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Indoor Environmental Quality (IEQ) in Healthcare Settings and Cognitive Performance of Staff: The Role of Ventilation, Microclimate and Sensory Load for Medical Education and Patient Safety – A Narrative Review

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ABSTRACT

Introduction. Clinical work is performed under conditions of high cognitive load, time pressure and frequent interruptions. Research on patient safety has traditionally focused on sleep deprivation, fatigue and work organisation, whereas environmental factors are analysed less frequently, despite their chronic and cumulative effects.

Aim. The aim of this narrative review is to present the current state of knowledge on the relationship between indoor environmental quality (IEQ) and cognitive performance of healthcare professionals and trainees, and to discuss the implications of these associations for medical education and patient safety.

State of knowledge. IEQ encompasses ventilation and air quality, thermal and humidity conditions, lighting, and sensory load, including noise. Experimental and observational evidence suggests that even moderate deviations of environmental parameters may be associated with impairments in vigilance, attention, working memory, reaction time and executive functions, particularly when combined with sleep deficit, multitasking and high distraction. Indirect effects may also arise from exposures typical of hospital environments and from factors increasing respiratory discomfort and communication burden.

Conclusions. Framing IEQ within a human factors perspective supports a systems-based approach to quality and safety. Monitoring environmental parameters and implementing low-cost organisational interventions may represent a practical component of strategies aimed at supporting cognitive performance of staff and the effectiveness of medical education.

Keywords: Indoor environmental quality, cognitive performance, human factors, patient safety, medical education

1. Introduction

Contemporary clinical environments require sustained high-level cognitive functioning under conditions of time pressure, multitasking and frequent interruptions, where performance depends on vigilance, attention control, working memory and executive functions [12,16]. In ward settings, even modest reductions in these functions can translate into omissions and sequential errors, particularly when interruptions are frequent and task resumption is cognitively costly [12,16]. This is consistent with patient-safety research showing that interruptions are not merely “nuisance events”, but are associated with increased risk and severity of medication administration errors [12]. The patient safety literature has largely focused on work hours, sleep restriction, fatigue and organisational drivers of error [19,20]. While this perspective is justified, it does not fully capture the contribution of physical working conditions that may erode cognitive reserves and amplify vulnerability to distraction over time [14,15]. In practice, environmental strain can interact with organisational strain: occupational stress and burnout are prevalent in healthcare and may lower tolerance of cognitive load, increasing the functional impact of otherwise moderate environmental deviations [28–30]. Indoor environmental quality (IEQ) can be conceptualised as a set of boundary conditions that modulate arousal, sleepiness, tolerance of mental effort and the cognitive cost of task performance [5]. Its impact is often chronic and cumulative: performance does not necessarily “collapse”, but becomes less stable and more error-prone when compensatory reserves are limited [14,15]. This framing aligns with human factors models in which adverse events emerge from interactions between people, tasks, tools and the environment rather than from isolated individual failures [14,15]. IEQ integrates parameters related to ventilation and air quality, thermal and humidity comfort, lighting conditions and sensory load (including noise and stimulus density) [5]. In healthcare, particular importance attaches to spaces where staff spend prolonged periods and perform cognitively demanding tasks—duty rooms, nursing stations, handover rooms, documentation areas, emergency departments, lecture halls and simulation centres—because these environments combine sustained mental effort with communication demands and frequent interruptions [12,13,16]. Under intensive use, especially with insufficient air exchange, indoor carbon dioxide concentration (treated primarily as an indicator of ventilation effectiveness) may increase and co-occur with discomfort and reduced perceived air quality [7]. In everyday terms, staff often describe these conditions as “stale air”, “stuffiness” or a sense that concentration drops faster in small, crowded rooms. Such descriptions are imperfect, but they matter because they reflect perceived effort and irritation that can shape how long people can stay attentive. In this review, we treat these subjective cues as context rather than endpoints, but they help explain why IEQ is noticed by clinicians even when objective deviations appear modest. Unlike many organisational determinants, IEQ is often measurable, auditable and modifiable with relatively low-cost interventions, making it a practical target for quality improvement and safety programmes. The aim of this review is to synthesise evidence on the relationship between IEQ and cognitive performance in clinical and educational contexts, and to outline implications for patient safety.

