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Ten questions concerning the economics of indoor environmental quality in buildings[☆,☆☆]

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ABSTRACT

Indoor environmental quality in buildings encompasses air quality, thermal environment, acoustics, and lighting. While engineering and health sciences have studied the impact of these attributes on occupants, a limited number of economic studies have investigated their financial implications. However, the profitability of optimizing the indoor environment for real estate developers, investors, and tenants remains unclear. This ten-question paper summarizes existing literature on the economic value of improvements in indoor environmental quality. The first four questions summarize existing evidence, showing that these factors influence human performance, health, and well-being through different pathways, not all of which are sufficiently understood. The second part explores the economic value of optimized indoor environments and how economic research on energy-efficient buildings can serve as a suitable blueprint. This literature confirms that energy-efficient buildings provide a higher property value and offer a profitable investment case. However, to our knowledge, no research so far could effectively quantify the financial benefits of improved occupant productivity, health, and well-being due to an optimized indoor environmental quality, and how it could be used in a cost–benefit analysis to compare it with the rent and price premium tenants and owners need to pay for health-certified buildings. Existing studies on this topic often rely on indirect measures and lack direct evidence linking these improvements to objectively measured productivity or health outcomes. Therefore, this paper concludes with suggestions for future research to facilitate studies on the economic value of indoor environmental quality improvements and related healthy building attributes.

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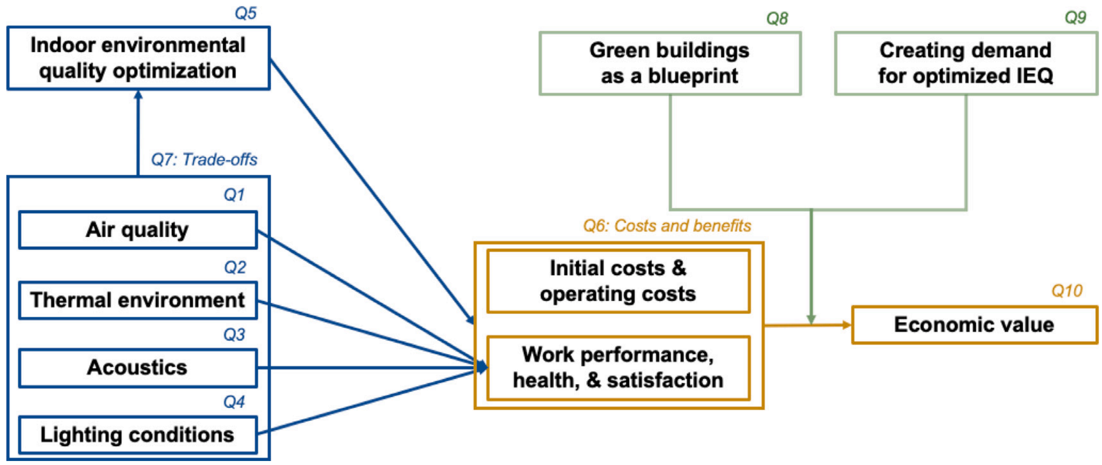

Fig. 1. Examined relations per question.

1. Introduction

In the early 1970s, researchers emphasized that modern humans spend the vast majority of their time indoors [1]. Over time, this statement has been reinforced by multiple studies in North America and Europe [2–4], underscoring the significant influence of indoor environments on human performance, health, and overall well-being and related satisfaction. Key factors such as indoor air quality, thermal environment, acoustics, and lighting play pivotal roles in shaping occupants' experiences [5–8]. Studies have not only demonstrated the individual effects of these factors on occupants, but also highlighted their complex interactions [9].

Despite growing evidence on the importance of indoor environmental quality (IEQ) for building occupants, much less is known about the economic value and costs of investments in IEQ optimization. For real estate developers, investors, tenants, and building managers, understanding the cost-effectiveness of improving specific IEQ elements is essential. The adoption of healthy building attributes, such as advanced ventilation and filtration systems, dynamic indoor temperature control, improved acoustical conditions, and adaptive lighting require a well-defined business case to justify adoption. Better insights into the economics of IEQ could unlock significant opportunities for the capital market to incorporate health-promoting and performance-enhancing attributes into commercial and residential buildings. Lessons from the adoption of green-certified building features, such as energy-efficient systems and water management strategies, showcase that a clear business case can accelerate investments, driving a transition towards a more sustainable built environment [10,11].

This ten-question paper addresses the gap by reviewing existing literature on the economic value and costs of optimizing IEQ in buildings. It explores the relationships between IEQ and occupants, and synthesizes studies on the benefits and costs of IEQ-improvements. The paper aims to encourage new research on the business case of optimized IEQ and serves as an effective guideline for stakeholders in the real estate sector designing healthy buildings and seeking to make profitable investments in the built environment.

The paper is structured around ten key questions designed to explore the economics of IEQ in buildings. As illustrated in Fig. 1, the first four questions give an overview of current evidence on the impact of each IEQ factor on building occupants' performance, health, well-being, and satisfaction. Question 5 addresses aspects of design and operation strategies for optimizing IEQ. Questions 6 and 7 evaluate studies on the costs, benefits and trade-offs associated with IEQ investments. Question 8 explores business case parallels with green-certified buildings that can serve as a blueprint for healthy buildings. Question 9 suggests strategies to stimulate demand for improvements of IEQ and healthy buildings. Finally, question 10 focuses on monetizing the impact of IEQ improvements. Lastly, the paper concludes with suggestions for future research, aimed at accelerating the adoption of IEQ investments and fostering a deeper understanding of their economic potential in real estate development.

2. Ten questions and answers on the economics of indoor environmental quality in buildings

2.1. Question 1: How does indoor air quality affect building occupants?

Indoor air quality (IAQ) refers to the air pollutants indoors, which comprise a broad spectrum of physical, chemical, and biological pollutants that can originate from outdoor sources, indoor activities, materials, and processes [12–14]. Indoor pollutants are best controlled by eliminating or reducing sources, increasing ventilation with outdoor air (assuming outdoor air is free of significant pollutants) [15,16], local exhaust systems, filtration, air cleaning, isolation, or other capture techniques [17].

Public interest in IAQ surged in the early 1980s following widespread reports of Sick Building Syndrome (SBS) - symptoms like headache, fatigue, and eye or throat irritation associated with poor indoor environments. These symptoms were attributed to energy conservation, such as tightening building envelopes without using mechanical outdoor air ventilation, which reduced the amount of outdoor air supply. Modern buildings, typically more air-tight than older structures [18], further exacerbate IAQ concerns. Advances in construction technology and the proliferation of synthetic materials have introduced a greater variety of chemicals into indoor environments [19]. Notably, for approximately 95% of these chemicals, health effects remain poorly understood [20]. Consequently, modern buildings are more likely to generate and accumulate pollutants.

