,” Sustainable Energy Technologies and Assessments, vol. 44, p. 101020, 4 2021.
[116] X. Wu, B. Lin, G. Papachristos, P. Liu, and N. Zimmermann, “A holistic approach to evaluate building performance gap of green office buildings: A case study in China,” Building and Environment, vol. 175, p. 106819, 5 2020.
[117] T. E. Kuhn, S. Herkel, F. Frontini, P. Strachan, and G. Kokogiannakis, “Solar control: A general method for modelling of solar gains through complex facades in building simulation programs,” Energy and Buildings, vol. 43, no. 1, pp. 19–27, 1 2011.
[118] M. Gonçalves, A. Figueiredo, R. M. Almeida, and R. Vicente, “Dynamic façades in buildings: A systematic review across thermal comfort, energy efficiency and daylight performance,” Renewable and Sustainable Energy Reviews, vol. 199, p. 114474, 7 2024.
[119] G. Jamilu, A. Abdou, and M. Asif, “Dynamic facades for sustainable buildings: A review of classification, applications, prospects and challenges,” Energy Reports, vol. 11, pp. 5999–6014, 6 2024.
[120] H. Alkhatib, P. Lemarchand, B. Norton, and D. T. O’Sullivan, “Deployment and control of adaptive building facades for energy generation, thermal insulation, ventilation and daylighting: A review,” Applied Thermal Engineering, vol. 185, p. 116331, 2 2021.
[121] “ISO 52016-3:2023 - Energy performance of buildings — Energy needs for heating and cooling, internal temperatures and sensible and latent heat loads — Part 3: Calculation procedures regarding adaptive building envelope elements.” [Online]. Available: https://www.iso.org/standard/75395.html
[122] S. Stevens, “INTELLIGENT FACADES: OCCUPANT CONTROL AND SATISFACTION,” https://doi.org/10.1080/01425910108914369, vol. 21, no. 2-3, pp. 147–160, 2007. [Online]. Available: https://www.tandfonline.com/doi/abs/10.1080/01425910108914369
[123] O. Straeter, “Human and Automation: System Design and Research Issues: Thomas B. Sheridan (Ed.); Wiley, New York, 2002,” Reliability Engineering & System Safety, vol. 81, no. 1, pp. 111–114, 7 2003.
[124] A. K. Frison, Y. Forster, P. Wintersberger, V. Geisel, and A. Riener, “Where We Come from and Where We Are Going: A Systematic Review of Human Factors Research in Driving Automation,” Applied Sciences 2020, Vol. 10, Page 8914, vol. 10, no. 24, p. 8914, 12 2020. [Online]. Available: https://www.mdpi.com/2076-3417/10/24/8914/htmhttps://www.mdpi.com/2076-3417/10/24/8914
[125] K. Goddard, A. Roudsari, and J. C. Wyatt, “Automation bias: a systematic review of frequency, effect mediators, and mitigators,” Journal of the American Medical Informatics Association : JAMIA, vol. 19, no. 1, pp. 121–127, 1 2012. [Online]. Available: https://pubmed.ncbi.nlm.nih.gov/21685142/
[126] U. Knaack, “Facades : principles of construction,” p. 135, 2007. [Online]. Available: https://books.google.com/books/about/Fa%C3%A7ades.html?hl=es&id=u81G-G4V3aAC
[127] J. Carmody, S. Selkowitz, E. S. Lee, D. Arasteh, T. Willmert, C. Wagus, W. Lingnell The, W. Group, R. Clear, R. Sullivan, K. Haglund, and W. Weber, “Window Systems for High-Performance Buildings Additional Contributors,” 2004. [Online]. Available: www.wwnorton.com
[128] S. K. Tang, “A Review on Natural Ventilation-enabling Façade Noise Control Devices for Congested High-Rise Cities,” Applied Sciences 2017, Vol. 7, Page 175, vol. 7, no. 2, p. 175, 2 2017. [Online]. Available: https://www.mdpi.com/2076-3417/7/2/175/htmhttps://www.mdpi.com/2076-3417/7/2/175
[129] N. Izadyar, W. Miller, B. Rismanchi, and V. Garcia-Hansen, “Impacts of façade openings’ geometry on natural ventilation and occupants’ perception: A review,” Building and Environment, vol. 170, p. 106613, 3 2020.
[130] L. Heschong, R. L. Wright, and S. Okura, “Daylighting Impacts on Human Performance in School,” http://dx.doi.org/10.1080/00994480.2002.10748396, vol. 31, no. 2, pp. 101–114, 2013. [Online]. Available: https://www.tandfonline.com/doi/abs/10.1080/00994480.2002.10748396
[131] C. Balocco, G. Petrone, C. Balocco, and G. Petrone, “Numerical Modelling for the Thermal Performance Assessment of a Semi-Opaque Façade with a Multilayer of Nano-Structured and Phase Change Materials,” Buildings 2017, Vol. 7,, vol. 7, no. 4, 10 2017. [Online]. Available: https://www.mdpi.com/2075-5309/7/4/90
[132] S. M. Hosseini, M. Mohammadi, and O. Guerra-Santin, “Interactive kinetic façade: Improving visual comfort based on dynamic daylight and occupant’s positions by 2D and 3D shape changes,” Building and Environment, vol. 165, p. 106396, 11 2019.

[133] S. Grynning, N. Lolli, S. Wågø, and B. Risholt, “Solar Shading in Low Energy Office Buildings - Design Strategy and User Perception,” Journal of Daylighting, Vol. 4, Issue 1, pp. 1-14, vol. 4, no. 1, pp. 1–14, 6 2017. [Online]. Available: http://www.solarlits.com/jd/4-1.htmlhttp://solarlits.com/jd/4-1.html

[134] S. Jain and V. Garg, “A review of open loop control strategies for shades, blinds and integrated lighting by use of real-time daylight prediction methods,” Building and Environment, vol. 135, pp. 352–364, 5 2018.

[135] A. Tabadkani, A. Roetzel, H. X. Li, and A. Tsangrassoulis, “A review of occupant-centric control strategies for adaptive facades,” p. 103464, 2 2021.

[136] A. Motamed, L. Deschamps, and J. L. Scartezzini, “Eight-month experimental study of energy impact of integrated control of sun shading and lighting system based on HDR vision sensor,” Energy and Buildings, vol. 203, p. 109443, 11 2019.

[137] C. L. Cheng, L. M. Liao, and C. P. Chou, “A study of summarized correlation with shading performance for horizontal shading devices in Taiwan,” Solar Energy, vol. 90, pp. 1–16, 4 2013.

[138] E. Lee, D. DiBartolomeo, E. Vine, and S. Selkowitz, “Integrated Performance of an Automated Venetian Blind/Electric Lighting System in a Full-Scale Private Office | Center of Expertise for Energy Efficiency in Data Centers,” in Proceedings of the ASHRAE/DOE/BTECC Conference, Thermal Performance of the Exterior Envelopes of Buildings VII, Clearwater Beach, Florida, December 7-11, 1998, 1998.

[139] T. Taniguchi, T. Iwata, and D. Ito, “Blind Control Method Based on Prevention of Discomfort Glare Taking Account of Building Conditions,” 2012.

[140] J. H. Choi and D. Yeom, “Development of the data-driven thermal satisfaction prediction model as a function of human physiological responses in a built environment,” Building and Environment, vol. 150, pp. 206–218, 3 2019.

[141] Y. Wu, J. H. Kämpf, and J. L. Scartezzini, “A survey study of occupants? visual satisfaction on an automated venetian blind based on sky luminance monitoring and lighting simulation,” Proceedings of the ISES Solar World Congress 2019 and IEA SHC International Conference on Solar Heating and Cooling for Buildings and Industry 2019, pp. 685–692, 2020.

