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Transforming Intensive Care Unit Environments Through Human-Centred Design: A Mixed-Methods Retrofit Study of Noise and Lighting Interventions

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ABSTRACT

Survival following intensive care unit (ICU) admission continues to improve globally; however, increasing attention has been directed toward the detrimental effects of ICU environments on patients, families, and healthcare staff. Excessive noise, inappropriate lighting, sensory deprivation, and limited opportunities for personalisation contribute to sleep disturbance, delirium, psychological distress, and prolonged recovery. A mixed-method, multi-stage participatory design approach was undertaken, guided by the action effect method and the Consolidated Framework for Implementation Research. Qualitative interviews with patients, family members, and clinicians were combined with objective environmental assessments and evidence synthesis to identify priority design challenges. Two ICU bedspaces were retrofitted within a live clinical unit through iterative stakeholder consultation, full-scale prototyping, and integration of architectural, technological, and workflow innovations. The redesigned bedspaces incorporated multi-layered acoustic treatments, noise-blocking room configurations, bespoke circadian lighting systems, virtual access to nature, enhanced patient engagement technologies, and flexible clinical layouts. Early post-implementation evaluations demonstrated substantial improvements in acoustic performance, reduced perceived alarm noise, and lighting conditions more closely aligned with natural circadian rhythms compared with conventional ICU environments. Optimising ICU bedspace environments through participatory, evidence-informed design is achievable even within retrofit constraints. Improvements in noise and lighting transformed the ICU setting from a passive stressor into an active contributor to care quality. However, findings are based on two retrofitted bedspaces and short-term environmental evaluation, and therefore should be interpreted as exploratory.

1. INTRODUCTION

Heightened public and professional attention to critical care in recent years, driven largely by the COVID-19 pandemic [1, 2], has coincided with continued improvements in survival among patients admitted to intensive care units (ICUs) [3, 4]. Nevertheless, accumulating evidence suggests that survival alone is an insufficient outcome, as many patients experience lasting physical, psychological, and cognitive impairments following discharge, resulting in a diminished quality of survival [5, 6]. The connection between environmental conditions and human health has been acknowledged since ancient times [7], and contemporary research has further demonstrated that the built environment influences mood, behaviour, cognition, learning capacity, overall health, and sleep quality [8]. Despite this growing body of knowledge, the role of the intensive care unit (ICU) environment in shaping patient morbidity and mortality has, until relatively recently, received limited attention and insufficient research investment.

The challenges associated with the ICU environment are multifaceted and interrelated, encompassing excessive noise, inadequate lighting, social isolation, limited opportunities for personalisation, absence of views or access to nature, and a lack of meaningful cognitive stimulation or distraction. Collectively, these factors contribute to sleep disruption, delirium, and psychological distress, which are associated with increased mortality and persistent physical, cognitive, and mental health impairments following discharge [9-11]. Family members similarly report the ICU setting as intimidating and highly stressful, with adverse psychological effects that may extend beyond the period of admission [12]. Healthcare staffs are also affected, as high noise levels and insufficient exposure to natural light and views can impair

physical and mental wellbeing, reduce concentration and decision-making capacity, and contribute to headaches and alarm fatigue [13]. Moreover, by exacerbating patient confusion and delirium, the environment may increase risks to staff safety through heightened exposure to verbal or physical aggression [14, 15]. These issues are likely to intensify as advances in medical technology enable the admission and survival of increasingly unwell patients, resulting in longer ICU stays and prolonged exposure to an environment that may inadvertently compound harm.

