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Introducing Personalized Environmental Control Systems for Daylighting and Lighting

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Abstract. Buildings are striving to be both energy-efficient and occupant-centered. Personalized systems for lighting and dynamic fenestration systems, e.g., switchable glazing, are emerging as a key solution. These systems, called Personalized Environmental Control Systems (PECS), allow individuals to adjust their immediate environment without impacting others. While PECS initially focused on temperature and air quality, this study explores the potential for the luminous environment, introducing the concept of Visual PECS.

Daylighting and lighting controls build on a long history of personalized systems and methods, from prehistoric torches to adjustable desk lamps. They allow for individual control over (day)light spectrum and intensity, catering to personal needs and promoting circadian health and cellular processes (i.e., photobiomodulation). Additionally, they can reduce glare and improve visual comfort, leading to

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increased productivity and well-being. Despite this long history, studies formulating "personalized environmental control systems" (PECS) in the daylighting and lighting domain are rare. In this paper, we present preliminary results from a comprehensive review, where 31 papers were identified from an initial pool of 5,238. The findings highlighted two key benefits. First, semi-automated PECS offer the highest energy savings, highlighting the importance of understanding the relationship between users and automation. Secondly, PECS provides improved occupant experience since the ability to control their environment empowers occupants, leading to increased comfort and productivity. Overall, PECS have the potential to facilitate individual control over lighting and visual parameters, ultimately enhancing visual comfort and satisfaction as well as beyond-visual well-being. Our research builds upon the ongoing work of IEA EBC - Annex 87, which investigates the energy and environmental benefits of PECS.

Keywords: Personalized Environmental Control System · Comfort · Visual · Daylight · Lighting

1 Introduction

Indoor environments play a crucial role in occupants' comfort, health, and productivity, given that people spend the majority of their time indoors [1]. The quality of indoor environmental conditions directly impacts not only occupant well-being but also the energy consumption of buildings. For instance, indoor temperature control alone accounts for approximately 50% of a building's total energy usage [2]. As such, creating adaptive and efficient systems to meet individual needs while minimizing energy consumption has become a priority in modern building design [3].

Personalized Environmental Control Systems (PECS) are designed to address this challenge by providing occupants with the ability to tailor their environment to suit their specific needs [4]. Initially focused on thermal comfort and air quality, PECS have evolved to offer more diverse functionalities, including visual comfort [5]. In particular, PECS for the luminous environment (visual and non-visual effects of light) can enhance user satisfaction, well-being, and energy efficiency, particularly in open-plan office spaces. By giving individuals control over their luminous environment, PECS allow for personalized adjustments to light intensity and spectrum, which are necessary for optimizing both comfort and health [6, 7].

However, evidence regarding the performance of these devices is still fragmented and lacks a clear overview. Moreover, there is limited understanding of the definition and requirement of PECS in the light domain, particularly in terms of their impact on both occupant comfort and energy consumption.

This study explores the potential of PECS for the luminous environment, introducing the concept of visual and non-visual PECS. A literature review is conducted, and a questionnaire is distributed among experts in the field to gain deeper insights into the definition of PECS for the visual and non-visual effects of light, in relation to both daylighting and artificial lighting.

2 Methodology

This manuscript comprises two complementary parts: a systematic literature review and an expert questionnaire. The review identifies current research on PECS, while the questionnaire captures expert insights into how these concepts are understood and implemented in practice.

We searched Scopus, Web of Science, and PubMed up to 25 October 2023, yielding a total of 5,238 unique publications. The final search query, outlined in Table 2, was divided into three segments. After removing duplicates and screening for occupant-centered, individually adaptive lighting and façade systems, 31 papers were retained by the authors for in-depth review (Table 1).

Table 1. Literature review methodology description and query

Search segment	Query	Rationale
Personalized Control	"Personalized control*" OR "self?adjust* control" OR "individual* control*" OR "personal* light*" OR "personal* fa?ade" OR "personal* shad*" OR "personal* solar control*" OR "human* centr*" OR "smart lighting*" OR "adapt* control"	Capture studies focusing on occupant-centered, user-adaptive or self-adjusting strategies for lighting or façade systems (e.g., personalized or adaptive controls).
Visual Domain	"visual comfort*" OR "non?visual*" OR "spectral* lighting" OR "adapt*" OR "Adapt* fa?ade" OR "integrate* light"	Include research addressing visual comfort, and building services related to visual environmental parameters.
Built Environment Context	"build*" OR "built environment" OR "home*" OR "school*" OR "office*" OR "workplace*" OR "workspace*" OR "hospital"	Restrict results to real-world building applications, such as residential, educational, workplace, and healthcare settings.