1.1. IEQ in medicine as a human factors issue

Within systems approaches to patient safety, adverse events are understood as the result of interactions between people, processes, tools and the environment [14,15]. The physical environment is not a neutral backdrop: it can shape communication quality, information selection and the effectiveness of error-control mechanisms [14,15]. Improvements in handover procedures can reduce medical errors, yet their effectiveness depends on conditions that support attention, audibility and reliable information transfer [13]. Accordingly, improving IEQ parameters may strengthen the performance of other safety barriers—procedures, checklists and communication standards—whose effectiveness relies on available attentional resources, working memory and executive control [14].

2. Methodology of the review

This study is a narrative review integrating evidence on the relationship between indoor environmental quality (IEQ) and cognitive functioning in contexts relevant to healthcare delivery and medical education. The review focused on environmental parameters that are measurable in real-world settings and potentially amenable to organisational or technical modification, including ventilation and indoor air quality, thermal and humidity comfort, lighting conditions and sensory load, particularly noise [5]. In the ventilation domain, carbon dioxide concentration was treated primarily as an indicator of ventilation effectiveness and occupancy-related accumulation of exhaled air, rather than as a toxicant at typical indoor levels [7].

The literature was identified through targeted searches of major biomedical and interdisciplinary sources, supplemented by reference list screening to capture influential work not consistently indexed across databases. Search strategies combined terms describing indoor environmental parameters (e.g. ventilation, CO_2, temperature, humidity, lighting, noise) with terms referring to cognitive outcomes (e.g. vigilance, attention, working memory, executive functions, reaction time) and applied clinical contexts (e.g. patient safety, human factors, handover, teamwork, simulation-based education) [12–14,16]. This approach reflects the interdisciplinary distribution of relevant evidence across ergonomics, environmental and building research, occupational health, cognitive psychology and medical education [5].

Eligible sources included experimental studies, observational field studies, methodological papers and reviews examining associations between indoor environmental conditions and cognitive performance or providing mechanistic insights relevant to applied settings [1,2,5]. Given heterogeneity in exposures, designs and outcome measures, the synthesis prioritised interpretability and clinical relevance. Greater weight was assigned to studies with clearly characterised environmental exposures (e.g. measured CO_2, temperature, humidity, illuminance or noise), validated cognitive measures or functional proxies, and task demands resembling healthcare work, such as time pressure, multitasking, interruptions and communication-critical activities [1,2,12,16]. Evidence derived from non-clinical indoor settings was interpreted cautiously, with emphasis on mechanisms and contextual similarity rather than assumed direct transferability [5].

As a narrative review, the objective was not to estimate pooled effect sizes but to identify consistent patterns, plausible mechanisms and contextual conditions under which IEQ is most likely to influence cognitive performance in healthcare environments. Particular attention was paid to interactions between environmental factors and common clinical modifiers, including sleep restriction and extended shifts, which may amplify functional consequences of moderate environmental deviations [19,20]. The synthesis was framed within a human factors perspective, emphasising performance stability over time, vulnerability to distraction and reliability of communication as outcomes relevant to patient safety and medical education [13,14].

The searches prioritised peer-reviewed English-language publications. Preference was given to studies published in the last two decades, while seminal earlier papers were included when methodologically influential. Papers were excluded if exposure was not objectively characterised (e.g., no measured environmental parameters) or if outcomes were unrelated to cognitive performance or practice-relevant proxies.

2.1. Conceptualisation of cognitive performance

Cognitive performance was conceptualised as the capacity to sustain reliable and accurate task execution over time. It was operationalised through domains central to clinical work, including vigilance, selective attention, working memory, executive control and processing speed [12,16]. This reflects the fact that clinical safety depends less on isolated "peak" decisions than on maintaining consistency across prolonged periods, multiple parallel tasks and repeated context switching [16].