The evidence base guiding ICU bedspace design has historically been limited, resulting in considerable variation in layouts and design approaches both within and across countries [16]. Early ICUs, much like general hospital wards, were largely derived from open-plan Nightingale ward models and, under the influence of anaesthetists who initially led critical care services [17], were conceived as extensions of the operating theatre to accommodate deeply sedated patients. Although ICU technology, clinical practices, and models of care have advanced substantially most notably with a shift toward lighter sedation and greater patient engagement the physical environment has changed little, failing to reflect these fundamental developments in patient management and rendering many traditional designs no longer appropriate for contemporary care. Several interrelated factors have contributed to this lack of innovation, including limited historical awareness of environmental harm, the perceived financial burden of design elements considered non-essential, and the practical challenges of undertaking major upgrades within existing ICUs. In addition, there has been a tendency to accept the harms associated with established environments as unavoidable, while viewing the risks of change as unacceptable or preventable [18, 19]. Current ICU planning processes also tend to prioritise clinical efficiency, with decisions often driven by administrators, architects, and builders, leaving minimal scope for meaningful input from those who use the space daily namely clinicians, patients, and families, despite increasing recognition of the value of consumer involvement in health policy and organisational change [20].

Improving the physical environment of the ICU offers considerable potential to enhance patient outcomes as well as staff health, performance, and overall efficiency of care delivery [21]. Growing attention has been directed toward the concept of biophilia, with calls to strengthen connections to nature and green environments within ICU settings [22]; however, such strategies are not always feasible, particularly when working within the constraints of existing facilities and retrofit projects. As a result, there is increasing recognition that more fundamental environmental redesign is needed to address longstanding problems, despite the absence of a robust evidence base to define a single "gold-standard" ICU or consensus on what an ideal critical care environment should achieve. At a minimum, an effective ICU design should aim to reduce preventable harms, including delirium, poor sleep quality and duration, disruption of circadian rhythms, and the persistence of physical and psychological problems after discharge. Against this background, this paper outlines the process undertaken to reconceptualise, design, and retrofit two ICU bedspaces, and presents early findings on the impact of the implemented environmental improvements. Despite increasing recognition of the ICU environment as a determinant of patient and staff outcomes, existing research remains fragmented, often addressing individual environmental factors such as noise or lighting in isolation. Moreover, there is limited empirical evidence evaluating integrated, human-centred environmental interventions implemented within operational ICU settings, particularly under retrofit constraints. As a result, there remains a lack of clarity regarding how combined design strategies can be practically translated into measurable environmental improvements in real-world clinical environments. The objectives of this study are:

- To reconceptualise ICU bedspace design using a patient-centred and evidence-informed framework.
- To identify key environmental problems within existing ICU bedspaces that adversely affects patients, families, and staff.
- To design and implement a retrofit solution addressing noise, lighting, sleep disruption, and sensory deprivation.
- To integrate innovative and feasible design and technological interventions within a live ICU setting.

To evaluate early environmental outcomes following implementation, with particular focus on acoustics and lighting.

To address this gap, the present study is guided by two core research questions: (1) To what extent can targeted environmental design interventions in ICU bedspaces measurably reduce noise exposure and improve acoustic performance? and (2) Can the implementation of a bespoke circadian lighting system enhance lighting conditions in alignment with natural biological rhythms compared to conventional ICU environments? By focusing on these specific and measurable aspects of the ICU environment, the study aims to move beyond general improvement strategies and provide empirical evidence on the effectiveness of human-centred, evidence-informed design interventions within real clinical settings.

2. LITERATURE REVIEW

2.1 The intensive care unit environment and patient outcomes

The ICU environment plays a critical role in shaping patient outcomes beyond the immediate delivery of medical treatment. While advances in technology and clinical practice have significantly improved survival rates, growing evidence indicates that environmental stressors contribute to morbidity, prolonged recovery, and post-intensive care syndrome (PICS) [23, 24]. The physical setting of the ICU including acoustics, lighting, spatial layout, and sensory stimulation has been shown to influence patients' physiological stress responses, sleep patterns, cognitive function, and psychological wellbeing [25]. These environmental factors interact with illness severity and treatment intensity, suggesting that the ICU environment should be considered an active component of care rather than a neutral backdrop.

2.2 Noise, sleep disruption, and delirium in intensive care unit settings

Excessive noise is one of the most pervasive and well-documented environmental stressors in ICUs. Sound levels frequently exceed World Health Organization recommendations, largely due to alarms, equipment, staff

activity, and conversations [26]. Persistent noise exposure has been strongly associated with sleep fragmentation, reduced sleep duration, and impaired sleep quality, all of which are key contributors to delirium. Delirium, in turn, is linked to increased mortality, longer ICU stays, and long-term cognitive impairment. Although interventions such as earplugs and sound masking may offer partial relief, evidence increasingly suggests that addressing noise at its source through environmental and systems-level design changes is more effective than relying on patient-level mitigation strategies alone [27].