To complement the literature review findings, a questionnaire was distributed among eight experts in the field. Its purpose was to gather deeper insights into how PECS are understood, particularly regarding daylighting and artificial lighting. Participants were asked to define the scope and aims of PECS, identify controlled domains (e.g., visual and non-visual parameters), and provide concrete examples.

3 Results

3.1 Current Evidence on the Benefits of PECS

Among 31 reviewed studies, 48% used experimental approaches, 42% relied on simulation studies, and 10% addressed both methodologies. Regarding the evidence reported, 29% provided information on energy performance, 19% focused on occupant-related benefits, and 13% provided combined evidence addressing both energy and occupant outcomes. The 39% did not report information on PECS performance as described in Table 2.

Table 2. Distribution of studies investigating PECS impact on energy and occupant.

Energy Evidence	No	No	Yes	Yes	**Total papers**
Occupant Evidence	No	Yes	No	Yes	
Both	1 (3%)	0 (0%)	0 (0%)	2 (7%)	**3 (10%)**
Experimental	4 (13%)	5 (15%)	2 (7%)	3 (10%)	**14 (45%)**
Simulation	7 (23%)	0 (0%)	6 (19%)	1 (3%)	**14 (45%)**
Total papers	**12 (39%)**	**5 (16%)**	**8 (26%)**	**6 (19%)**	**31 (100%)**

3.2 Benefits of PECS on Energy Savings

The energy performance of PECS was evaluated in 14 studies that focused on energy consumption related to lighting, specifically ceiling and task lights. Additionally, one study reported energy savings in heating and cooling when testing shading devices. Three studies did not provide clear information on the energy performance achieved. Among the reviewed studies, ceiling lighting was the most investigated type of PECS (Fig. 1), with 11 studies testing different control logics. These included recommender systems for ceiling lighting, closed-loop targeting desk lights, and optimization for color and illuminance. Control approaches were the main aspect tested, covering automated, semi-automated, and rule-based systems. Baseline scenarios often assumed that lights were always on or manually controlled, providing a reference point to quantify energy savings.

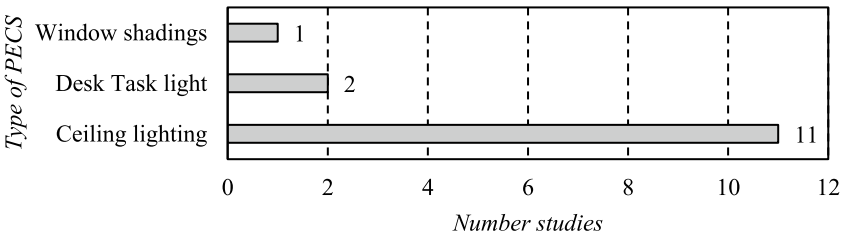


Fig. 1. The distribution of studies reporting evidence on energy savings per type of PECS.

The performance of PECS changes based on the level of automation and the type of experiment conducted. Regarding the level of automation (Fig. 2a), automated systems, employing predictive or rule-based controls, exhibit a wide range of performance, with lighting energy savings between 10% and 45%. Manual systems, such as task lighting and window shading, show significant energy savings, with reductions ranging from 10% to 30%. Semiautomated systems (i.e., automated control with occupant override options), especially for

ceiling lighting, demonstrate reductions in energy consumption, with savings ranging from

20% to 72%, depending on the control logic used. As shown in Fig. 2b, experimental studies

typically report more variable savings, such as 40% to 72% simulation studies show more consistency, with savings ranging from 10% to 40%, likely due to controlled assumptions and fewer real-world factors.

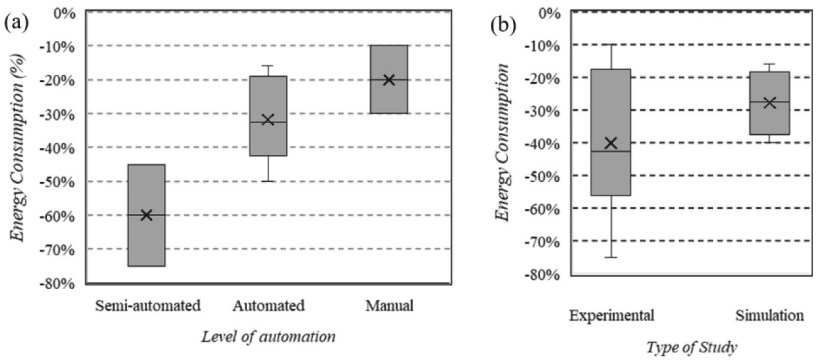


Fig. 2. Boxplots showing the distribution of reported energy consumption (in percentage) across studies. Energy consumption is compared based on (a) the level of automation and (b) the type of study**.**