Numerous studies link air pollution to various health effects, including asthma, allergies, and infectious diseases [21–24]. Attention has predominantly been focused on respirable particulate matter because of its strong association with mortality [25]. However, other pollutants, such as carbon dioxide (CO_2), radon, formaldehyde, volatile organic compounds, house dust mites, mold, and bacteria, also pose concerns. CO_2, a by-product of human metabolism [12], is a widely used proxy for IAQ, though this approach has significant limitations [26,27]. However, no systematic evidence suggests that CO_2 at common concentration levels should be classified as a pollutant [28,29]. Overall, while indoor air pollution is critical for human health, the physiological responses it triggers are poorly understood. The mechanisms through which IAQ impacts human health differ substantially, as IAQ encompasses a wide range of pollutants.

Beyond health, IAQ influences cognitive performance [30,31]. Exposure to elevated pollutant levels can lead to cognitive impairments, physiological stress, reduced sleep quantity and quality, or higher rates of sickness-related absenteeism [30,32–34]. Insufficient ventilation in offices has been associated with reduced cognitive performance and decision-making abilities [30,35], and increased sick leave [33,36,37]. Reduced ventilation rates in schools can negatively impact learning and increase sickness absence [32]. However, the mechanisms underlying the impact of IAQ on human performance remain largely hypothetical. Currently, no empirically robust evidence confirms a causal or statistically significant mediating role for the proposed mechanisms.

Understanding the distinction between physical IAQ and perceived IAQ is also critical to assess its impact on well-being. Laboratory studies suggest that volatile organic compounds and related bioeffluents significantly contribute to perception of poor IAQ, while CO_2 appears to play a lesser role [38,39]. Environmental factors such as temperature, humidity, and air movement also influence perceived air quality, independent of actual pollutant levels [9,40,41]. However, despite advancements in ventilation standards, large-scale occupant satisfaction surveys reveal that the percentage of individuals satisfied with and positively perceiving IAQ falls significantly short of the levels prescribed by building guidelines [42].

In conclusion, evidence consistently demonstrates that IAQ affects human health, performance, and well-being. However, the underlying mechanisms are not yet fully understood. Existing research primarily focuses on mitigating negative impacts, with limited attention given to promoting positive outcomes such as satisfaction or pleasure [7]. Thereby, most findings stem from laboratory studies, while robust field studies remain relatively scarce. Additionally, many studies rely on single dose–response and static models, overlooking the complex interactions among various indoor air pollutants and with other IEQ factors [7,43]. Addressing these gaps requires greater emphasis on real-world research and holistic approaches, as well as consideration of the economic implications, including absenteeism, productivity, and healthcare costs.

2.2. Question 2: How does the thermal environment affect building occupants?

The indoor thermal environment is crucial for building designers and can influence health and well-being [30,44,45]. Four physical parameters, air temperature, relative humidity, air velocity and mean radiant temperature, partially define the thermal environment [46]. To maintain a stable body core temperature of approximately 37 ± 0.5 °C (98.6 ± 0.9 °F), the human body is constantly balancing out these external and internal influences (e.g. physical activity or the thermal effect of food) through three major mechanisms: (i) the regulation of blood flow to the skin for heat dissipation (peripheral vasodilation and vasoconstriction), (ii) evaporative heat loss via sweating, and (iii) metabolic heat production, with or without shivering [47]. Thermoregulatory behaviour (seeking sunlight or shade, or adjusting clothing) complements physiological processes [48]. Thereby, humans can safely withstand a wide range of thermal environments [47,49,50].

Providing thermal comfort is one of the main goals of building guidelines [51,52]. Assuming thermal neutrality would translate into comfort for the majority of building occupants, and thus represent the optimal indoor environment. Research by P.O. Fanger established the indices of "*predicted mean vote*" (PMV) and "*predicted percentage of dissatisfied*" (PPD) [1,53]. The PMV and PPD models present a straightforward method to predict thermal comfort, taking into account physical parameters of the thermal environment, and aspects of clothing, physical activity, and metabolic rate [54]. Most standards recommend these thermally neutral conditions to minimize discomfort and ensure optimal performance [51,52]. Consequently, most mechanically conditioned buildings accept only minor fluctuations around the targeted set point [50,55]. However, the PMV has a low prediction accuracy (~34%) while the PPD is an unreliable metric [56] and has been removed from the ASHRAE 55-2023 guideline [51].

However, maintaining indoor temperatures within a narrow range may adversely affect health, such as physiological energy metabolism, glucose and lipid metabolism [57–59]. Persistent thermal comfort could contribute to global obesity and diabetes epidemic [49,60–62]. In contrast, periodic exposure to temperatures slightly outside comfort zones can improve cardiovascular and metabolic health, even for vulnerable groups such as older, overweight, and metabolically compromised individuals [49,63,64].

Interestingly, uniform indoor conditions and standard thermal set-points have been applied in different geographical areas, despite vast differences in outdoor climatic and cultural conditions [54]. This approach overlooks the role of acclimatization, inter-individual and population differences. However, it is now well-established and widely accepted that the human body adapts to its thermal environment [65–68].

Acclimatization enhances thermal resilience to heat and cold [69]. An adjustment of the core temperature balance, blood flow and skin temperature redistribution, more efficient sweating and adapted fluid balance, or increased metabolic heat production and less shivering, represent examples of physiological acclimatization [65–68,70]. These physiological adaptations typically develop over a few days of exposure, stabilize over time to a new "*optimal*" situation, and thereby ensure improved thermal tolerance. Adaptation capabilities of the human body are, however, limited, and a slow approach to acclimatisation over an extended period of time, can aid in avoiding major discomfort [50]. Importantly, prolonged exposure to uniform and strictly controlled, thermally neutral environments attenuates opportunities for adaptation [49,71].

Studies have shown that also the preferred temperature of people differs and changes, based on the habitual thermal exposure [72,73]. Occupants of naturally ventilated buildings in the United Kingdom reported different preferred temperatures in winter versus summer. Additionally, thermal preferences in warmer regions such as Singapore or Baghdad rise with increasing outdoor temperatures [72–74]. This concept of "*adaptive thermal comfort*" was introduced to the ASHRAE 55 standard in 2002, suggesting that in naturally conditioned buildings, thermal set-points should be linked to the mean running outdoor temperature [51,55]. However, the implementation in practice has been slow and rather limited. So far, it has only been applied as an evaluation tool, rather than in the design phase [50]. Having been limited to naturally ventilated buildings only, recently, the revised ASHRAE 55-2023 standard [75] is now also recommending the adaptive comfort model for mixed-mode buildings.