In ward-based practice, resistance to distraction and interruptions is particularly critical. Interruptions impose a cognitive cost related to task resumption, requiring reconstruction of context and re-establishment of action sequences [12,16]. Even modest reductions in vigilance, attentional control or working memory capacity may therefore increase susceptibility to sequential errors, omissions and premature closure, especially in routine but safety-critical processes such as medication management, documentation and handover communication [12,13]. Within this framework, cognitive performance is treated as a functional resource supporting both individual decision-making and team-based information exchange, which may be progressively eroded by environmental discomfort, competing sensory demands and increased communication effort [14].

3. IEQ in healthcare: definitions, components and clinical specificity

IEQ comprises a set of indoor environmental parameters influencing comfort and functioning of occupants. In healthcare, its relevance extends beyond wellbeing to the stability of performance over time, as clinical environments are characterised by limited opportunities for breaks, high task dynamics and frequent interruptions [16]. Under such conditions, even moderate deviations from favourable environmental parameters may entail a tangible functional cost [5].

With respect to ventilation and air quality, carbon dioxide concentration is widely used as a proxy indicator of ventilation effectiveness, reflecting the relationship between occupancy, outdoor air supply and accumulation of exhaled air in intensively occupied spaces [7]. The evidence base includes controlled exposure and field studies in which cognitive outcomes were associated with ventilation/CO_2 and related indoor exposures, supporting the plausibility that suboptimal ventilation conditions can co-occur with decrements in decision-related performance and cognitive function [1,2]. Thermal and humidity conditions may modulate sleepiness, irritability and tolerance of mental effort, while sensory load—particularly noise—affects information selection and communication quality [5,8]. The key components of indoor environmental quality and their relevance to cognitive performance, medical education and patient safety in healthcare settings are summarised in Table 1. In hospital settings, IEQ profiles may be further shaped by chemical and biological exposures related to materials, disinfection processes and aerosols/particulates [6].

Table 1. Key indoor environmental quality (IEQ) components and their relevance to cognitive performance and patient safety in healthcare settings

IEQ component and indicator	Relevance for cognition, medical education and patient safety
Ventilation and air quality (CO_2 level)	Attention, vigilance, decision stability and sustained cognitive performance of staff and trainees
Thermal comfort (ambient temperature)	Sleepiness, tolerance of mental effort and executive control under workload
Humidity (relative humidity)	Respiratory comfort, fatigue accumulation and concentration stability during prolonged tasks
Lighting (illuminance and spectrum)	Alertness, circadian regulation and vigilance, especially during night

	shifts and teaching activities
Noise and sensory load (sound level)	Working memory, attention control, communication accuracy and error prevention in teams
Chemical and particulate load (odours, particles)	Irritation, distraction and cumulative cognitive fatigue in busy hospital areas
Micro-IEQ from PPE (mask or respirator use)	Breathing effort, fatigue and communication burden during critical clinical exchanges

Importantly, these IEQ components rarely occur in isolation. On a busy ward, noise, crowding and poor perceived air quality often appear together, and staff adapt by speaking louder, moving faster and relying more on memory than on deliberate checking. This is precisely the type of "background strain" that human factors frameworks treat as a contributor to performance variability rather than a single causal trigger.

3.1. Bioaerosols, mould and allergenic factors

Despite stringent hygiene standards, healthcare environments are not free from bioaerosols, allergens and mould spores, particularly when moisture problems occur after leaks, technical failures or inadequate drying [6]. In this review, their relevance is largely indirect: irritation, headache and subjective discomfort may increase distraction and accelerate fatigue, thereby reducing the capacity to sustain concentration over time [6].

3.2. Chemical agents, disinfectants and irritation as cognitive cost

Healthcare settings involve widespread use of disinfectants and cleaning agents, contributing to odour load and, in some contexts, airway irritation [6]. Such exposures rarely imply acute toxicity at typical levels, but persistent discomfort may act as a distractor, increase subjective fatigue and weaken executive control under time pressure [14,15]. In team environments, increased irritability may also compromise communication clarity and willingness to seek clarification, which is relevant where safety depends on reliable information transfer [13,14].