[142] B. Painter, K. N. Irvine, R. K. Waskett, and J. Mardaljevic, “Evaluation of a Mixed Method Approach for Studying User Interaction with Novel Building Control Technology,” Energies 2016, Vol. 9, Page 215, vol. 9, no. 3, p. 215, 3 2016. [Online]. Available: https://www.mdpi.com/1996-1073/9/3/215/htmhttps://www.mdpi.com/1996-1073/9/3/215

[143] Y. Bian, Q. Dai, Y. Ma, and L. Liu, “Variable set points of glare control strategy for side-lit spaces: Daylight glare tolerance by time of day,” Solar Energy, vol. 201, pp. 268–278, 5 2020.

[144] J. H. Choi and J. Moon, “Impacts of human and spatial factors on user satisfaction in office environments,” Building and Environment, vol. 114, pp. 23–35, 3 2017.

[145] M. He, H. Pen, M. Li, Y. Huang, D. Yan, S. Lou, and L. Wen, “Investigation on typical occupant behavior in air-conditioned office buildings for South China’s Pearl River Delta,” Architectural Intelligence, vol. 1, 12 2022.

[146] A. N. Tak, B. Becerik-Gerber, L. Soibelman, and G. Lucas, “A framework for investigating the acceptance of smart home technologies: Findings for residential smart HVAC systems,” Building and Environment, vol. 245, p. 110935, 11 2023.

[147] B. Becerik-Gerber, G. Lucas, A. Aryal, M. Awada, M. Bergés, S. Billington, O. Boric-Lubecke, A. Ghahramani, A. Heydarian, C. Höelscher, F. Jazizadeh, A. Khan, J. Langevin, R. Liu, F. Marks, M. L. Mauriello, E. Murnane, H. Noh, M. Pritoni, S. Roll, D. Schaumann, M. Seyedrezaei, J. E. Taylor, J. Zhao, and R. Zhu, “The field of human building interaction for convergent research and innovation for intelligent built environments,” Scientific Reports 2022 12:1, vol. 12, no. 1, pp. 22 092–, 12 2022. [Online]. Available: https://www.nature.com/articles/s41598-022-25047-y

[148] K. Ravulakollu, P. Rajput, and A. Varanasi, Acceptance: A Forgotten Dimension of Usability in Ambient Intelligent Environments, 9 2021.

[149] B. W. Meerbeek, C. de Bakker, Y. A. de Kort, E. J. van Loenen, and T. Bergman, “Automated blinds with light feedback to increase occupant satisfaction and energy saving,” Building and Environment, vol. 103, pp. 70–85, 7 2016.

[150] N. Balta-Ozkan, R. Davidson, M. Bicket, and L. Whitmarsh, “Social barriers to the adoption of smart homes,” Energy Policy, vol. 63, pp. 363–374, 12 2013.

[151] D. Malekpour Koupaei, T. Song, K. S. Cetin, and J. Im, “An assessment of opinions and perceptions of smart thermostats using aspect-based sentiment analysis of online reviews,” Building and Environment, vol. 170, p. 106603, 3 2020.

[152] T. A. Nguyen and M. Aiello, “Energy intelligent buildings based on user activity: A survey,” Energy and Buildings, vol. 56, pp. 244–257, 1 2013.

[153] F. Mofidi and H. Akbari, “Intelligent buildings: An overview,” Energy and Buildings, vol. 223, p. 110192, 9 2020.

[154] J. K. Day, C. McIlvennie, C. Brackley, M. Tarantini, C. Piselli, J. Hahn, W. O’Brien, V. S. Rajus, M. De Simone, M. B. Kjærgaard, M. Pritoni, A. Schlüter, Y. Peng, M. Schweiker, G. Fajilla, C. Becchio, V. Fabi, G. Spigliantini, G. Derbas, and A. L. Pisello, “A review of select human-building interfaces and their relationship to human behavior, energy use and occupant comfort,” Building and Environment, vol. 178, p. 106920, 7 2020.

[155] M. Koyaz and A. Ünlü, "Human-centred performance criteria for adaptive façade design: Based on the results of a user experience survey," Building and Environment, vol. 222, p. 109386, 8 2022.

[156] S. Bilir and S. U. d. L. . D. A. . T. d. c. d. b. Attia, "Performance Evaluation of Adaptive Facades: A case study with electrochromic glazing," COST Action TU1403 Adaptive Facades Conference, no. Luible 2014, pp. 315–324, 11 2018. [Online]. Available: https://orbi.uliege.be/handle/2268/213742

[157] d. la Barra Luegmayer, P. Hoces, P. de la Barra, A. Luna-Navarro, A. Prieto, C. Vásquez, and U. Knaack, "Influence of Automated Façades on Occupants: A Review," Journal of Facade Design and Engineering, vol. 10, no. 2, pp. 19–38, 2022. [Online]. Available: https://research.tudelft.nl/en/publications/influence-of-automated-fa%C3%A7ades-on-occupants-a-review

[158] A. Luna-Navarro and M. Overend, "Design, construction and validation of MATELab: A novel outdoor chamber for investigating occupant-facade interaction," Building and Environment, p. 108092, 6 2021. [Online]. Available: https://linkinghub.elsevier.com/retrieve/pii/S0360132321004947

[159] M. Hassen, P. de la Barra, S. Oke, M. Overend, M. Bilow, and A. Luna-Navarro, "Glass serviceability limits: new evidence from human-centred studies," Glass Structures and Engineering, vol. 9, no. 3, pp. 657–669, 12 2024. [Online]. Available: https://link.springer.com/article/10.1007/s40940-024-00280-1

[160] R. W. Picard, E. Vyzas, and J. Healey, "Toward machine emotional intelligence: Analysis of affective physiological state," IEEE Transactions on Pattern Analysis and Machine Intelligence, vol. 23, no. 10, pp. 1175–1191, 2001.

[161] M. Allen and M. Overend, "Towards a New Way of Capturing Occupant Well-being," pp. 631–636, 2018.

[162] B. Y. Kim and Y. Ham, "Personal thermal comfort modeling based on facial expression," Journal of Building Engineering, vol. 75, p. 106956, 9 2023.

[163] C. Bedon and S. Mattei, "Facial Expression-Based Experimental Analysis of Human Reactions and Psychological Comfort on Glass Structures in Buildings," Buildings 2021, Vol. 11, Page 204, vol. 11, no. 5, p. 204, 5 2021. [Online]. Available: https://www.mdpi.com/2075-5309/11/5/204/htmhttps://www.mdpi.com/2075-5309/11/5/204

[164] Y. Li, X. Nian, C. Gu, P. Deng, S. He, and B. Hong, "Assessing children's outdoor thermal comfort with facial expression recognition: An efficient approach using machine learning," Building and Environment, vol. 258, p. 111556, 6 2024.

[165] M. Allen and M. Overend, "Can a building read your mind? Results from a small trial in facial action unit detection," Journal of Physics: Conference Series, vol. 1343, no. 1, p. 012056, 11 2019. [Online]. Available: https://iopscience.iop.org/article/10.1088/1742-6596/1343/1/012056https://iopscience.iop.org/article/10.1088/1742-6596/1343/1/012056/meta

[166] M. Sarey Khanie, J. Stoll, W. Einhäuser, J. Wienold, and M. Andersen, "Gaze and discomfort glare, Part 1: Development of a gaze-driven photometry," Lighting Research and Technology, vol. 49, no. 7, pp. 845–865, 11 2017. [Online]. Available: https://journals.sagepub.com/doi/10.1177/1477153516649016

[167] J. H. Lee and M. J. Ostwald, "The 'visual attractiveness' of architectural facades: measuring visual complexity and attractive strength in architecture," Architectural Science Review, vol. 66, no. 1, pp. 42–52, 1 2023. [Online]. Available: https://www.tandfonline.com/doi/abs/10.1080/00038628.2022.2137458

[168] M. R. Saleem, R. Mayne, and R. Napolitano, "Analysis of gaze patterns during facade inspection to understand inspector sense-making processes," Scientific Reports 2023 13:1, vol. 13, no. 1, pp. 2929–, 2 2023. [Online]. Available: https://www.nature.com/articles/s41598-023-29950-w

[169] T. Baltrusaitis, A. Zadeh, Y. C. Lim, and L. P. Morency, "OpenFace 2.0: Facial behavior analysis toolkit," Proceedings - 13th IEEE International Conference on Automatic Face and Gesture Recognition, FG 2018, pp. 59–66, 6 2018.