One of the critical drivers for comfort-based operation of buildings has been the question of optimal productivity. Contrary to previous beliefs of an optimal temperature for peak productivity at 21.8 °C (71.24 °F) [76], a recent meta-analysis shows a weaker relationship between productivity and the ambient temperature, in a range between 18–34 °C (64.4–93.2 °F) [77–79]. Inconsistent findings on cognitive performance further challenge the notion of an optimal indoor temperature [5,30,80]. Given that multiple factors determine thermal comfort, establishing a thermal environment that is optimal for cognitive performance becomes even more complex.

In conclusion, the thermal indoor environment has major implications for building occupants and should provide a safe, healthy, salutogenic and performance-enhancing indoor environment. To this end, a rethinking and shift in how we design and operate thermal indoor conditions is inevitable and urgent.

2.3. Question 3: How do acoustics affect building occupants?

Acoustic conditions significantly influence occupant experience, performance, well-being, and satisfaction, depending on the intended use of a space. For example, classrooms require high speech intelligibility to support effective learning [81]; hospitals demand tranquil environments conducive to patient recover [82,83]; restaurants benefit from acoustics that enhance social interactions within close proximity [84]; while storage closets typically require minimal acoustic consideration.

To achieve acceptable acoustics, one must account for (1) geometric factors that impact the distribution of reverberation in rooms, such as the room's dimensions, form, surface materials and type of construction, and (2) noise sources internal and external to the space that may influence the sound environment unduly, such as mechanical systems, alarms, occupant activity, and traffic [7]. Eliminating all ambient noise, though, is not entirely the solution to achieving optimal acoustic environments, as very low background noise levels can also create issues. Across the dynamic nature of soundscapes in occupied buildings, sudden sounds or the lack of speech privacy can become more noticeable and distracting when the background noise is too low; in these cases, some level of constant ambient noise can help to 'mask' other acoustic distractions [85,86].

Metrics commonly used to evaluate acoustics typically include ones that categorize the overall level of ambient sound in the space, such as the A-weighted equivalent sound pressure level (LAeq), and ones that describes how long sound persists in a space after the source stops, such as reverberation time (RT). Higher reverberation times (above 1.0 s) typically result in impaired speech intelligibility but may enhance music quality. An added complication is that acoustic performance can vary across the range of audible acoustic frequencies, 20 Hz to 20 kHz, with the speech frequency octave bands of 250 Hz, 500 Hz, 1000 Hz, and 2000 Hz being considered most important.

Acoustic conditions in buildings significantly impact occupant task performance, their health, well-being, and satisfaction. Higher sound levels have been linked to reduced task performance [87] and student achievement scores [88]. Besides high sound levels, higher reverberation times could also impact speech perception by non-native English speaking listeners compared to native English speakers [89]. Higher sound levels (above 85 dBA) have been shown to affect both auditory health via noise-induced hearing loss, and non-auditory health such as through stress, sleep disturbance, and heart disease [90,91].

While optimal or acceptable acoustic environments are achievable, many buildings do not address acoustics adequately, resulting in distractions, annoyance, and difficulty in communication between occupants [92]. Recent studies have found that 81% of respondents in 600 office buildings were dissatisfied with at least one aspect of their workplace, with 54% listing acoustics as a source of discomfort [93]. Elevated sound levels result in significant decreases in overall comfort and increased annoyance [94]. Additionally, acoustic discomfort becomes more pronounced when other indoor environmental factors, such as thermal comfort and air quality, are ideal [95].

To conclude, the optimal acoustical environment depends on the building use and characteristics, type of work, and occupant characteristics. Past studies provide evidence how the acoustical environment affect human performance, health, and well-being, making it an important factor to consider when optimizing the indoor environment.

2.4. Question 4: How does indoor lighting affect building occupants?

Just as our ears have two distinct functions (i.e., hearing and balance), our eyes also have two critical roles. Light enables vision, which begins at the level of the visual photoreceptors in the eye. However, light also acts through a non-visual photoreceptor in the eye to influence a wide range of non-visual functions. These non-visual effects can be broadly categorized into circadian resetting and acute effects, such as, pupil constriction, melatonin suppression, and increasing alertness.

Both the circadian resetting and acute melatonin suppression effects of light exposure are mediated by the eye and through projections from the retina to the central circadian pacemaker, which is located in the suprachiasmatic nucleus (SCN) of the hypothalamus. Light information via the SCN and/or other brain areas induce a wide range of acute neurobehavioural and physiologic changes [96–98]. The acute effects of light on outcome measures are restricted to during (or shortly) after light exposure. The effects of light on the phase (timing) of the circadian pacemaker, and thereby its influence on physiology, alertness, and well-being, outlast the light exposure by more than an hour, affecting circadian rhythms across subsequent days [96].

It is thus important to think not only about the acute effects, but also about the circadian resetting effects, especially when occurring in the evening, night, or early morning [99,100]. Key factors affecting non-visual effects of light include timing, intensity, duration, wavelength, and an individual's prior light exposure history [96,100]. Typically, high-intensity and short-wavelength (blue-enriched) light is more effective in inducing physiological responses than dim and blue-depleted light during the day and night [101–111].

In the context of the built environment, non-visual effects of light have recently started to garner attention based on the realization that understanding and leveraging these effects may optimize work performance, health, and well-being. Research consistently demonstrates that lighting impacts several, but not all, cognitive domains [5]. Different physiological endpoints are impacted differently, and to a different degree, based on whether the exposure occurs during the day or night. Nighttime exposure typically suppresses melatonin, heightens alertness and potentially disrupts sleep, which can impair alertness the following day [112].

Field studies confirm that natural light exposure has a measurable positive impact, including improving alertness, mood, and cognitive performance [113–116]. Exposure to natural daylight in office spaces improves self-reported sleep, health, and well-being [117–122]. However, there may be limited exposure to daylight for most occupants due to design constraints and occupancy needs, necessitating electric lighting [115,121,123–125]. The standards for indoor lighting, however, are based primarily on optimizing visual needs (e.g., acuity), without considering the physiological responses, which can lead to suboptimal lighting for non-visual responses [115,124,126].