3.3. Particulate matter and procedural environments

Suspended particles in hospitals may originate from staff and patient movement, textiles, technical works and renovations, as well as aerosol-generating procedures [6,27]. Although direct links to cognitive function are difficult to quantify, indirect effects include irritation and discomfort, which may raise the cognitive cost of work and shorten periods of effective concentration [6].

3.4. Lighting, circadian rhythm and shift work

Lighting is an important component of IEQ, especially in settings characterised by shift and night work. Experimental evidence indicates that light spectra and intensity can influence alertness and vigilance, with short-wavelength–sensitive pathways implicated in direct alerting effects [21]. Workplace studies using blue-enriched white light have reported improvements in self-reported alertness and performance-related outcomes, supporting the plausibility that lighting optimisation may be operationally relevant [22].

3.5. Respiratory protective equipment as "micro-IEQ"

Although masks and respirators are not classical components of room-level IEQ, they create a micro-environment at the interface between user and surroundings. Prolonged use can increase perceived breathing effort and thermal/humidity discomfort, potentially accelerating fatigue under high workload [14]. Communication may also be affected: speech attenuation and reduced intelligibility become especially consequential in noisy, time-pressured contexts, increasing repetition and working-memory load during critical exchanges such as handovers or medication orders [8,13]. Consequently, evaluation of IEQ in healthcare may require consideration of interactions between room parameters, work organisation and user-level micro-IEQ factors [14].

4. Neurophysiological and neurocognitive mechanisms

The influence of indoor environmental quality on cognitive performance can be conceptualised as the combined effect of direct physiological modulation and indirect increases in cognitive cost. Direct effects include changes in ventilation-related respiratory conditions and thermal strain, which influence arousal regulation and neural efficiency, particularly in prefrontal cortical networks responsible for executive control, response inhibition and cognitive flexibility [2,5]. These functions are essential for maintaining performance quality under interruption, uncertainty and time pressure, which characterise routine clinical work [16].

Indirect effects operate through discomfort, sensory irritation and increased effort required to maintain task engagement. Thermal discomfort, inadequate humidity and perceived "stale" air may increase sleepiness and reduce tolerance of mental effort, while excessive sensory stimulation competes for attentional resources [5,8]. Noise is particularly disruptive in this regard, as it interferes simultaneously with attentional selection and verbal communication, increasing the likelihood of misinterpretation and delayed response under pressure [8,10].

4.1. IEQ and cognitive load theory in clinical contexts

According to cognitive load theory, performance depends on the balance between task demands and available processing resources. Clinical environments are structurally demanding due to multitasking, frequent interruptions, uncertainty and prioritisation requirements [16]. Under such conditions, even modest environmental deviations may reduce available resources sufficiently to impair performance stability [5].

Empirical studies in non-clinical settings demonstrate that ventilation and air quality parameters are associated with changes in decision-making performance and cognitive efficiency, supporting the plausibility of similar effects in healthcare environments where baseline cognitive load is already high [1,2]. Clinically, these effects are more likely to manifest as increases in minor errors, omissions and delays in routine processes rather than as isolated catastrophic failures [14,15]. Over time, such deviations may accumulate, increasing overall system risk.

4.2. Cognitive functions critical for patient safety

Vigilance, selective attention, working memory and executive control are particularly critical in healthcare. Impairment in these domains increases susceptibility to omission errors, hampers effective task resumption after interruption and promotes premature closure in diagnostic and procedural reasoning [12,16]. Given the frequency of attentional shifts in ward environments, even small decrements may have disproportionate consequences for safety-critical tasks [14].

Research on interruptions has shown that task switching and resumption are cognitively costly and error-prone, especially when working memory capacity is taxed or vigilance is reduced [12,16]. Environmental stressors that further load these systems may therefore amplify the risk associated with routine interruptions.

4.3. Measurement of cognition and its relevance

Studies examining environmental effects on cognition typically employ standardised measures of vigilance, reaction time, attention and working memory, as well as tests of executive function [1,2,18]. While such measures do not directly assess clinical decision quality, they capture cognitive components known to underlie error mechanisms and performance instability [15].