[170] A. Kuznetsova, P. B. Brockhoff, and R. H. Christensen, "lmerTest Package: Tests in Linear Mixed Effects Models," Journal of Statistical Software, vol. 82, no. 13, pp. 1–26, 12 2017. [Online]. Available: https://www.jstatsoft.org/index.php/jss/article/view/v082i13

[171] N. Nachar, "The Mann-Whitney U: A Test for Assessing Whether Two Independent Samples Come from the Same Distribution," Tutorials in Quantitative Methods for Psychology, vol. 4, no. 1, pp. 13–20, 3 2008.

[172] P. Virtanen, R. Gommers, T. E. Oliphant, M. Haberland, T. Reddy, D. Cournapeau, E. Burovski, P. Peterson, W. Weckesser, J. Bright, S. J. van der Walt, M. Brett, J. Wilson, K. J. Millman, N. Mayorov, A. R. Nelson, E. Jones, R. Kern, E. Larson, C. J. Carey, Polat, Y. Feng, E. W. Moore, J. VanderPlas, D. Laxalde, J. Perktold, R. Cimrman, I. Henriksen, E. A. Quintero, C. R. Harris, A. M. Archibald, A. H. Ribeiro, F. Pedregosa, P. van Mulbregt, A. Vijaykumar, A. P. Bardelli, A. Rothberg, A. Hilboll, A. Kloeckner, A. Scopatz, A. Lee, A. Rokem, C. N. Woods, C. Fulton, C. Masson, C. Häggström, C. Fitzgerald, D. A. Nicholson, D. R. Hagen, D. V. Pasechnik, E. Olivetti, E. Martin, E. Wieser, F. Silva, F. Lenders, F. Wilhelm, G. Young, G. A. Price, G. L. Ingold, G. E. Allen, G. R. Lee, H. Audren, I. Probst, J. P. Dietrich, J. Silterra, J. T. Webber, J. Slavič, J. Nothman, J. Buchner, J. Kulick, J. L. Schönberger, J. V. de Miranda Cardoso, J. Reimer, J. Harrington, J. L. C. Rodríguez, J. Nunez-Iglesias, J. Kuczynski, K. Tritz, M. Thoma, M. Newville, M. Kümmerer, M. Bolingbroke, M. Tartre, M. Pak, N. J. Smith, N. Nowaczyk, N. Shebanov, O. Pavlyk, P. A. Brodtkorb, P. Lee, R. T. McGibbon, R. Feldbauer, S. Lewis, S. Tygier, S. Sievert, S. Vigna, S. Peterson, S. More, T. Pudlik, T. Oshima, T. J. Pingel, T. P. Robitaille, T. Spura, T. R. Jones, T. Cera,

T. Leslie, T. Zito, T. Krauss, U. Upadhyay, Y. O. Halchenko, and Y. Vázquez-Baeza, “SciPy 1.0: fundamental algorithms for scientific computing in Python,” Nature Methods 2020 17:3, vol. 17, no. 3, pp. 261–272, 2 2020. [Online]. Available: https://www.nature.com/articles/s41592-019-0686-2

[173] A. Verma, S. Prakash, V. Srivastava, A. Kumar, and S. C. Mukhopadhyay, “Sensing, Controlling, and IoT Infrastructure in Smart Building: A Review,” IEEE Sensors Journal, vol. 19, no. 20, pp. 9036–9046, 10 2019.

[174] P. de la Barra, E. Brembilla, A. Prieto, C. Vásquez, U. Knaack, and A. Luna-Navarro, “Influence of automated façades on comfort and energy: A critical review,” Energy and Buildings, vol. 347, p. 116290, 11 2025. [Online]. Available: https://www.sciencedirect.com/science/article/pii/S0378778825010205

[175] T. Van De Werff, K. Niemantsverdriet, H. Van Essen, and B. Eggen, “Evaluating interface characteristics for shared lighting systems in the office environment,” DIS 2017 - Proceedings of the 2017 ACM Conference on Designing Interactive Systems, pp. 209–220, 6 2017. [Online]. Available: https://dl.acm.org/doi/pdf/10.1145/3064663.3064749

[176] K. Niemantsverdriet, T. Van De Werff, H. Van Essen, and B. Eggen, “Share and share alike? Social information and interaction style in coordination of shared use,” Conference on Human Factors in Computing Systems - Proceedings, vol. 2018-April, 4 2018. [Online]. Available: https://dl.acm.org/doi/pdf/10.1145/3173574.3173877

[177] T. Van De Werff, C. Van Lotringen, H. Van Essen, and B. Eggen, “Design considerations for interactive office lighting interface characteristics, shared and hybrid control,” Conference on Human Factors in Computing Systems - Proceedings, vol. 14, 5 2019. [Online]. Available: https://dl.acm.org/doi/pdf/10.1145/3290605.3300640

[178] T. Lashina, S. Chraibi, M. Despenic, P. Shrubsole, A. Rosemann, and E. van Loenen, “Sharing lighting control in an open office: Doing one’s best to avoid conflict,” Building and Environment, vol. 148, pp. 1–10, 1 2019. [Online]. Available: https://www.sciencedirect.com/science/article/pii/S0360132318306656?via%3Dihub

[179] J. Day, J. Theodorson, and K. Van Den Wymelenberg, “Understanding controls, behaviors and satisfaction in the daylit perimeter office: A daylight design case study,” Journal of Interior Design, vol. 37, no. 1, pp. 17 – 34, 3 2012.

[180] G. Brager, H. Zhang, and E. Arens, “Evolving opportunities for providing thermal comfort,” Building Research & Information, vol. 43, no. 3, pp. 274–287, 5 2015. [Online]. Available: https://www.tandfonline.com/doi/abs/10.1080/09613218.2015.993536

[181] R. T. Hellwig, “User friendliness and building automation - A conceptual approach to understanding perceived control.” p. 14041, 2014. [Online]. Available: https://vbn.aau.dk/en/publications/user-friendliness-and-building-automation-a-conceptual-approach-t/

[182] D. Perry, C. Aragon, A. Meier, T. Peffer, M. Pritoni, D. Perry, C. Aragon, A. Meier, T. Peffer, and M. Pritoni, “Making Energy Savings Easier: Usability Metrics for Thermostats Publication Date,” JOURNAL OF USABILITY STUDIES, vol. 6, no. 4, pp. 226–244, 2011. [Online]. Available: https://escholarship.org/uc/item/9gz9x7br

[183] A. M. Dugar, M. R. Donn, and W. Osterhaus, “Tangible lighting controls-Reporting endusers’ interactions with lighting control interfaces,” LEUKOS - Journal of Illuminating Engineering Society of North America, vol. 8, no. 2, pp. 123 – 136, 10 2011.

[184] S. Karjalainen and O. Koistinen, “User problems with individual temperature control in offices,” Building and Environment, vol. 42, no. 8, pp. 2880–2887, 8 2007.