Evidence from intervention studies underscore the benefits of optimized lighting [109,127–132]. Short-wavelength enriched white light (17,000 K, with high melanopic strength) improved subjective alertness, mood, cognitive performance, and reduced fatigue, irritability, and eye discomfort compared to standard white light (4000 K) with low melanopic strength [114]. Similar interventions in schools, hospitals, and care-homes facilities have demonstrated enhanced alertness, mood, and health outcomes [133–137].

Emerging evidence has led to recommendations supporting the incorporation of lighting technologies engineered to support work performance and health [138–140]. Recommendations depend on users' sleep/wake schedules rather than clock time. For instance, shift workers require higher nighttime light levels to maintain productivity, while most other users benefit from reduced levels to support healthy sleep patterns. In conclusion, the lighting environment has a profound effect on humans. When optimizing the lighting conditions, it is important to consider the type of tasks [132], and the time of day at which it needs to be performed. Lighting for shift workers differ in their requirements to reduce adverse health effects, compared to daytime workers.

2.5. Question 5: How can we optimize the design and operation of indoor environments to improve indoor environmental quality?

The design and operation of indoor environments typically approach each factor of the four IEQ factors independently. For example, one firm may be responsible for IAQ and thermal comfort, another firm for lighting, and yet another for acoustics, each likely using a set of related but independent standards and building code rules. As discussed in *Questions 1 and 2*, these requirements have usually been developed based on field or laboratory experiments that focus on one dimension at a time [141]. However, people experience these factors simultaneously, and their combined effect can influence both perception and outcomes. Research efforts have aimed to capture the interactions between these different dimensions. A critical review of such multi-domain studies found that existing research lacks qualitative requirements to be included in meta-analysis. To compensate for that, they tried to develop guidelines and recommendations for designing, deploying and reporting multi-domain studies [142].

The lack of accepted and implementable knowledge that can be incorporated into standards and building codes leaves designers and engineers without a reliable foundation for making informed decisions. Currently there is a lack of a model that simultaneously accounts for the various environmental factors and their interactions. These factors often influence each other in complex ways. For instance, increasing daylight and window view might involve using open spaces and transparent vertical elements, which can create acoustical, air quality and thermal comfort issues. Similarly, increasing ventilation rates and filtration levels can lead to higher noise levels. This raises the question: How do we prioritize among IEQ factors to maximize benefits?

One approach is to rely on green and healthy building certifications, such as LEED and WELL, to guide design and operational decisions. However, few field studies exist on their effectiveness, with contradicting findings, primarily relying on self-reported measures of productivity and health [143–147]. Additionally, these certifications typically address environmental factors separately, neglecting the interactive relationships among IEQ parameters [148]. Although, such certification schemes often include survey results asking occupants for their overall satisfaction with IEQ, which can be considered as a way to cover interactive effects.

Another approach is to select a specific outcome to optimize productivity, health or well-being, exploring possible solutions for different types of combinations of environmental factors. A major challenge is that there is a lack of standardized or objective measures of variables like work performance, health, and well-being. While objective measures of health can include monitoring physiological parameters, work performance and well-being are multifaceted concepts, which should be measured using a combination of objective and subjective, self-reported measures.

One proxy for well-being that has been explored is occupant satisfaction [8]. The Center for the Built Environment at the University of California, Berkeley, has the largest dataset on this topic (~90,000 answers from ~900 buildings over 20 years) showing that a total of 68% of the respondents are satisfied with their workspace. Satisfaction is highest with spaces' ease of interaction (75% satisfied), amount of light (74%), and cleanliness (71%). Dissatisfaction is highest with sound privacy (54% dissatisfied), temperature (39%), and noise level (34%) [42]. One way to use this data is to address the aspects with the highest dissatisfaction, by reducing noise, providing personal control, and offering more space to occupants. Additionally, enhancing the environmental characteristics associated with high satisfaction, such as proximity to a window and having a private office, can also improve overall satisfaction [93].

Another approach involves applying a weighting scheme to the four main factors. An early attempt to do this assigned 39% of the total certification credits to acoustics, 29% to lighting, 20% to IAQ, and 12% to thermal comfort [149]. This was obtained by quantifying the individual contribution of each factor on determining the overall satisfaction. Panels of experts or surveys of a large group of professionals have been used to develop these weightings [150–152]. While certifications might simplify the complex interactions between different IEQ factors, such schemes nevertheless help to derive practical solutions for decision-makers in the real estate sector [150,153].

Overall, there is not a deterministic solution to optimize IEQ and, for the time being, we will continue to rely on the ability of professionals to make the trade-off based on project objectives and constraints. The situation could be different in building operations, where occupant feedback could be collected and IEQ can be measured continuously. In that case, evidence-based improvements can be obtained. There are certification programs like WELL and RESET that guide operators towards the continuous collection of data during operation and there are products like *ComfyApp*, helping to close the feedback loop. However, evidence on their effectiveness remains scant. Future research should consider objective and subjective measures of performance, health, and well-being, in order to capture a holistic picture to assess the effectiveness of such certification schemes [154].

2.6. Question 6: What evidence exists on the cost and benefits of optimizing indoor environmental quality?

Previous research has highlighted the relevance of IEQ for human health, cognitive performance, and well-being. While the beneficial effects of optimized IEQ parameters are well-documented, their implementation in practice often entails considerable capital expenditures and increased operational energy demand. Consequently, a comprehensive evaluation of the economic implications, balancing investment costs against measurable benefits, is essential to support evidence-based decision-making. Multiple studies have addressed this issue through cost-benefit analyses targeting individual IEQ factors.

Air quality has emerged as a key determinant of cognitive performance, health and well-being. Evidence presented in *Question 1* supports the notion that increased ventilation rates can enhance cognitive performance and reduce adverse health effects. However, higher ventilation rates are commonly associated with increasing electricity consumption due to higher fan speed, underscoring the need for a cost-benefit trade-off.

Empirical analyses suggest that the productivity-related economic gains of enhanced ventilation can offset the associated energy costs [155,156]. Furthermore, adequate selection of air filtration systems can reduce the energy consumption associated with ventilation [157–159]. Although, the efficacy and economic benefits of air filtration vary based on factors such as city-specific climate conditions, building type (residential or commercial), and health-related cost assumptions derived from epidemiological models [24]. Furthermore, some filters may increase heating, ventilation, and air conditioning (HVAC) energy use due to added airflow resistance, underscoring the need for careful system design [159–161]. Despite these nuances, the literature broadly supports the economic viability of IAQ improvements via ventilation and filtration.