In applied healthcare research, brief vigilance tasks, subjective fatigue scales and simulation-based functional measures are often used to approximate real-world performance without disrupting clinical workflows [18]. This approach is methodologically justified when the focus is on identifying conditions that degrade cognitive reserves rather than on evaluating isolated decisions.

4.4. Affect, irritability and frustration tolerance

Affective state is an important modulator of cognitive control. Environmental discomfort may increase irritability and reduce frustration tolerance, weakening executive oversight and promoting abbreviated verification strategies under time pressure [14]. Such effects are particularly relevant in team-based work, where communication clarity and willingness to seek clarification are critical for error detection and recovery [13,14].

Chronic exposure to unfavourable working conditions may also interact with occupational stress and burnout, lowering baseline tolerance of cognitive load and increasing vulnerability to environmental stressors [28–30].

4.5. Breathing effort, arousal regulation and cognitive cost

Regulation of arousal in demanding environments depends partly on the physiological cost of maintaining respiratory comfort. Under prolonged workload, limited ventilation and the use of respiratory protective equipment may increase perceived breathing effort and thermal discomfort, contributing to fatigue accumulation [14]. These effects are typically subacute and cumulative, manifesting as declining performance stability and increasing frequency of minor cognitive slips rather than acute impairment [5]. Table 2 synthesises IEQ-related mechanisms and their practice-relevant implications for clinical performance, communication and patient safety.

Table 2. IEQ-related mechanisms and practice-relevant implications for clinical performance, communication and patient safety

IEQ factor	Likely mechanism (cognitive/physiological)	Practice-relevant implication
Ventilation / perceived air quality	Reduced alertness and decision efficiency	Slower task completion and increased minor slips
Heat stress or thermal discomfort	Sleepiness and reduced executive control	Lower tolerance of interruptions and multitasking
Low/high humidity	Respiratory discomfort and fatigue accumulation	Shorter periods of stable concentration
Suboptimal lighting (night shifts)	Circadian misalignment and reduced vigilance	Higher risk during prolonged or overnight work
Noise and high sensory load	Attentional capture and increased working-memory	Communication losses during handovers and orders

	load	
Odours, disinfectants, particulates	Irritation and distraction (cumulative microstress)	Earlier fatigue and reduced precision in routine tasks
PPE-related micro-IEQ (masks/respirators)	Breathing effort and speech attenuation	Increased repetition and higher cognitive load in teams

In clinical settings, IEQ rarely “breaks” performance in a visible way. More often, it shifts work toward instability: attention wanders sooner, task resumption after interruptions becomes less reliable, and small checks are skipped under time pressure. The result is not one spectacular mistake, but a higher frequency of minor slips—omissions, delayed reactions, misunderstood messages—that accumulate in complex systems. This matters particularly in handovers, medication processes and documentation, where precision depends on sustained attention and clear communication rather than isolated decision moments. IEQ also tends to cluster with other real-world stressors (night work, sleep loss, crowding, high noise), so its impact is easiest to notice when cognitive reserves are already low. From a safety perspective, the practical question is therefore not only whether air, temperature or noise meet comfort criteria, but whether they support stable performance and reliable information transfer over time.

5. Practical context: clinical work, communication and human factors

Clinical environments function simultaneously as cognitive and communicative systems. Most activities are team-based and rely on rapid information exchange under time pressure, distraction and competing priorities [13,14]. Cognitive performance directly shapes communication quality, as effective exchange requires parallel listening, selection of relevant information, contextual integration and precise message formulation.

Under degraded IEQ conditions, cognitive fatigue and irritability may develop more rapidly, encouraging abbreviated communication, reduced attentiveness and increased transmission errors [8,13]. From a human factors perspective, IEQ constitutes a background condition that modulates the reliability of teamwork rather than a single-point cause of error [14,15]. A practical point is that clinicians often “self-manage” a poor environment without naming it as such—opening doors, stepping into corridors to finish notes, or postponing a handover conversation until a quieter moment. These micro-adjustments are small, but they are signals that the environment is shaping workflow. In other words, IEQ can be inferred not only from sensors, but also from the workarounds teams routinely use. For example, documentation completed in small duty rooms during peak occupancy often combines suboptimal air quality with noise and repeated interruptions, creating conditions where task resumption errors become more likely.