3.3 Benefits of PECS for Occupants

Eleven studies investigated the impact of adaptive lighting, task lighting, tunable white lighting, and open-plan personalized control systems on user satisfaction (n = 2), comfort (n = 4), task performance (n = 3), and environmental perception (n = 2). While some systems automatically adjust illuminance based on user conditions (e.g., fatigue), others rely on manual adjustments to enhance flexibility and user control. The findings suggest that personalized lighting can improve comfort and performance but also highlight certain limitations, such as the varying effectiveness across different task types and potential discomfort caused by high direct lighting ratios.

As described in Table 3, evidence on objective outcomes highlights a mixed impact of different lighting systems on occupant experience. Ceiling lighting systems, particularly those with automatic control, adjust illuminance based on user fatigue but remain

untested for their effectiveness in fatigue recovery. These systems were found to meet heterogeneous illuminance requirements, although their impact on fatigue alleviation needs further validation. Desk task lighting, particularly when manual, was shown to improve task performance for paper-based activities, but it did not benefit computer work. Additionally, direct lighting was more effective for social activities, while diffuse lighting performed better for task-oriented tasks. Systems with no control logic showed no benefits.

Table 3. Overview of impacts reported by articles when considering objective assessments.

n	Type of PECS	Control	Objective assessment metric(s)	Impact on user
3	Ceiling lighting	Automatic	Fatigue scoring, Illuminance threshold (lx)	**Positive:** The System adjusts illuminance based on fatigue. Achieved heterogeneous illuminance requirements. **Neutral:** effectiveness for fatigue recovery untested.
5	Desk task light	Manual	Average illuminance over working hours (lx), Task performance, Posture	**Positive:** Task lighting improved paper-based work, but not computer work. Direct lighting improves users' indoor experience; diffuse lighting is better for task-oriented work. Users maintained illuminance conditions within a desired range. Task light improved wrist and arm posture.
1	Ceiling lighting	No control logic	Illuminance threshold (lx)	**Neutral:** No benefits were reported in fixed lighting conditions.

Table 4. Overview of impacts reported by articles when considering subjective assessments.

n	Type of PECS	Control	Subjectieve assessment metric(s)	Impact on occupant
6	Desk Task Light	Manual	Satisfaction with lighting, Preferences, Comfort, Visual appearance, Atmosphere (coziness, glare, naturalness), Perception of job control (creativity, decision-making, freedom, work posture), Environmental satisfaction, Mood, Visual & Physical discomfort, Performance satisfaction, Thermal comfort, Willingness to volunteer, Vigilance.	**Positive:** Personal control improved satisfaction, even though personal control happened sparingly. **Neutral:** Satisfaction is influenced by daylight variation. No significant comfort differences, meaning lighting conditions did not significantly affect users' perceived comfort level. **Negative:** While direct lighting improved brightness, it introduced glare, which could negatively impact comfort and perception.

Subjective Assessments, Presented in Table
Table 4, demonstrated that manual desk task lighting, especially tunable white, improved satisfaction with lighting, comfort, and performance. Satisfaction was influenced by daylight variation, with no significant comfort differences across studies. Direct lighting increased brightness and shadow contrast, but it also introduced glare, which impacted comfort for some users. While personal control generally improved satisfaction, its use remained limited, with less than one adjustment per person per day. The lighting system's impact on job control varied, with some aspects improving, while others diminished.

3.4 Expert Perspectives on PECS in the Visual Domain

Most experts agree that PECS can address both visual and non-visual factors, enhancing multiple aspects of occupant comfort. As shown in Table 5, there is a consensus that PECS for daylighting and artificial lighting should enable individualized adjustments without disrupting co-occupants in shared spaces. However, experts differ on whether PECS should focus solely on comfort or also pursue energy efficiency objectives.

When defining PECS, some experts emphasized that daylighting solutions remain primarily manual, while artificial lighting PECS can range from simple switches to advanced adaptive automated systems. In shared office settings, personal daylight control poses spatial challenges, whereas localized artificial lighting is generally seen as more practical for individual control.

Table 5. Summary of key aspects from expert definitions, showing common themes and discrepancies.