The thermal indoor environment can also be optimized in a cost-effective fashion, in particularly when using personal comfort systems (PCS) [162]. PCS enables individuals to adapt their microclimate around the workplace according to their preferences, which can result in energy savings of 17% to 48% for cooling spaces with localized air movement to reduce thermal discomfort [163]. PCS can also lead to substantial energy savings in hot and humid climates, where air-conditioning is particularly energy-intensive [164]. However, the energy-saving potential of PCS depends on factors such as building type, usage, and outdoor climate. Improperly designed or operated PCS can even increase energy usage [162,165,166]. Introducing more seasonal and daily thermal dynamics, in consideration of the natural thermal environments, can also be considered to reduce energy demand and enhance occupant resilience at the same time [50,167].

Indoor acoustic quality, despite its demonstrated relevance for a healthy indoor environment, remains understudied in terms of cost-benefit analyses. This lack of evidence is notable considering existing evidence on the negative impact of high noise levels on human performance, health, and well-being, as discussed in *Question 3* [6,7]. Studies with a focus on economic outcomes commonly examine outdoor noise pollution, showing its impact on health outcomes [168] and real estate valuation [169–171]. One study investigated the impact of noise on productivity in a manufacturing setting, suggesting a productivity reduction of 3% for a 7 dB increase in noise level. Notably, only a very low willingness to pay among workers to move to a quieter workplace is reported [172].

Light interventions appear to offer some of the more conclusive evidence for cost-effective environmental enhancements. For instance, replacing traditional lighting with LED systems in a garment factory significantly increased production output while reducing thermal discomfort among workers [173]. Using daylight access can improve energy efficiency due to lower energy usage from electrical lighting [174], while increased daylight exposure is also related to important benefits, as discussed in *Question 4*. These papers provide evidence of the beneficial effects of solid-state lighting technology to improve energy efficiency and provide greater control over intensity regulation and spectral modulation compared to incandescent or fluorescent lighting. These upgrades can provide a favourable return on investment from energy savings [174,175] and improve occupants' perception [175].

Despite these findings, a central limitation of current cost-benefit literature lies in the methodological reliance on indirect measures and estimations. Most analyses estimate economic value based on energy modelling, salary-based productivity assumptions, or healthcare cost savings [24,155–159,176]. Productivity outcomes are frequently extrapolated from laboratory settings and translated into performance equations without validation through field data [176,177]. An innovative exception is the use of occupational health insurance claims as proxies for the economic burden of suboptimal IEQ, though such approaches remain rare [177].

In conclusion, while many studies suggest that the monetary benefits of IEQ improvements outweigh their implementation costs, the current evidence base is limited by a lack of rigorous causal methodologies, such as natural experiments or controlled field interventions. Objective, longitudinal data linking IEQ conditions to directly measurable health and productivity outcomes remains scarce. Furthermore, the economic valuation of subjective well-being improvements remains methodologically underdeveloped. The absence of robust empirical data hinders definitive conclusions on the universal cost-effectiveness of IEQ optimization. Moreover, a low awareness among stakeholders and decision-makers regarding the economic benefits of improved IEQ translates into limited willingness to invest, ultimately constraining the implementation of healthier indoor environments.

2.7. Question 7: Which trade-offs need to be considered when optimizing indoor environmental quality?

Designing and operating indoor spaces for optimal work performance, health, and well-being involves balancing competing priorities, which can be thought of as a process of constrained optimization. If indoor spaces were exclusively optimized for one factor, such as IAQ, while ignoring other factors, they would fall short to most definitions of a healthy building. Mathematically, adding more constraints to an optimization problem reduces the feasible solution space, thereby preventing individual values or objectives to reach their maximum unconstrained value. Hence, building designers and engineers must carefully evaluate and prioritize relevant parameters, deciding which aspects to emphasize and which to compromise on in order to achieve an optimal balance, as it has already been discussed in *Question 5*.

IEQ aligns with broader goals of real estate management, particularly in the context of a larger sustainability strategy. For instance, maximizing natural light through large windows and skylights reduces the need for artificial lighting, thereby potentially shrinking energy consumption and carbon footprints. Similarly, smart LED lights and daylight harvesting can save over 60% of energy compared to conventional lighting systems under certain conditions while also maintaining visual comfort for occupants [178]. Using LED lighting is estimated to lead to a 6.7 times reduction in energy consumption [179]. However, an important caveat is that large windows may simultaneously increase energy requirements for heating and cooling due to their thermal and insulation properties.

Exposure to natural light is also linked to improved mood, enhanced sleep quality, and increased productivity, as discussed in *Question 4*, which creates advantageous synergies. Similarly, non-toxic materials with low volatile organic compounds emissions improve IAQ and promote overall health while reducing environmental impact, as summarized in *Question 1*. Access to green spaces, such as rooftop gardens or indoor plants, can improve air quality, reduce urban heat island effects and reduce stress. These features align environmental sustainability with mental and physical health benefits [180].

Perhaps one of the most intractable trade-offs revolves around building and urban density versus human well-being. Higher urban density is associated with lower greenhouse gas emissions due to reduced energy use from transport and buildings [181]. However, dense environments often lack green spaces, which are critical for physical and mental health [182,183]. This constitutes an important trade-off between what is effective for lowering carbon emissions and what is desirable from a health and well-being point of view. Similarly, efforts to integrate greenery and recreational areas into urban and real estate development schemes often require additional space, posing energy and design challenges.

A number of solutions have been proposed to address these trade-offs. For example, advanced ventilation systems like energy recovery ventilators or demand-controlled ventilation can balance IAQ and energy efficiency [184,185]. Biophilic design integrates natural elements, such as indoor green spaces, natural light and water features, thereby improving mental well-being and IAQ while enhancing energy efficiency by reducing the need for artificial lighting and cooling [186]. Personal comfort systems optimize space usage and energy demands while supporting individual occupant needs [162,187,188]. At the urban level, creating accessible green spaces, even if they are relatively compact, can help balance the benefits of high-density living with access to nature. This can be achieved by integrating small parks or rooftop gardens into the design [189].

Overall, evidence shows that optimizing IEQ goes beyond just improving IAQ, thermal conditions, lighting and noise levels. IEQ is influenced by more than just these four factors; it also depends on elements such as access to nature, biophilic features, and control over one's personal micro-climate. Additionally, subjective criteria such as psychological safety and mental health are only poorly researched with respect to their relation with different IEQ conditions. However these factors are equally important as objective measures of health and satisfaction to improve occupant well-being [7]. Understanding the trade-offs between factors is crucial for optimizing work performance, health and well-being without neglecting energy efficiency and sustainability criteria. Several papers have pointed out the need for a more holistic view on IEQ and its impact on occupants to avoid costly mistakes [142,154].