5.1. Interruptions and the cost of task resumption

Interruptions are intrinsic to clinical work and arise from alarms, conversations, administrative demands and parallel patient management [16]. Each interruption imposes a task-resumption cost, requiring reconstruction of context and verification of task stage [12,16]. When vigilance or working memory capacity is reduced, this process becomes more error-prone, increasing the likelihood of omitted steps or incorrect assumptions that a task has already been completed [12].

Suboptimal IEQ may increase this cost by reducing attentional stability and increasing cognitive fatigue, particularly during extended shifts or periods of high workload [19,20].

5.2. Environmental microstressors and team dynamics

Noise, unfavourable microclimate and sensory irritation may heighten tension and shorten frustration tolerance within teams [8]. This is not merely a comfort issue: reduced patience and increased irritability can impair communication precision, discourage clarification and increase the risk of misunderstandings [13,14]. In high-variability and time-pressured environments, such interactional effects may compromise teams' capacity to detect and correct emerging errors.

5.3. Noise, renovations and transitional spaces

Noise is among the most prevalent environmental stressors in hospitals and directly interferes with attentional and communicative processes [8,10]. Empirical measurements demonstrate that sound levels in intensive care units and hospital wards often exceed recommended limits, particularly during peak activity periods [9,10]. Renovations and technical works further exacerbate this problem by introducing impulsive and unpredictable noise patterns that disrupt task flow and concentration.

In addition, many hospital spaces function as transit routes between units, increasing traffic density and micro-interruptions. Such transitional spaces pose a particular risk when used for handovers or concentration-intensive tasks, as incidental interruptions may reduce information completeness and precision [13].

5.4. Spatial conditions, cognitive privacy and communication safety

Effective clinical communication requires conditions that support concentration and limit sensory and social intrusion. In high-traffic environments, ensuring "cognitive privacy"—the ability to discuss and decide without excessive disturbance—is challenging. Its absence promotes message shortening and reliance on working memory rather than explicit, closed-loop communication, increasing transmission error risk under fatigue and distraction [13,14].

6. Medical education and IEQ: lectures, procedural learning and simulation

Medical education depends on sustained attention, working memory and executive control, particularly as training increasingly emphasises clinical reasoning, teamwork and communication. Lectures, seminars and practical sessions often take place in intensively occupied spaces where IEQ parameters deteriorate over time as occupancy increases [3,5]. Under such conditions, declining concentration may impair information integration and retention.

Simulation-based education represents a specific context. Although designed to reproduce clinical stress, uncontrolled environmental variability may introduce unintended noise and fatigue effects that influence performance independently of competence [18]. Stabilising IEQ in simulation centres may therefore support standardisation and assessment reliability.

6.1. IEQ in lecture halls and seminars as a hidden factor

Educational effectiveness depends not only on content and pedagogy, but also on the ability to sustain attention. Environmental parameters may modulate cognitive fatigue and processing efficiency, influencing learning outcomes [3,5]. Identical teaching sessions delivered under different IEQ conditions may yield divergent results that are incorrectly attributed to instructional quality or learner motivation.

6.2. Procedural learning and cognitive ergonomics

Procedural skill acquisition requires concentration, repetition and error correction. When environmental conditions increase distraction or discomfort, the risk of sequential errors and consolidation of suboptimal habits rises [14]. Consequently, more repetitions may be required, with organisational and cost implications.

6.3. Competency assessment and environmental variability

Simulation-based assessment assumes comparable testing conditions. Variability in noise, temperature or sensory load across sessions may influence performance independently of true competence, introducing systematic bias [18]. IEQ therefore becomes a methodological consideration in assessment validity rather than merely a comfort issue.

7. Patient safety: IEQ as a systemic factor and protective layer

Patient safety emerges from interactions between multiple protective layers, including training, procedures, decision support tools and organisational culture [14,15]. IEQ may be considered an enabling condition for these safeguards, as it influences fatigue accumulation and availability of cognitive reserves. Environmental optimisation does not replace competence or procedures, but may enhance system resilience during overload [14].