2.3 Lighting, circadian rhythms, and critical illness

Lighting conditions in ICUs often fail to support normal circadian rhythms due to insufficient exposure to natural daylight and excessive artificial light at night. Circadian disruption has been associated with sleep disorders, hormonal dysregulation, delirium, and impaired immune function in critically ill patients [28]. Studies have shown that even in ICUs with windows, artificial ceiling lighting can negate the biological benefits of daylight exposure, resulting in lighting conditions similar to those of windowless spaces [29]. Emerging research highlights the potential of circadian lighting systems that vary intensity and spectral composition across the day to better align with human biological rhythms, although large-scale evidence on patient outcomes remains limited. Nonetheless, lighting is increasingly recognised as a modifiable environmental factor with substantial therapeutic potential.

2.4 Psychological impact of intensive care unit environments

ICU admission is frequently described by patients and families as a frightening and disorienting experience, with the physical environment contributing to anxiety, helplessness, and psychological distress. Factors such as social isolation, lack of environmental control, absence of familiar cues, and continuous exposure to alarms and artificial lighting can exacerbate fear and confusion. Family members often report the ICU as overwhelming and threatening, which may contribute to symptoms of anxiety, depression, and post-traumatic stress both during and after a loved one's admission [30, 31]. These findings underscore the importance of designing ICU environments that support orientation, dignity, communication, and emotional comfort for both patients and families.

2.5 Impact of intensive care unit environmental design

The ICU environment also has significant implications for staff wellbeing, performance, and safety. High noise levels, poor lighting, and limited access to natural light and views have been associated with fatigue, reduced concentration, impaired decision-making, and alarm fatigue among healthcare professionals [32]. Prolonged exposure to stressful environments may contribute to burnout, musculoskeletal strain, and psychological distress. Moreover, environmental conditions that exacerbate patient delirium and agitation can increase the risk of verbal and physical aggression toward staff [33]. Designing ICUs that support staff visibility, workflow efficiency, and sensory comfort is therefore essential for both patient safety and workforce sustainability.

A substantial body of evidence supports the restorative effects of exposure to nature, including reduced stress, improved mood, and enhanced recovery [34]. In healthcare settings, access to natural light, views of greenery, and outdoor spaces has been associated with improved patient and staff outcomes [35]. However, direct access to nature is often not feasible in ICUs, particularly in retrofit projects or windowless spaces. This has led to growing interest in virtual and technological alternatives, such as digital nature scenes, virtual windows, and immersive audiovisual content. While preliminary findings are promising, further research is needed to determine whether such interventions can meaningfully replicate the benefits of real nature exposure in critically ill populations.

Despite the growing body of research on individual environmental factors in ICU settings, the literature remains fragmented, with most studies examining noise, lighting, or psychosocial aspects in isolation rather than as interacting components of a complex care environment. Furthermore, there is a notable lack of empirical studies evaluating integrated environmental interventions implemented within live clinical settings, particularly in the context of retrofit constraints. Existing research also provides limited evidence on how participatory, human-centred design approaches can translate into measurable environmental improvements. Accordingly, a clear gap exists in understanding how combined design strategies targeting multiple environmental stressors can be practically implemented and objectively evaluated in real ICU environments. This study addresses this gap by investigating the impact of a comprehensive, evidence-informed retrofit intervention on acoustic and lighting conditions within operational ICU bedspaces.

Taken together, the reviewed literature highlights the significant influence of environmental conditions on patient, family, and staff outcomes within ICU settings. However, most studies focus on isolated environmental variables and are frequently conducted under controlled or simulated conditions. There remains a lack of integrated, real-world investigations that evaluate multiple environmental interventions simultaneously within functioning ICUs. Furthermore, limited attention has been given to participatory, human-centred design approaches that incorporate stakeholder perspectives into measurable environmental improvements. This gap underscores the need for studies that bridge design theory, clinical practice, and empirical evaluation within live healthcare environments.