2.8. Question 8: What can we learn from the economics of green-certified buildings?

To define a business case for healthy buildings, it is informative to examine the development and evidence based on green-certified buildings. While green-certified buildings focus primarily on minimizing energy, material and water use, site disturbance, and waste generation, they also serve as an instructive precedent for evaluating the economic viability of health-oriented building strategies. They can be identified through certifications, with numerous schemes available worldwide [148,190]. Investments in green-certified buildings have experienced a strong growth in recent years, driven by substantial evidence supporting their profitable business case [191]. Healthy buildings and associated certification schemes, such as WELL and Fitwel, can be considered as an extension of green buildings, emphasizing IEQ,

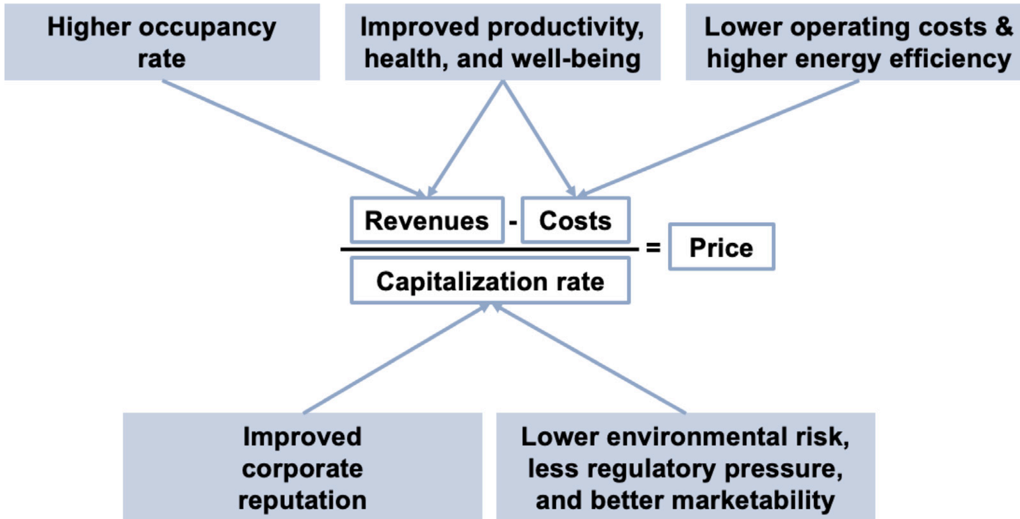

Fig. 2. Benefits of green-certified buildings.

health and well-being of occupants [148]. Consequently, insights derived from green-certified building economics offer a valuable foundation for understanding the financial rationale behind healthy building strategies.

Evidence from the last decade consistently shows better financial performance for green-certified buildings, such as those labelled by LEED, Energy Star or BREEAM. The financial premium of green-certified buildings is attributed to several advantages, some of which are also relevant for healthy buildings. These include higher rents, higher occupancy rates, lower operating expenses, lower risk, and improved productivity, comfort and health of occupants [191,192]. Numerous empirical studies have confirmed that green-certified buildings command higher rents and selling prices [10,193], although the magnitude of these benefits is influenced by contextual factors, such as local climate conditions and energy prices [194]. A review on green-certified buildings reports average rental premiums of 6.3%, 0.4% lower operating costs, and a 14.8% higher sales price, albeit with substantial heterogeneity across studies and markets [192]. Higher occupancy rates and tenant retention are as well frequently observed in green-certified buildings [192,195], alongside better corporate reputation for investors [196]. These reputational advantages may contribute to a lower equity cost of capital [197] and reduced borrowing costs [198].

While operational savings contribute to the observed financial premiums, they do not fully account for the differences in valuation [199] and they are not entirely driven by energy savings [192,200]. Notably, green-certified buildings do not always achieve lower energy consumption, suggesting a discrepancy between certification and actual performance [201–205]. However, variation in the market premium is linked to the actual energy performance. This illustrates that energy savings play a role in determining the value premium although the value of green-certified buildings goes beyond lower operating costs and higher energy saving potential [10].

As illustrated in Fig. 2, the business case for green-certified and, by extension, healthy buildings can be conceptualized through their effects on both revenue and cost components of net operating income. Enhanced productivity, better health, improved well-being, and higher occupancy rates contribute to increased revenues. Improvements in productivity and health, leading to lower production errors and lower sickness absenteeism can also reduce overall costs. Furthermore, reduced energy use and operational efficiency lower costs as well. These factors constitute the net operating income of a building. Divided by the capitalization rate, which improves due to better corporate reputation and reduced risk, this determines the price and thus value of a building.

In addition to measurable advantages, green-certified buildings offer a range of intangible benefits, such as higher tenant satisfaction, higher probability of renewing leases, and decreased rent concessions, all of which contribute to lower risk and increased cash flows [206]. These benefits may also include improved productivity, well-being and health of occupants, which are strongly influenced by IEQ. Nevertheless, there is mixed evidence as to whether green-certified buildings consistently lead to better IEQ and its associated benefits, such as higher productivity, better health, or higher satisfaction [143,207,208].

Despite these potential advantages, constructing green buildings often incurs higher upfront design and construction costs, leading to higher marginal costs [191,209]. Observed cost premiums range from a small decrease of 0.4% to substantially higher upfront costs of 11% [191]. From an investor perspective, such investments are only justifiable if the present value of future income streams and risk reduction outweighs the additional initial expenditure [11].

Taken together, the business case for green-certified buildings underscores that attracting investments into healthy buildings requires demonstrating positive financial returns from developing, investing in, and renting healthy buildings with improved IEQ. While green-certified buildings show the difficulty of pinpointing the exact sources of financial benefits, they also emphasize the importance of understanding not only if, but also why healthy buildings could provide financial returns, potentially even superior to those of green-certified buildings. Attracting capital towards buildings with enhanced IEQ depends not only on confirming their economic viability but also on understanding the underlying mechanisms that generate value.

2.9. Question 9: How can demand for investments in optimized indoor environmental quality be stimulated?

To assess the demand for buildings with optimized IEQ, it is important to consider the range of stakeholders involved across the building's life cycle. While multiple incentives for investing, developing or renting a healthy building exist, the benefits are not evenly distributed among stakeholders. Developers primarily benefit from increased market value, especially when the building is sold shortly after construction. Owners benefit from lower operational costs, higher occupancy rate, and lower risk. Tenants, on the other hand, directly benefit from higher productivity, improved health and well-being, and from lower operating costs and energy savings.