7.1. From cognitive error to adverse event

Cognitive errors often arise from attentional overload, decision shortcuts and task interruptions [15]. IEQ may act as a risk amplifier by accelerating fatigue and increasing reliance on automatisms. As a result, minor errors are more likely to escape detection at secondary control stages, particularly when vigilance is compromised [12,14].

7.2. Communication and handover as high-risk areas

Handover requires precise selection and transmission of information under time constraints. Noise, discomfort and fatigue increase the risk of omissions and ambiguity, with errors often surfacing only later in the care process [13]. Environmental conditions supporting audibility and concentration should therefore be regarded as integral to risk management.

7.3. IEQ, safety culture and staff wellbeing

Chronically unfavourable environmental conditions may contribute to normalisation of discomfort and reduced reporting of environmental issues, indirectly reflecting organisational safety culture [28–30]. In this sense, IEQ has both a physical and organisational dimension that may influence adherence to procedures and collaboration quality.

8. Data limitations and methodological challenges

Despite a growing body of research linking indoor environmental quality to cognitive performance, several methodological limitations constrain direct inference for healthcare settings. A substantial proportion of IEQ–cognition studies has been conducted in laboratory environments or non-clinical indoor spaces such as offices and schools, which limits ecological validity for ward-based practice characterised by interruptions, time pressure and emotional load [3,5,26]. A further limitation is that a considerable share of high-quality experimental evidence originates from office or educational settings; therefore, translation to complex clinical workflows should be treated as mechanistically informed rather than directly equivalent.

Another challenge lies in the co-occurrence of environmental and organisational stressors. In clinical settings, unfavourable IEQ often coincides with high workload, sleep restriction, night work and staffing shortages, making causal attribution difficult [19,20]. Under such circumstances, environmental effects may be masked during low-load periods but amplified when compensatory reserves are depleted, suggesting that interactional rather than single-factor models are more appropriate [14].

Outcome measurement presents an additional limitation. Many studies rely on short standardised tests of vigilance, reaction time or working memory, which capture relevant cognitive components but relate only indirectly to clinical decision quality [1,2]. While this approach is justified from a human factors perspective, linking environmental parameters to functional clinical outcomes remains methodologically challenging.

8.1. Co-occurrence of factors and attribution of causality

Disentangling the independent contribution of IEQ from sleep deficit, stress and workload is particularly difficult in field studies. During periods of system overload, both microclimate and sensory load typically deteriorate while recovery opportunities diminish [16,19]. In practice, IEQ often acts as a risk amplifier rather than a primary cause, with effects emerging most clearly when baseline cognitive reserves are limited [14,15]. Analytical approaches incorporating cumulative load and interaction effects may therefore offer greater explanatory power than attempts to isolate individual parameters.

8.2. Practice-proximal measures and clinical relevance

Demonstrating statistically significant changes in vigilance or reaction time does not automatically establish clinical relevance. Measures that approximate real care processes—such as handover completeness, error detection in medication tasks, procedural sequencing accuracy or team communication quality in simulation—are particularly informative [12,18]. Incorporating such indicators strengthens translational relevance by linking environmental conditions directly to operational risk elements.

9. Future research directions and practical implications

Future research should prioritise investigation of IEQ effects in real clinical and educational environments, integrating environmental monitoring with cognitive and functional performance measures relevant to patient safety. Interventional studies assessing whether improved ventilation, microclimate stabilisation or noise reduction translate into measurable improvements in vigilance, fatigue trajectories or communication quality are especially needed [1,5].

Interactions between IEQ and night work, extended shifts and sleep restriction warrant particular attention, as environmental effects are likely to be strongest when staff operate near physiological and cognitive limits [19,20]. Longitudinal designs examining performance stability over time may better capture cumulative effects than cross-sectional snapshots.

From a practical standpoint, IEQ-oriented actions can be implemented incrementally. Initial steps include identifying high-risk spaces—handover rooms, medication preparation areas, duty rooms, documentation stations and simulation facilities—and conducting simple measurements during typical occupancy [5]. Importantly, evaluation should extend beyond environmental stabilisation to include functional indicators such as subjective sleepiness, cognitive fatigue and task performance in simulation or audit scenarios.