[185] T. Lashina, S. van der Vleuten-Chraibi, D. Aliakseyeu, J. de Jongh-Teunisse, P. Shrubsole, and T. Speelpenning, “User interaction for personalized total light management,” Intelligent Buildings International, vol. 14, no. 3, pp. 346–362, 5 2022. [Online]. Available: https://scholar.google.com/scholar_url?url=https://www.tandfonline.com/doi/pdf/10.1080/17508975.2021.1902258%3Fcasa_token%3DNZScljbzs5cAAAAA:5yFuMH2H6po4QXH0UBGqjumCT6VPh_emMvX8n5soT6dXizwvYio_G8inCOQOgWllc-IDDRYyi98&hl=en&sa=T&oi=ucasa&ct=ucasa&ei=84bAaKCnKJ-R6rQP28moiQw&scisig=AAZF9b8xAjUwfr8w0RkVurVL03fU

[186] F. S. Yllmaz, C. Ticleanu, G. Howlett, S. King, and P. J. Littlefair, “People-friendly lighting controls – User performance and feedback on different interfaces,” http://dx.doi.org/10.1177/1477153515583180, vol. 48, no. 4, pp. 449–472, 4 2015. [Online]. Available: https://journals.sagepub.com/doi/10.1177/1477153515583180

[187] K. L. van Someren, C. P. Beaman, and L. Shao, “Users’ experiences of lighting controls: A case-study,” Lighting Research and Technology, vol. 50, no. 7, pp. 1091 – 1106, 11 2018.

[188] S. Kianpour rad, P. Agee, A. Akanmu, J. Iorio, and L. Zhang, “A summative user evaluation of connected thermostats,” Building and Environment, vol. 262, p. 111814, 8 2024. [Online]. Available: https://www.sciencedirect.com/science/article/pii/S0360132324006565?via%3Dihub

[189] K. McGlinn, B. Yuce, H. Wicaksono, S. Howell, and Y. Rezgui, “Usability evaluation of a web-based tool for supporting holistic building energy management,” Automation in Construction, vol. 84, pp. 154–165, 12 2017. [Online]. Available: https://www.sciencedirect.com/science/article/pii/S0926580516303545?via%3Dihub

[190] W. Albert, T. Tullis, and W. Albert, “Measuring the User Experience,” Measuring the User Experience, 2008. [Online]. Available: http://www.sciencedirect.com:5070/book/9780123735584/measuring-the-user-experience

[191] J. Sauro and E. Kindlund, “Using a Single Usability Metric (SUM) to Compare the Usability of Competing Products,” 2005.

[192] N. D. Murphy, “Front panel : designing software for embedded user interfaces,” p. 315, 1998. [Online]. Available: https://books.google.com/books/about/Front_Panel.html?id=jF-6iTt2NccC

[193] N. Gentile, “Improving lighting energy efficiency through user response,” Energy and Buildings, vol. 263, p. 112022, 5 2022. [Online]. Available: https://www.sciencedirect.com/science/article/pii/S0378778822001931?via%3Dihub

[194] “Home Assistant.” [Online]. Available: https://www.home-assistant.io/?utm_source=chatgpt.com

[195] J. Sauro and J. R. Lewis, “Quantifying the User Experience,” Quantifying the User Experience, 2012. [Online]. Available: http://www.sciencedirect.com:5070/book/9780123849687/quantifying-the-user-experience

[196] H. Yanai and M. Ichikawa, “Factor Analysis,” Handbook of Statistics, vol. 26, pp. 257–296, 1 2006. [Online]. Available: https://www.sciencedirect.com/science/article/abs/pii/S0169716106260097?via%3Dihub

[197] H. Taherdoost, S. Sahibuddin, and N. Jalaliyoon, “Exploratory Factor Analysis ; Concepts and Theory,” 2014.

[198] H. F. Kaiser, “The Application of Electronic Computers to Factor Analysis,” Educational and Psychological Measurement, vol. 20, no. 1, pp. 141–151, 1960. [Online]. Available: https://journals.sagepub.com/doi/10.1177/001316446002000116

[199] R. F. DeVellis, “Scale development : theory and applications,” p. 205, 2012. [Online]. Available: https://books.google.com/books/about/Scale_Development.html?id=vmwBHYuchfAC

[200] C. Distefano, M. Zhu, and D. Mîndrila, “Understanding and Using Factor Scores: Considerations for the Applied Researcher,” Practical Assessment, Research and Evaluation, 2009.

[201] A. S. Fullerton, “A Conceptual Framework for Ordered Logistic Regression Models,” Sociological Methods & Research, vol. 38, no. 2, pp. 306–347, 11 2009. [Online]. Available: https://journals.sagepub.com/doi/10.1177/0049124109346162

[202] F. H. Botelho, “Accessibility to digital technology: Virtual barriers, real opportunities,” Assistive Technology, vol. 33, no. sup1, pp. 27–34, 12 2021. [Online]. Available: https://www.tandfonline.com/doi/abs/10.1080/10400435.2021.1945705

[203] J. Arnera, C. H. M. Chan, and M. Cherubini, “Digital, Analog, or Hybrid: Comparing Strategies to Support Self-Reflection,” Proceedings of the 2024 ACM Designing Interactive Systems Conference, DIS 2024, pp. 3435–3452, 7 2024. [Online]. Available: https://dl.acm.org/doi/pdf/10.1145/3643834.3661558

[204] A. Meier, M. Pritoni, and C. Aragon, “Thermostat Interface and Usability: A Survey,” 9 2010. [Online]. Available: http://www.osti.gov/servlets/purl/1004198-Ff7EhC/

[205] “Climate Change 2022: Mitigation of Climate Change.” [Online]. Available: https://www.ipcc.ch/report/ar6/wg3/

[206] T. Hong, S. D’Oca, W. J. Turner, and S. C. Taylor-Lange, “An ontology to represent energy-related occupant behavior in buildings. Part I: Introduction to the DNAs framework,” Building and Environment, vol. 92, pp. 764–777, 10 2015.

[207] D. Yan, W. O’Brien, T. Hong, X. Feng, H. Burak Gunay, F. Tahmasebi, and A. Mahdavi, “Occupant behavior modeling for building performance simulation: Current state and future challenges,” Energy and Buildings, vol. 107, pp. 264–278, 11 2015.

[208] P. Hoes, J. L. Hensen, M. G. Loomans, B. de Vries, and D. Bourgeois, “User behavior in whole building simulation,” Energy and Buildings, vol. 41, no. 3, pp. 295–302, 3 2009.

[209] S. Carlucci, M. De Simone, S. K. Firth, M. B. Kjærgaard, R. Markovic, M. S. Rahaman, M. K. Annaqeeb, S. Biandrate, A. Das, J. W. Dziedzic, G. Fajilla, M. Favero, M. Ferrando, J. Hahn, M. Han, Y. Peng, F. Salim, A. Schlüter, and C. van Treeck, “Modeling occupant behavior in buildings,” Building and Environment, vol. 174, p. 106768, 5 2020.

[210] A. Mahdavi and F. Tahmasebi, “Predicting people’s presence in buildings: An empirically based model performance analysis,” Energy and Buildings, vol. 86, pp. 349–355, 1 2015.

[211] C. de Bakker, M. Aries, H. Kort, and A. Rosemann, “Occupancy-based lighting control in open-plan office spaces: A state-of-the-art review,” Building and Environment, vol. 112, pp. 308–321, 2 2017.

[212] R. Parasuraman, T. B. Sheridan, and C. D. Wickens, “A model for types and levels of human interaction with automation,” IEEE Transactions on Systems, Man, and Cybernetics Part A:Systems and Humans., vol. 30, no. 3, pp. 286–297, 2000.

[213] S. Ahmadi-Karvigh, A. Ghahramani, B. Becerik-Gerber, and L. Soibelman, “One size does not fit all: Understanding user preferences for building automation systems,” Energy and Buildings, vol. 145, pp. 163–173, 6 2017.