Developers bear the initial costs and higher risks associated with investing in new technology to construct a healthy building and optimized IEQ. Their ability to recoup these costs often hinges on achieving higher selling prices post-construction. Indeed, emerging empirical evidence suggests that health-certified office buildings command a sales price premium [210,211]. Despite this evidence, the principal-agency problem, characterized by information asymmetry, imposes a barrier for developers, because the true value of provided benefits might reveal itself only gradually over time [212,213]. One study shows that the resale price of green-certified buildings is much higher than during the pre-sale phase, indicating that developers bear most of the costs but may not be adequately compensated [214]. To overcome this barrier, developers must signal the value of healthy buildings to potential buyers and thereby reduce information asymmetry to receive a price which compensates them for additional upfront costs. Certifications from independent institutions can serve as an effective indicator of superior building quality and help bridge the information gap [215].

For building owners, healthy buildings offer potential long-term advantages. These benefits include lower holding costs due to lower vacancy rates, longer tenant retention, and reduced regulatory risk, because the building already fulfils stricter standards on IEQ that might be implemented in the future [193]. Also, healthy building certifications such as WELL and Fitwel are complementary with energy efficiency certifications [216]. Thus, owners can also benefit from lower operating costs due to utility savings if the leasing structure is an all-inclusive contract in which the tenant pays a fixed amount for utility costs, independent of the actual consumption. Such a full-gross leasing contract would shift the benefit of energy savings to the owner, however, it provides the tenant no more incentive to save energy [191]. However, under net lease structures, where tenants pay utilities directly, the benefits of reduced consumption primarily accrue to the tenant, creating a split-incentive problem [191,217]. While developers or owners are investing into the energy efficiency and IEQ, it is mostly the tenant, as building occupant, who benefits from the lower energy bill and positive effects of optimized IEQ on performance and health. Thus, the owner would have no incentive to invest in the building [192,215].

Generally, the intangible benefits of improved productivity, health and well-being are less easy to attribute to a specific stakeholder. In principle, tenants primarily benefit from higher productivity, better health and improved well-being, because IEQ has a direct impact on building occupants. These benefits can justify paying a higher rent to lease a healthy building [191,215]. However, such willingness to pay is dependent upon the tenant's ability to convert these benefits into measurable financial returns. To date, limited empirical evidence exists to quantify the financial benefits of improved occupant productivity, health, and well-being, discussed in *Question 6*, which supports a cost–benefit analysis comparing rent premiums with the expected productivity and health-related gains.

Furthermore, the slow adoption of green-certified buildings is often attributed to higher marginal costs and higher design fees [209], potentially also affecting the adoption rate of healthy buildings with an optimized IEQ. For example, BREEAM-certified buildings are approximately 6.5% more expensive to construct, primarily driven by higher design fees and building finishing and fitting costs. Although design fees are 150% higher for those buildings, they constitute only 3% of the overall costs. The challenge is that design fees often need to be paid upfront by the developer and are primarily equity financed, implying higher financial risk. Furthermore, these buildings often require longer construction times — on average 11% longer — delaying income streams and adding to the financial burden for developers [209].

To reduce this barrier, financial institutions are increasingly offering green loans to construct or refurbish a building which fulfil certain environmental performance standards. These loans have lower rates and a higher loan-to-value ratio than conventional loans, making them attractive for developers to finance the higher upfront design fees [209]. Expanding such mechanisms to include IEQ-focused developments, through *"healthy loans"*, could create additional incentives for investment. However, banks typically require clear cash flow forecasts to determine favourable loan terms. Demonstrating consistent rental premiums, higher sales prices, and reduced vacancy rates is therefore essential to improving the risk profile of healthy buildings and making them attractive additions to mortgage and investment portfolios.

In summary, successful adoption of healthy buildings depends on a clear understanding of who bears the initial costs and who benefits from the returns. Challenges to the adoption of healthy buildings, such as the split-incentive problem and higher upfront costs must be addressed through appropriate lease structures and financing models that align costs and benefits across stakeholders. Only through equitable risk-return distribution can broader market adoption of healthy buildings be achieved.

2.10. Question 10: How can tenants and investors monetize indoor environmental quality?

Corporate tenants need to know if providing good IEQ is enough to justify paying a premium rent, particularly with the rise of hybrid work. The working-from-home trend imposes a major challenge for the office real estate market, potentially leading to substantial financial losses [218–220]. Thus, corporations may need to go further than the minimum to entice workers back to the office [221,222]. This can be challenging since workplaces have multiple interrelating factors that impact the experience of a space, and studies on the cumulative benefits of all possible IEQ conditions in the workplace are difficult given their interdisciplinary nature. Further complicating any analysis are psychosocial and organizational management factors [223–225] and environmental perception [116]. Thus, to understand if a healthy building is profitable for tenants and investors, three key aspects need to be addressed: (i) clarification and broadening the definition of a healthy building; (ii) exploring holistic approaches to workplace health and well-being; and (iii) and analysing current drivers for real estate and associated risks of not investing in a healthy building.

Expanding towards a health-promoting approach has been linked with positive health and well-being outcomes. These can include Active Design [226], Activity Based Working models to increase physical activity [227], and biophilic design [228] to create place attachment, and social cohesion, all pivotal in providing resources to employees to balance against the demands and stressors of work [229]. While these approaches are not always included in traditional definitions of IEQ, their growing research base may be a vital component of encouraging people back to the office and fostering a sense of engagement and social cohesion [230,231]. Recent reviews have examined a range of built environment factors that influence mental health [232] and overall health and performance [233], supporting the case for more holistic frameworks in workplace design.

Another approach is to look at building certifications which capture data across a range of built environment factors. While green certified buildings are not always healthier buildings [143] and can conflate comfort with health, they can provide a positive financial return, as discussed in *Question 8*. Recent studies on the WELL certification show that occupants in WELL-certified spaces are more satisfied with the indoor environment, outperforming other high-performing buildings [144,147,222]. Nevertheless, more research is needed to fully tease apart the impact of WELL on improving IAQ and consistent occupants satisfaction, given previous studies which have been inconclusive [144–147]. More research is needed to determine whether IEQ improvements at a tenant level justify a higher rent, including better metrics for performance, health, and well-being.