9.1. Designing interventions: from measurement to organisational decisions

Environmental interventions should be guided by indicators that support decision-making rather than data collection alone. Risk mapping allows prioritisation of spaces with high cognitive load and limited recovery opportunities, followed by targeted measurement under real-use conditions [14]. Interventions may include adjustment of ventilation schedules, occupancy management in small rooms, optimisation of HVAC settings, structured breaks or redesign of handover spaces. Effectiveness depends on alignment with work rhythms and staff acceptance.

9.2. Evaluating outcomes: from "better air" to "better performance"

Outcome evaluation should integrate IEQ parameters with cognitive and functional measures. Parallel monitoring of environmental indicators and brief assessments of sleepiness or fatigue, supplemented by vigilance tasks or simulation-based performance metrics, allows demonstration that interventions support performance stability rather than merely improving comfort [1,18]. Such evidence is critical for embedding IEQ into quality and safety frameworks.

9.3. Implementation barriers and normalisation of discomfort

IEQ interventions face infrastructural, financial and organisational barriers. Chronic exposure to suboptimal conditions may lead to normalisation of discomfort and reduced reporting, limiting organisational awareness [28–30]. Gradual implementation through pilot projects, clear success metrics and staff involvement in solution design may improve uptake. In many cases, meaningful benefits arise from relatively low-cost organisational changes when supported by leadership.

9.4. Renovation-related challenges and transitional spaces

Renovations are often prolonged and unavoidable in healthcare facilities. Exposure reduction and mitigation of functional impact should therefore be pragmatic goals. Protecting safety-critical areas—handover rooms, medication preparation spaces, documentation hubs and simulation centres—should be prioritised [9,10]. Identifying peak noise periods and scheduling concentration-intensive tasks accordingly may further reduce risk. For transit-heavy wards, limiting incidental interruptions can improve cognitive stability and communication quality.

10. Conclusions

Indoor environmental quality represents an important yet frequently underrecognised determinant of performance stability among healthcare professionals and trainees. Ventilation and air quality, microclimate parameters, lighting conditions and sensory load—particularly noise—are not merely comfort variables; they shape the background conditions under which clinicians maintain vigilance, allocate attention, hold information in working memory and exert executive control under interruption and time pressure [1,5,8].

The available evidence indicates that even moderate departures from favourable indoor conditions may be associated with measurable decrements in cognitive domains that are operationally relevant to safe care. Crucially, these effects are cumulative. Environmental stressors rarely produce dramatic failures in isolation; instead, they gradually erode cognitive reserves and increase the probability of small lapses—omitted steps, abbreviated checks, delayed task resumption and communication losses—that matter in complex clinical systems [14,15].

Viewing IEQ through a human factors lens positions the work environment as an active component of the safety system rather than a passive backdrop. Environmental optimisation does not replace clinical competence, staffing or robust procedures, but it can strengthen the conditions under which these safeguards function, particularly at known high-risk points such as handovers, medication processes, documentation tasks and emergency coordination [13,14].

From an implementation perspective, IEQ improvement can be introduced incrementally and cost-sensitively. Mapping high-cognitive-load spaces, monitoring a limited set of meaningful indicators and applying targeted organisational or technical interventions provide a pragmatic pathway. Low-cost measures—structured ventilation routines, noise reduction in critical zones, occupancy management and environmental standardisation in educational and simulation settings—may yield disproportionate benefits in performance stability.

Finally, future research linking environmental measurements with practice-proximal outcomes will further strengthen translation from "better indoor conditions" to "more reliable clinical performance". In the interim, the existing evidence base is sufficient to justify incorporation of IEQ into quality and safety programmes as a modifiable layer of defence supporting staff cognition, medical education effectiveness and patient safety.

DISCLOSURE

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AUTHOR CONTRIBUTIONS

Conceptualization: M.K.

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CONFLICT OF INTEREST STATEMENT

The authors declare no conflict of interest.

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