[214] S. Karjalainen, “Should it be automatic or manual—The occupant’s perspective on the design of domestic control systems,” Energy and Buildings, vol. 65, pp. 119–126, 10 2013. [Online]. Available: https://www.sciencedirect.com/science/article/pii/S0378778813003319?via%3Dihub

[215] M. Kwon, H. Remøy, A. van den Dobbelsteen, and U. Knaack, “Personal control and environmental user satisfaction in office buildings: Results of case studies in the Netherlands,” Building and Environment, vol. 149, pp. 428–435, 2 2019.

[216] A. Soleimanijavid, I. Konstantzos, and X. Liu, “Challenges and opportunities of occupant-centric building controls in real-world implementation: A critical review,” Energy and Buildings, vol. 308, p. 113958, 4 2024.

[217] M. Frontczak and P. Wargocki, “Literature survey on how different factors influence human comfort in indoor environments,” Building and Environment, vol. 46, no. 4, pp. 922–937, 4 2011.

[218] I. Sakellaris, D. Saraga, C. Mandin, Y. de Kluizenaar, S. Fossati, A. Spinazzè, A. Cattaneo, T. Szigeti, V. Mihucz, E. d. O. Fernandes, K. Kalimeri, P. Carrer, and J. Bartzis, “Personal Control of the Indoor Environment in Offices: Relations with Building Characteristics, Influence on Occupant Perception and Reported Symptoms Related to the Building—The Officair Project,” Applied Sciences 2019, Vol. 9, Page 3227, vol. 9, no. 16, p. 3227, 8 2019. [Online]. Available: https://www.mdpi.com/2076-3417/9/16/3227/htmhttps://www.mdpi.com/2076-3417/9/16/3227

[219] A. Boerstra, M. Loomans, and J. Hensen, “Personal control over indoor climate and productivity,” pp. 1–8, 2014. [Online]. Available: https://research.tue.nl/en/publications/personal-control-over-indoor-climate-and-productivity/

[220] G. Derbas, A. Xhonneux, and D. Müller, “Assessment of a cloud-based heating controller: Impact on user behaviour, comfort, and perceived control,” Building and Environment, vol. 283, p. 113345, 9 2025.

[221] S. Hammes, D. Geisler-Moroder, M. Hauer, J. Weninger, M. Obleitner, J. Miller, D. Plörer, V. Van Karsbergen, R. Weitlaner, and R. Pfluger, “Concepts of user-centred lighting controls for office applications: A systematic literature review,” Building and Environment, vol. 254, p. 111321, 4 2024.

[222] P. Correia da Silva, V. Leal, and M. Andersen, “Occupants interaction with electric lighting and shading systems in real single-occupied offices: Results from a monitoring campaign,” Building and Environment, vol. 64, pp. 152–168, 6 2013.

[223] A. Meier, C. Aragon, T. Peffer, D. Perry, and M. Pritoni, “Usability of residential thermostats: Preliminary investigations,” Building and Environment, vol. 46, no. 10, pp. 1891–1898, 10 2011.

[224] T. Peffer, D. Perry, M. Pritoni, C. Aragon, and A. Meier, “Facilitating energy savings with programmable thermostats: evaluation and guidelines for the thermostat user interface,” Ergonomics, vol. 56, no. 3, pp. 463–479, 3 2013. [Online]. Available: https://www.tandfonline.com/doi/abs/10.1080/00140139.2012.718370

[225] G. Brager, G. Paliaga, R. D. Dear, and J. Wen, “Operable Windows, Personal Control, and Occupant Comfort,” ASHRAE transactions, vol. 110, 2004. [Online]. Available: https://researchdiscovery.drexel.edu/esploro/outputs/journalArticle/Operable-Windows-Personal-Control-and-Occupant/991019173532004721

[226] L. Zagreus, C. Huizenga, E. Arens, and D. Lehrer, “Listening to the occupants: a Web-based indoor environmental quality survey,” Indoor Air, vol. 14, no. 8, pp. 65–74, 2004. [Online]. Available: https://onlinelibrary.wiley.com/doi/full/10.1111/j.1600-0668.2004.00301.xhttps://onlinelibrary.wiley.com/doi/abs/10.1111/j.1600-0668.2004.00301.xhttps://onlinelibrary.wiley.com/doi/10.1111/j.1600-0668.2004.00301.x

[227] T. Cheung, S. Schiavon, L. T. Graham, and K. W. Tham, “Occupant satisfaction with the indoor environment in seven commercial buildings in Singapore,” Building and Environment, vol. 188, p. 107443, 1 2021.

[228] T. Parkinson, S. Schiavon, J. Kim, and G. Betti, “Common sources of occupant dissatisfaction with workspace environments in 600 office buildings,” Buildings and Cities, vol. 4, no. 1, pp. 17–35, 2023.

[229] A. D. Galasiu and J. A. Veitch, “Occupant preferences and satisfaction with the luminous environment and control systems in daylit offices: a literature review,” Energy and Buildings, vol. 38, no. 7, pp. 728–742, 7 2006.

[230] D. Kim, “Categorical Data Analysis, 3rd Edition by AGRESTI, ALAN,” Biometrics, vol. 69, no. 4, 2013.

[231] J. Cohen, “Weighted kappa: Nominal scale agreement provision for scaled disagreement or partial credit,” Psychological Bulletin, vol. 70, no. 4, 1968.

[232] F. Wilcoxon, “Individual Comparisons by Ranking Methods Author (s): Frank Wilcoxon Published by : International Biometric Society,” Biometrics Bulletin, vol. 1, no. 6, 1945.

[233] W. J. Conover, “Practical nonparametric statistics Third Edition,” 1999.

[234] A. Stuart, “A Test for Homogeneity of the Marginal Distributions in a Two-Way Classification,” Biometrika, vol. 42, no. 3/4, 1955.

[235] A. H. Bowker, “A Test for Symmetry in Contingency Tables,” Journal of the American Statistical Association, vol. 43, no. 244, 1948.

[236] S. Holm, “A simple sequentially rejective multiple test procedure,” Scandinavian journal of statistics, vol. 6, no. 2, 1979.

[237] P. Mccullagh, “Regression Models for Ordinal Data Peter McCullagh,” Journal of the Royal Statistical Society, vol. 42, no. 2, 1980.

[238] J. S. Long and J. Freese, Regression Models for Categorical Dependent Variables Using STATA, 2001, vol. Revised ed.

[239] I. Gaetani, P. J. Hoes, and J. L. Hensen, “Estimating the influence of occupant behavior on building heating and cooling energy in one simulation run,” Applied Energy, vol. 223, pp. 159–171, 8 2018.

[240] S. D’Oca, D. Podjed, J. Vetršek, S. Dolinšek, and P. Op’t Veld, “Contextual and behavioural factors influencing human-building interaction in university offices: a cross-cultural comparison,” E3S Web of

Conferences, vol. 111, p. 04064, 8 2019. [Online]. Available: https://www.e3s-conferences.org/articles/e3sconf/abs/2019/37/e3sconf_clima2019_04064/e3sconf_clima2019_04064.html

[241] S. D'Oca and T. Hong, "A data-mining approach to discover patterns of window opening and closing behavior in offices," Building and Environment, vol. 82, pp. 726–739, 12 2014.

[242] W. O'Brien and H. B. Gunay, "The contextual factors contributing to occupants' adaptive comfort behaviors in offices – A review and proposed modeling framework," Building and Environment, vol. 77, pp. 77–87, 7 2014.

[243] S. Wei, R. Buswell, and D. Loveday, "Factors affecting 'end-of-day' window position in a non-air-conditioned office building," Energy and Buildings, vol. 62, pp. 87–96, 7 2013.

[244] S. Nikou, "Factors driving the adoption of smart home technology: An empirical assessment," Telematics and Informatics, vol. 45, p. 101283, 12 2019.