Considering the question if healthy buildings and optimized IEQ provide a similar return on investment than green-certified buildings, we can look at premiums associated with healthy buildings or healthy building features. One working paper found that health-certified buildings achieved approximately 4.4% to 7.7% higher effective rent per square foot than comparable non-certified buildings [211]. Another recently published working paper records a 4% to 6% higher rental premium for WELL-certified office buildings [210], similar to premiums found for green-certified buildings. Other empirical evidence focused on the price impact of individual healthy building features. For instance, offices in Manhattan with more natural light indoors achieve 5.0% to 6.1% more effective rent than comparable offices with less natural light [234]. However, evidence on the financial return and economic value overall of health-certified buildings and IEQ optimization is scarce, thus any conclusions would be premature.

Evidence on the financial value of buildings located close to health-supportive amenities is stronger, due to better data availability. For example, there seems to be a rent, and sales price premium for office buildings in the vicinity of visible green areas compared to office buildings with very low levels of visible green areas [235]. Previous studies also demonstrate a positive relationship between the walkability of an area and real estate related prices [236–239]. These amenities impact the health, well-being, and performance of office workers but are not typically included in IEQ calculations. Future studies should include both IEQ-specific data as well as other factors influencing occupant and financial outcomes.

Despite past studies, current evidence is sparse that examines the economic value of an improved IEQ. As discussed in *Question 6*, a few studies investigated the economic value of IEQ and related certifications, and these use limited metrics to measure financial or individual performance, often conflating health, satisfaction, and owner and tenant incentives. More research is needed which quantifies the benefits and costs of improving IEQ, both alone and in combination with other influencing factors, to answer the question how tenants and investors can monetize IEQ improvements. These other factors include both larger drivers of investment in healthy buildings as risk management, as well as psychosocial and organizational factors that influence outcomes such as performance and well-being. The onset of certification schemes for healthy buildings allows for empirical investigations of the investment value of healthy buildings, as it has been already done for green building certification schemes [191,192]. Furthermore, understanding the individual contributions from various IEQ factors becomes more important in order to estimate the generated cash flows from optimizing IEQ.

3. Conclusion

Past evidence provide a comprehensive understanding of the impact of individual IEQ factors on humans. However, the interactions between these factors and how changes in one factors impacts others remain less understood. Future research should focus on understanding the interaction of building environment factors, which also allows to identify which factor most effectively improve occupants' performance, health, and well-being.

More research is also needed across the entire building lifecycle, including development, initial sale, operation, and demolition of healthy buildings. As this paper highlights, incentives vary between developers, investors, and tenants. A holistic approach is needed for establishing a profitable business case for investments in IEQ. Understanding how adoption of healthy buildings shapes the availability and pricing of IEQ technologies is also essential. Increased adoption could boost supply, reduce acquisition risks, and lower uncertainty for developers regarding technologies and materials. Finally, institutional factors, such as the signalling function of certifications, should be considered in future research. Certifications can reduce uncertainty caused by information asymmetry and future regulatory pressure.

Future research should explore if healthy buildings and IEQ investments can differentiate developers' offerings in an increasingly saturated real estate market. Comparative studies on the price and rent premiums of green and healthy buildings over time are particularly valuable. A declining premium for green-certified buildings due to market saturation might be observed over time. Healthy buildings could emerge as a novel source of price and rent premium, because they include additional improvements in IEQ. IEQ improvements could become a strategy to maintain a value and rental premium as highly energy-efficient buildings become the standard. Furthermore, understanding how changes in IEQ affect financial returns for investors and owners, occupants' health, productivity, and well-being, is critical. Such insights could demonstrate whether the benefits outweigh any additional costs during both design and operation.

Finally, the efficacy of certification programs in achieving their intended IEQ outcomes requires scrutiny. Objective measures are needed to confirm whether certified buildings meet IEQ targets and how these align with enhanced financial performance. Special attention should be given to the financial return of benefits of improved productivity, health and well-being. Understanding these pathways is important for developing cost-effective schemes to design or renovate healthy buildings that optimize IEQ while ensuring attractive returns on investment.

CRediT authorship contribution statement

Stefan Flagner: Writing – review & editing, Writing – original draft, Supervision, Project administration, Conceptualization. **Stefano Schiavon:** Writing – review & editing, Writing – original draft, Conceptualization. **Nils Kok:** Writing – review & editing, Writing – original draft, Conceptualization. **Franz Fuerst:** Writing – review & editing, Writing – original draft. **Dusan Licina:** Writing – review & editing, Writing – original draft. **Angela Loder:** Writing – review & editing, Writing – original draft. **Shadab A. Rahman:** Writing – review & editing, Writing – original draft. **Frank A.J.L. Scheer:** Writing – review & editing, Writing – original draft. **Lily Wang:** Writing – review & editing, Writing – original draft. **Gabriel Weeldreyer:** Writing – review & editing, Writing – original draft. **Hannah Pallubinsky:** Writing – review & editing, Writing – original draft, Conceptualization.

Declaration of competing interest

The authors declare the following financial interests/personal relationships which may be considered as potential competing interests:

Angela Loder reports a relationship with International WELL Building Institute (IWBI) that includes: employment.

Shadab A. Rahman reports a relationship with Melcort Inc. that includes: equity or stocks. Shadab A. Rahman has patent "Method and device for preventing alterations in circadian rhythm" (U.S. patent application Ser. No. 10/525,958 licensed to Shadab A. Rahman). Shadab A. Rahman has patent "Methods and devices for improving sleep performance in subject exposed to light at night (U.S. Application No. 61/810,985) licensed to Shadab A. Rahman".

Frank A.J.L. Scheer served on the Board of Directors for the Sleep Research Society and has received consulting fees from the University of Alabama at Birmingham and Morehouse School of Medicine. F.A.J.L.S. interests were reviewed and managed by Brigham and Women's Hospital and Partners HealthCare in accordance with their conflict of interest policies. F.A.J.L.S. consultancies are not related to the current work.

Shadab A. Rahman has provided paid consulting services to Sultan & Knight Limited, Bambu Vault LLC, Lucidity Lighting Inc.; and has received honoraria as an invited speaker and travel funds from Starry Skies Lake Superior, University of Minnesota Medical School, PennWell Corp., and Seoul Semiconductor Co. Ltd., FALK FOUNDATION E.V.; SAR has received grant/research support from Seoul Semiconductor Co. Ltd., Biological Innovation and Optimization Systems, LLC, Merck & Co., Inc., Pfizer Inc., Vanda Pharmaceuticals Inc., Lighting Science Group, NIH, and NASA. These interests were reviewed and managed by Brigham and Women's Hospital and MassGeneralBrigham in accordance with their conflict of interest policies. If there are other authors, they declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

No data was used for the research described in the article.

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