Aspect	PECS for daylighting	PECS for artificial lighting	Common themes	Points of discrepancy
Primary Aim	Adjust natural light to meet individual needs without affecting others. (n = 6)	Adjust artificial light to enhance comfort (n = 6) and usability without affecting others (n = 3).	PECS provides personal control over the visual environment (n = 6).	Whether PECS should only focus on comfort (n = 6) or also integrate energy efficiency goals (n = 2).
Examples of PECS	Blinds (n = 2), curtains (n = 1), smart glass (n = 1), transition lenses (n = 1).	Desk lamps (n = 6), dimmable lighting (n = 1).	Task lighting solutions are widely accepted as PECS. (n = 6)	Whether daylight PECS should be wearable (e.g., glasses) (n = 2) or building-integrated (e.g., electrochromic glass) (n = 2)

4 Discussion

Reviewed studies converge on the notion that PECS involves personalized control of lighting and other environmental factors to improve occupant comfort. However, experts differ on whether energy efficiency should be a key objective of PECs. Establishing a unified definition that integrates user needs and energy performance could guide future research and PECS innovation.

Evidence indicates that PECS typically reduces energy consumption, but discrepancies arise between simulation-based and experimental findings. From these preliminary results of the review, simulations yield more consistent savings, likely due to controlled assumptions, while real-world experiments reflect greater variability from occupant behavior and environmental factors.

Consistent with Human-Building Interaction research, studies indicate that granting occupants personal control over lighting can improve satisfaction and comfort. Nonetheless, higher occupant satisfaction does not necessarily correlate with optimal environmental conditions, as noted by [8]. The control logic may be crucial in maintaining minimum environmental standards for occupants.

Although fully automated controls often save energy, some semi-automated systems showed higher savings, illustrating the nuanced interplay between HBI and system efficiency. Further investigation into these dynamics, particularly how different levels or moments for automation align with user preferences, could build on top of these findings to design PECS that maximize both comfort and energy performance.

5 Conclusions

This study underscores the potential of Personalized Environmental Control Systems (PECS) in the visual domain to enhance both occupant comfort and energy efficiency. The literature review and expert questionnaire reveal that PECS, particularly for lighting control, contribute to user satisfaction, task performance, and energy savings. However, the effectiveness of these systems varies depending on the level of automation and the type of study, with manual and semi-automated approaches often yielding the highest benefits. While PECS offer promising advancements in adaptive lighting solutions, further research is needed to refine control strategies, address potential limitations, and ensure their effectiveness in diverse real-world applications.

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References

1. Frontczak, M., Wargocki, P.: Literature survey on how different factors influence human comfort in indoor environments. Build. Environ. **46**, 922–937 (2011). https://doi.org/10.1016/J.BUILDENV.2010.10.021
2. Pérez-Lombard, L., Ortiz, J., Pout, C.: A Review on buildings energy consumption information. Energ. Buildings. **40**, 394–398 (2008). https://doi.org/10.1016/J.ENBUILD.2007.03.007
3. Habibi, S.: Smart innovation systems for indoor environmental quality (IEQ). J. Build. Eng. **8**, 1–13 (2016). https://doi.org/10.1016/J.JOBE.2016.08.006
4. Ole Fanger, P.: Indoor air quality in the 21st century: Search for excellence. Indoor Air. **10**, 68–73 (2000). https://doi.org/10.1034/J.1600-0668.2000.010002068.X
5. Xie, K., Lee, M., Khalid, R., Zakka, V.G.: The impact of personal environmental control on the performance of thermal systems: building energy consumption, occupant thermal comfort, and productivity. Energ. Buildings. **298**, 113552 (2023). https://doi.org/10.1016/J.ENBUILD.2023.113552
6. Fischer, M., Wu, K., Agathoklis, P.: Intelligent illumination model-based lighting control. In: 2012 32nd International Conference on Distributed Computing Systems Workshops, pp. 245–249. Institute of Electrical and Electronics Engineers, Macau, China (2012). https://doi.org/10.1109/ICDCSW.2012.75
7. Veitch, J.A., Newsham, G.R., Boyce, P.R., Jones, C.C.: Lighting appraisal, well-being and performance in open-plan offices: A linked mechanisms approach. Light. Res. Technol. **40**, 133–148 (2008). https://doi.org/10.1177/1477153507086279
8. Kar, P., Shareef, A., Kumar, A., Harn, K.T., Kalluri, B., Panda, S.K.: ReViCEE: A recommendation based approach for personalized control, visual comfort & energy efficiency in buildings. Build. Environ. **152**, 135–144 (2019). https://doi.org/10.1016/J.BUILDENV.2019.01.035