Appendices

APPENDIX A

Questionnaires for an Experimental Campaign

This appendix presents the questionnaires used during the experimental campaign, including the recruitment questionnaire, the kick-off questionnaire, and the post-scenario questionnaire administered after each automated control condition.

Recruitment Questionnaire

TABLE APP. A.1 Recruitment questionnaire used prior to the experiment.

Question	Answer format
Please indicate your age	Open response
Please select your gender	Male / Female / Other
Highest level of education	Primary / Bachelor / Master / Doctorate / Professional
Country of origin	Open response
Familiarity with smart windows	1 (Not familiar) – 5 (Very familiar)
Familiarity with smart blinds	1 (Not familiar) – 5 (Very familiar)
Importance of control (home, blinds)	1 (Not important) – 5 (Very important)
Importance of control (office, blinds)	1–5 Likert scale
Importance of window opening (home/office)	1–5 Likert scale
Frequency of window interaction	1 (Never) – 5 (More than once/day)
Frequency of shading interaction	1–5 Likert scale
Random ID assignment	Generated automatically

Kick-off Questionnaire

TABLE APP. A.2 Kick-off questionnaire completed at the beginning of the experiment.

Question	Answer format
Participant ID	Open response
Satisfaction with office space, thermal environment, daylight	1–5 Likert scale
Glare perception	Yes / No
Satisfaction with outdoor view, window control, temperature, acoustics, air quality	1–5 Likert scale
Emotional state (calm, rested, familiarity)	1–5 Likert scale
Visual impairment	Yes (describe) / No
Additional feedback	Open response

Post-Scenario Questionnaire

TABLE APP. A.3 Questionnaire administered after each automated control scenario.

Question	Answer format
Did you notice changes in window, lighting, or heating?	Yes / No + description
“I did not feel distracted from the task”	1–5 Likert scale
“Satisfaction with visual environment”	1–5 Likert scale
“I was not annoyed with automated controls”	1–5 Likert scale
“Satisfaction with automated systems”	1–5 Likert scale
Reason for override (if applicable)	Open response

APPENDIX B

Questionnaires for a Large Survey Campaign

The following appendix presents the questionnaire used in the large-scale survey campaign. The questionnaire was structured into thematic sections, each targeting specific aspects of user background, workplace context, and preferences regarding building automation. Each section is described below together with the corresponding survey items.

Demographic Information

This section collected general background information about the respondents, including age, gender, education level, and country of residence. These variables were used to contextualize user preferences and enable segmentation analysis.

TABLE APP. B.1 Demographic Questions

Question	Type of answer	Answer
Please indicate your age range:	Single choice	1. Under 18 2. 18–24 3. 25–34 4. 35–44 5. 45–54 6. 55–64 7. 65–74 8. 75–84 9. 85 or older
What is your sex assigned at birth?	Single choice	1. Female 2. Male 3. Intersex 4. Prefer not to say 5. Other
Please indicate your level of education:	Single choice	1. Elementary school 2. Secondary school 3. Bachelor degree 4. Master’s degree 5. Doctoral degree
In which country have you lived the longest?	Single choice	Country selection

Office Context

This section aimed to characterize the respondents' workplace environment, including spatial conditions, building context, and exposure to environmental factors such as noise and view. It also included questions about the availability and control of building services.

TABLE APP. B.2 Office Context Questions

Question	Type of answer	Answer
In which country is your office situated?	Single choice	Text – country
On average, how many days a week do you spend in the office?	Single choice	Number (1–5)
On average, how many hours a day do you spend at your workplace?	Single choice	Number (1–10)
Are you usually working at the same desk?	Single choice	1. No, flexible desking 2. Always at the same desk
What is the outdoor context of your office building?	Single choice	1. Urban 2. Semi-urban 3. Rural
How satisfied are you with the outdoor noise from your window (e.g., traffic or people)?	Single choice	5-point Likert scale (very dissatisfied to very satisfied)
On which floor do you usually work?	Single choice	1. Ground floor 2. First floor 3. Second to fourth floor 4. Fifth floor or higher
Which of the following best describes your office environment?	Single choice	1. Enclosed office, private 2. Enclosed office, shared 3. Cubicles with high partitions 4. Cubicles with low partitions 5. Open office
How far is your desk from the window?	Single choice	1. 0–5 m 2. More than 5 m 3. No windows
How satisfied are you with the outdoor view from your window?	Single choice	5-point Likert scale (very dissatisfied to very satisfied)
Which building services are present in your workspace?	Multiple choice	Heating, air-conditioning, ventilation, windows, shading, lighting, personal devices, other
How are these building services typically controlled in your workspace?	Single choice	1. Manual 2. Semi-automated 3. Automated

Automation Preferences by Time of Day

This section investigated how user preferences for automation vary throughout different phases of the workday. Respondents were asked to indicate their preferred level of control during arrival, working hours, and departure.

TABLE APP. B.3 Time of Day (ToD) Questions

Question	Type of answer	Answer
For each situation (arrival, while working, leaving), how would you prefer building services to be controlled?	Single choice	1. Fully manual 2. Notification suggests manual actions 3. Automated with notification (override possible) 4. Automated without notification (override possible) 5. Fully automated (no override)

Automation Preferences by Building Service

This section focused on user preferences for specific building services, allowing respondents to express desired levels of control for each system independently.

TABLE APP. B.4 Building Services (Bs) Questions

Question	Type of answer	Answer
For each building service (e.g., heating, cooling, lighting, shading), how much personal control would you like to have?	Single choice	1. Fully manual 2. Notification suggests manual actions 3. Automated with notification (override possible) 4. Automated without notification (override possible) 5. Fully automated (no override)

Interface Preferences

This section explored user preferences regarding the type, location, and informational complexity of control interfaces used to interact with building systems.

TABLE APP. B.5 Interface Questions

Question	Type of answer	Answer
Which type of interface do you prefer for controlling building services?	Single choice	1. Analogue (switches, knobs, dials) 2. Digital (touchscreens) 3. No preference
Where would you prefer the control interface to be located?	Single choice	1. Near entrance 2. On desk 3. Near system 4. No preference
What level of information would you like the interface to provide?	Single choice	1. No information 2. Basic cues 3. System status 4. Status + suggestions 5. Status + suggestions + feedback 6. No preference

Curriculum Vitae

Pedro Pablo de la Barra Luegmayer was born on January 23, 1990, in Chile. He is an architect and researcher specializing in human-building interaction, smart building services, and daylighting strategies. He is currently based in The Hague, the Netherlands.

Education

2021 – 2025 | PhD in Human-Building Interaction
Delft University of Technology, The Netherlands
Research focused on smart building services control, occupant interaction, and user-centered environmental control strategies within the SMARTeeSTORY project.

2014 – 2016 | Magister in Architecture (MSc)
Pontifical Catholic University of Chile, Santiago, Chile
Specialization in Sustainable Architecture and Energy.

2008 – 2014 | Architect (Professional Degree)
Pontifical Catholic University of Chile, Santiago, Chile

Professional Experience

Research and Academic Positions

2026 – Present | Postdoctoral Researcher (ReACT Project)
Delft University of Technology, The Netherlands
Conducting postdoctoral research within the ReACT project, focusing on adaptive thermal comfort in buildings. The work combines high-resolution environmental monitoring, wearable physiological sensing, and occupant-centered data collection to investigate the mechanisms underlying thermal adaptation.

2021 – 2026 | PhD Researcher
Delft University of Technology, The Netherlands
Conducted interdisciplinary research on smart building services and human-building interaction. Activities included co-creation workshops for personalized control systems, development of user interfaces based on qualitative and quantitative analysis (questionnaires, interviews), and statistical modeling of occupant profiles using R and Python. Contributed to field implementation of sensing and control systems for indoor environmental quality.