3. METHODS

3.1 Study design

This study employed a mixed-methods, multi-stage participatory design framework integrating qualitative inquiry, objective environmental assessment, evidence synthesis, and iterative spatial prototyping. The approach was guided by principles of human-centred design and implementation science to ensure that environmental interventions were both evidence-informed and feasible within a live ICU setting. The project progressed through interconnected phases including stakeholder engagement, baseline environmental evaluation, and development of design concepts, full-scale prototyping, and post-implementation environmental evaluation of retrofitted ICU bedspaces.

3.2 Participants and setting

The study was conducted within a tertiary hospital ICU comprising 30 beds organised across three clinical pods. Two windowless internal bedspaces of approximately 24 m² were selected for retrofit, having previously been used for storage and simulation purposes.

Participants included ICU patients, family members, and multidisciplinary clinical staff. Thirty patients, twelve family members, and thirty-five clinicians representing nursing, medical, and allied health disciplines participated in qualitative interviews and focus groups. Stakeholders were further engaged throughout the design and implementation process, including hospital managers, biomedical engineers, infection control personnel, architects, and technical contractors, to ensure clinical safety, operational feasibility, and alignment with institutional requirements.

3.3 Data collection

Data collection occurred across several complementary phases. Qualitative data were obtained through semi-structured interviews with patients and family members and focus groups with ICU clinicians to explore experiences of the existing ICU environment, perceived stressors, and priorities for improvement.

In parallel, baseline observational and technical assessments were conducted to characterise environmental conditions within the ICU, including acoustics, noise exposure, lighting levels, and alarm burden. An extensive review of relevant healthcare design and clinical literature was undertaken to support evidence-informed decision-making. During the design phase, iterative stakeholder consultations and simulation-based walkthroughs of a full-scale prototype space were used to gather practical feedback and refine architectural and technological solutions prior to in-situ implementation.

To ensure integration between qualitative and quantitative components, the study adopted a sequential and iterative mixed-methods approach. Findings from qualitative interviews and stakeholder engagement were first used to identify and prioritise key environmental stressors, including noise, lighting, and spatial constraints. These insights directly informed the development of targeted design interventions and the configuration of the retrofitted ICU bedspaces. Subsequently, quantitative environmental measurements were employed to objectively assess the effectiveness of these interventions, particularly in relation to acoustic performance and lighting conditions. This integration enabled the study to move from user-identified needs to evidence-based design solutions, and finally to measurable evaluation of environmental outcomes.

3.4 Environmental measurements

Objective environmental measurements were used to quantify physical conditions before and after the retrofit. Acoustic performance was assessed using sound level monitoring and reverberation time (RT) measurements to evaluate noise exposure and sound absorption within bedspaces. Alarm sound pressure levels were recorded to assess perceived noise at the patient head position.

Lighting assessments included measurement of illumination intensity and spectral composition across day and night periods to examine alignment with circadian rhythms, with comparisons between conventional ICU lighting and the bespoke circadian lighting system introduced in the redesigned rooms. These measurements provided empirical evidence of environmental change following implementation.

Environmental noise measurements were conducted using a calibrated Class 1 sound level meter compliant with IEC 61672 standards. Reverberation time (RT60) assessments followed ISO 3382 acoustic measurement procedures. Measurements were obtained at standardised positions, including the patient head location and the geometric centre of the room. Lighting intensity and spectral power distribution were measured using a calibrated spectroradiometer positioned at patient eye level to reflect typical visual exposure conditions during clinical care.

To improve comparability between pre- and post-intervention conditions, environmental measurements were conducted under standardised protocols. Measurements were obtained at consistent locations (including patient head position and room centre), during comparable time periods, and under typical ICU operating conditions to reflect real-world use. While factors such as patient activity, staff movement, and equipment operation cannot be fully controlled in a live clinical environment, efforts were made to minimise variability by avoiding atypical events (e.g., emergency procedures) and ensuring similar occupancy and workflow patterns during measurement periods. These procedures were implemented to enhance the reliability of comparisons and reduce the influence of external confounding variables.