2024 – Present | Research Consultant
Building Impulse / Freelance
Performed in-situ assessment of glazing systems in operational buildings, focusing on haze and surface defects. Developed and applied methodologies to quantify occupant perception, linking physical measurements with user-centered performance evaluation.

2016 – 2020 | Lecturer
Pontifical Catholic University of Chile, Santiago, Chile
Delivered courses within the Master in Sustainable Architecture and Energy on daylighting strategies, façade systems, and environmental design. Guided students in simulation tools, experimental methods, and physical prototyping for daylight performance.

2016 – 2020 | Research Assistant
Pontifical Catholic University of Chile, Santiago, Chile
Coordinated the FONDEF research project “Variable Façade” and supervised the Solar and Lighting Laboratory. Conducted experimental campaigns, data acquisition, and performance analysis of façade systems and indoor environmental conditions.

2018 – 2019 | Research Consultant
GEAFUC – Grupo de Estudio de Arquitectura y Fachadas
Developed simulation-based evaluations of façade design strategies for office buildings, focusing on energy efficiency, daylight performance, and indoor comfort. Produced technical reports and supported multidisciplinary design teams.

Teaching and Supervision

Lecturing Activities
Delivered lectures and workshops at **TU Delft**, **Universidad de Santiago de Chile**, and **Pontifical Catholic University of Chile**. Topics included research methodology, sensing and IoT in architecture, experimental design, and daylight performance analysis. Teaching combined theoretical instruction with hands-on laboratory and fieldwork components.

Course Development and Instruction
Designed and delivered courses on daylight in architecture, dynamic façades, and façade prototyping. Teaching activities emphasized integration of simulation tools, physical measurements, and user-centered evaluation methods.

Master Thesis Supervision
Supervised Master's theses at TU Delft on topics including glass serviceability limits, biophilic glare control, human-window interaction, and green façade systems.

Research Funding and Awards

2025 | Open Research Hardware Stimulation Fund
Funding awarded to develop and disseminate open-source research hardware for sensing and building performance monitoring.

2020 | ANID Chile PhD Scholarship (Becas Chile)
Competitive national scholarship supporting full doctoral studies abroad.

2012 | Academic Exchange Scholarship
Pontifical Catholic University of Chile – Exchange semester at ETSAM, Madrid.

2008 | Bicentenario Scholarship
Chilean government scholarship supporting undergraduate studies.

List of Publications

Journal Papers

de la Barra Luegmayer, P., Martinez-Alcaraz, P., Brembilla, E., Brager, G., Exss, K., Luna-Navarro, A. Interface design for lighting and shading controls: device type, position, and system cues influencing user preference and acceptance, 2026. Building and Environment. Volume 295, 114439

Martinez-Alcaraz, P., **de la Barra Luegmayer, P.**, Andriotis, C. P., Knaack, U., Luna-Navarro, A., 2026. Current trends and future directions for addressing multi-domain occupant demands in building automation and control systems. Building and Environment. Volume 297, 114588

de la Barra Luegmayer, P., Brembilla, E., Prieto, A., Vásquez, C., Knaack, U., Luna-Navarro, A., 2025. Influence of automated façades on comfort and energy: A critical review. Energy and Buildings. Volume 347, 116290

Khovalyg, D., Bivolarova, M.P., Shinoda, J., Al-Assaad, D., Vellei, M., Bandurski, K., Martinez Alcaraz, P., **de la Barra Luegmayer, P.,** Luna-Navarro, A., et al., 2025. Personalized Environmental Control Systems (PECS): Systematic Review of Benefits for Thermal Comfort, Air Quality, Health, and Human Performance. Building and Environment. 113541

de la Barra Luegmayer, P., Luna-Navarro, A., Brembilla, E., Allen, M., Knaack, U., Overend, M., 2025. User interaction with smart glazing: Effect of switching speed under overcast sky condition. Building and Environment. 270, 112409

Da Rocha Hendzel, C., Vásquez, C., **de la Barra Luegmayer, P.,** 2025. Calculation Algorithm to Estimate the Hygrothermal Performance of Vegetation on Green Screen Façades. Anales de Arquitectura.

Hassen, M., **de la Barra Luegmayer, P.,** Oke, S., Overend, M., Bilow, M., Luna-Navarro, A., 2024. Glass serviceability limits: new evidence from human-centred studies. Glass Structures & Engineering. 9, 657–669

Luna-Navarro, A., Brembilla, E., **de la Barra Luegmayer, P.,** Moreau, L., Overend, M.,

2024. Luminance-based methodology for assessment of low level haze in glazing. Glass Structures & Engineering. 9, 671–683

Vasquez, C., **de la Barra Luegmayer, P.,** D'Alencon, R., Da Rocha, C., 2023. Visual Connectivity Index (VCI): Performance Metrics to Evaluate the Ability of Indoor Space and Facade Systems to Connect to Outdoors. Journal of Sustainable Architecture and Civil Engineering. 38(2), 5–16

de la Barra Luegmayer, P., Luna-Navarro, A., Prieto Hoces, A.I., Vásquez, C., Knaack, U., 2022. Influence of Automated Façades on Occupants. Journal of Facade Design and Engineering.

de la Barra Luegmayer, P., 2020. Hygrothermal Potential of Applying Green Screen Façades in Warm-dry Summer Mediterranean Climates. Journal of Facade Design and Engineering.

Vasquez, C., **de la Barra Luegmayer, P.,** 2018. The infrastructure of buildings: envelopes, installations and systems in office buildings. Anales de Arquitectura.

Conferences

Martinez-Alcaraz, P., **de la Barra Luegmayer, P.**, Andriotis, C.P., Luna-Navarro, A. (2026). Does One Size Fit All? A Bayesian Data-Mining Approach to Thermal Comfort in Office Spaces. Proceedings of the 15th REHVA HVAC World Congress - CLIMA 2025.

de la Barra Luegmayer, P., Martinez-Alcaraz, P., Brembilla, E., Luna-Navarro, A. (2026). Evaluating Occupant Preferences with Building Control Interfaces: Towards Personalized Interaction Strategies. Proceedings of the 15th REHVA HVAC World Congress - CLIMA 2025.

Li, W. T. , Luna-Navarro, A., **de la Barra Luegmayer, P.**, Win Tai Mak, M., Fang, H. Behaviour Nudging for User Acceptance in Smart Blinds Control: A Pilot Study on Behaviour Change and Indoor Environmental Enhancement. Conference Proceeding by ASHRAE , 2025.

de la Barra Luegmayer, P., Khanie, M.S., Luna-Navarro, A., Martinez-Alcaraz, P., Al Assaad, D., 2025. Introducing Personalized Environmental Control Systems for Daylighting and Lighting. Proceedings of the 15th REHVA HVAC World Congress - CLIMA 2025.

de la Barra Luegmayer, P., Martinez-Alcaraz, P., Luna-Navarro, A., 2025. Improving Indoor Air Quality and Awareness of Window Operation Strategies in Primary School

Classrooms Using Light-Based Signaling Systems. Healthy Buildings Iceland 2025.

Martinez-Alcaraz, P., **de la Barra Luegmayer, P.,** Luna-Navarro, A., 2025. Understanding the Importance of Tailoring Thermal Conditions: A Data-Mining Bayesian Approach. Clima Conference 2025.

de la Barra Luegmayer, P., Martinez-Alcaraz, P., Brembilla, E., Luna-Navarro, A., 2025. Evaluating Occupant Preferences with Building Control Interfaces: Towards Personalized Interaction Strategies. Clima Conference 2025.

de la Barra Luegmayer, P., Martinez-Alcaraz, P., Luna-Navarro, A., 2025. Identification of Factors Influencing Satisfaction with Interaction Strategies by Clustering Occupants in Buildings. Multiphysics and Multiscale Building Physics (IABP 2024). Lecture Notes in Civil Engineering. 555

Luna-Navarro, A., Welti, A., **de la Barra Luegmayer, P.,** Martinez-Alcaraz, P., Porta, M., 2025. Impact of Dynamic Façades on Smart Readiness Indicator and User Satisfaction. Multiphysics and Multiscale Building Physics (IABP 2024). Lecture Notes in Civil Engineering. 554

D'Amico, A., Fiume, F., **de la Barra Luegmayer, P.,** Luna-Navarro, A., 2025. Indoor Air and Thermal Quality in School Buildings: Demonstration of BIM-Integrated IoT Window Signaling System. Envisioning the Futures (Colloqui.AT.e 2025). Lecture Notes in Civil Engineering. 765

Martinez-Alcaraz, P., **de la Barra Luegmayer, P.,** Andriotis, C.P., Wang, Y., Luna-Navarro, A., 2025. Personalised Building Controls Based on Individual Thermal Preferences for Energy Efficiency and Thermal Comfort. Multiphysics and Multiscale Building Physics (IABP 2024). Lecture Notes in Civil Engineering. 555

Chiucchiù, A.C., Misuraca, I., Brembilla, E., Pigliautile, I., Tenpierik, M.J., Pisello, A.L., **de la Barra Luegmayer, P.,** Luna-Navarro, A., 2024. Effect of Blue-Tinted Glazing on Thermal and Visual Perception in Neutral and Warm Thermal Conditions. CATE 2024 - Comfort At The Extremes. Seville, Spain.

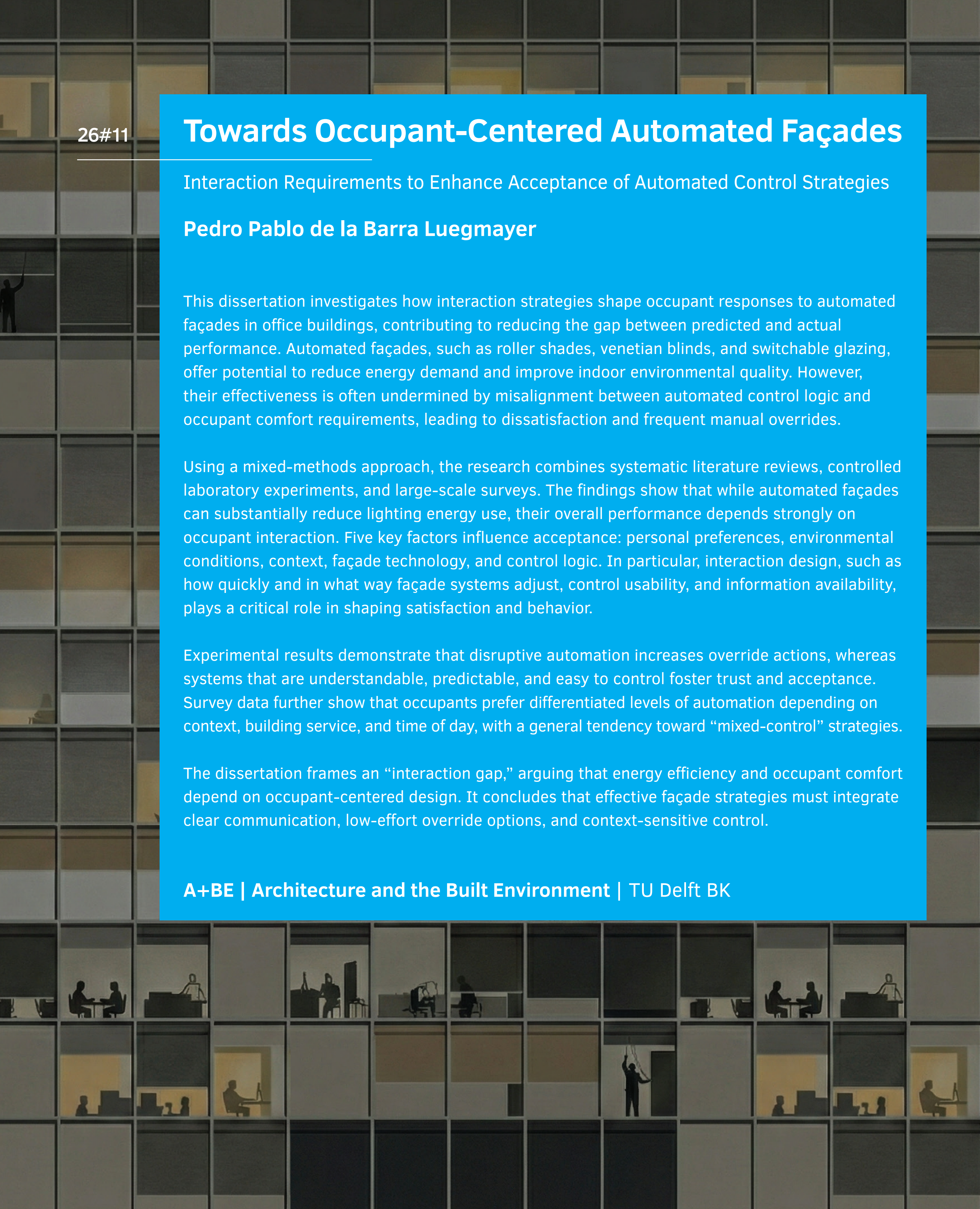
Luna-Navarro, A., Khandhachani, P., Brembilla, E., **de la Barra Luegmayer, P.,** Andriotis, C., 2023. Towards multi-domain user archetypes for user-centred façade design. Journal of Physics: Conference Series. 2600, 132012

de la Barra Luegmayer, P., Luna-Navarro, A., Knaack, U., Prieto Hoces, A., Vásquez, C., 2023. An Investigation on Occupant Preferences with Automated Façades. 18th Healthy Buildings Europe Conference. Aachen, Germany.

Yüksel, S., **de la Barra Luegmayer, P.,** Boerstra, A.C., Luna-Navarro, A., 2023. Effectiveness of window signalling systems in open-plan workplaces. BEHAVE. Conference on Behaviour Change for Energy Efficiency. Maastricht, The Netherlands.

Upcoming Publications

de la Barra Luegmayer, P., Martinez-Alcaraz, P., Brembilla, E., Luna-Navarro, A., 2026. What Should Be Automated in Offices? Occupants' Preferences for Automation Levels from a Large Survey in Spain and the Netherlands.



26#11

Towards Occupant-Centered Automated Façades

Interaction Requirements to Enhance Acceptance of Automated Control Strategies

Pedro Pablo de la Barra Luegmayer

This dissertation investigates how interaction strategies shape occupant responses to automated façades in office buildings, contributing to reducing the gap between predicted and actual performance. Automated façades, such as roller shades, venetian blinds, and switchable glazing, offer potential to reduce energy demand and improve indoor environmental quality. However, their effectiveness is often undermined by misalignment between automated control logic and occupant comfort requirements, leading to dissatisfaction and frequent manual overrides.

Using a mixed-methods approach, the research combines systematic literature reviews, controlled laboratory experiments, and large-scale surveys. The findings show that while automated façades can substantially reduce lighting energy use, their overall performance depends strongly on occupant interaction. Five key factors influence acceptance: personal preferences, environmental conditions, context, façade technology, and control logic. In particular, interaction design, such as how quickly and in what way façade systems adjust, control usability, and information availability, plays a critical role in shaping satisfaction and behavior.

Experimental results demonstrate that disruptive automation increases override actions, whereas systems that are understandable, predictable, and easy to control foster trust and acceptance. Survey data further show that occupants prefer differentiated levels of automation depending on context, building service, and time of day, with a general tendency toward “mixed-control” strategies.

The dissertation frames an “interaction gap,” arguing that energy efficiency and occupant comfort depend on occupant-centered design. It concludes that effective façade strategies must integrate clear communication, low-effort override options, and context-sensitive control.

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