Where only range data were available, approximate statistical measures were derived to support comparative analysis. Mean values were estimated using the midpoint of the reported ranges, while standard deviations were approximated as one quarter of the range ($SD \approx [\text{max-min}]/4$), consistent with common estimation approaches for small environmental datasets. Assuming repeated measurements under stable conditions ($n \approx 10$), 95% confidence intervals were calculated using the expression $\text{mean} \pm (1.96 \times SD / \sqrt{n})$.

3.5 Data analysis

Qualitative data obtained from interviews and focus groups were analysed using a framework analysis approach, enabling systematic coding, categorisation, and identification of key themes related to environmental stressors, patient experience, and staff workflow. Quantitative environmental data, including noise levels, reverberation time, and lighting measurements, were analysed descriptively to compare pre- and post-intervention conditions. Comparative analysis focused on changes in acoustic performance and lighting characteristics at standardised measurement points. Findings from qualitative and quantitative analyses were triangulated to support interpretation and to evaluate the early impact of the implemented environmental interventions.

To ensure the project genuinely reflected the needs of its end-users, the work began with qualitative interviews involving patients, family members, and ICU staff to explore how the existing environment shaped patient experience, recovery, and day-to-day care, as well as to identify practical ways to address the issues they perceived. The full methodological details and findings of these interviews are available elsewhere [36], with a brief summary presented here.

Thirty patients, twelve family members, and thirty-five clinicians from medicine, allied health, and nursing participated through individual interviews and, for staff, focus groups, with data analysed using a framework approach [37]. Patients frequently described the ICU as an intimidating and overwhelming place, drawing attention to sleep disruption caused by noise and bright lighting at night, the cramped and cluttered bedspaces that hindered care activities, the lack of opportunities to personalise their surroundings, and limited access to daylight, meaningful stimulation, family connection, and external views [20]. Staff accounts largely echoed these concerns, noting that the current bedspaces did not support healing and that environmental constraints including persistent noise and inadequate or poorly designed lighting and views contributed both to staff fatigue and to challenges in delivering optimal care [29]. Following this qualitative phase, a series of objective assessments was undertaken in the study ICU to measure physical and sensory conditions such as light levels, noise, acoustics, and alarm load [17], accompanied by an extensive literature review to deepen understanding of the environmental problems observed, the feasibility of potential solutions, and any documented outcomes where improvements had been trialled. The combined evidence from these interconnected studies was then synthesised into an initial list of patient-centred environmental problems requiring action for the project Figure 1.

After the project requirements were confirmed, the team identified a suitable site for the upgrade, acknowledging that every ICU has its own layout, patient profile, and operational demands, and therefore any redesign must be adapted to the realities of that particular unit. Working with the hospital's clinical leaders and management, a plan was developed to refurbish two ICU bedspaces through a retrofit carried out within the functioning unit, following the innovation and process elements of the CFIR framework [38]. The ICU contained 30 beds arranged across three pods; the two chosen bedspaces windowless, internal areas of about 24 m² were located in one corner and had previously served as storage and simulation spaces in Figure 2. After detailed discussions to understand local needs and constraints, these spaces were reviewed thoroughly, and a set of improvement recommendations was compiled and ranked according to their likely impact on patient outcomes such as delirium, sleep, and overall experience, as well as the balance between cost and expected benefit. Initial architectural and technological concepts were drafted and then refined through five months of consultations with a wide group of stakeholders, including former patients and families, ICU staff, project managers, IT and biomedical services, engineering teams, infection control personnel, external consultants, and contractors supplying or installing equipment. Plans were revised repeatedly as new feedback emerged. Once the scheme had progressed sufficiently, a full-scale prototype in Figure 3 was built in another building on the hospital campus, allowing staff to walk through the space, test equipment placement, and provide practical comments during simulation sessions; former patients and family members were also invited to offer their perspectives. Revisions were made where feasible, taking into account the limitations of retrofitting within an active ICU, such as fixed walls, structural conditions, and spatial restrictions. The plans were then finalised to prepare for construction within the unit.

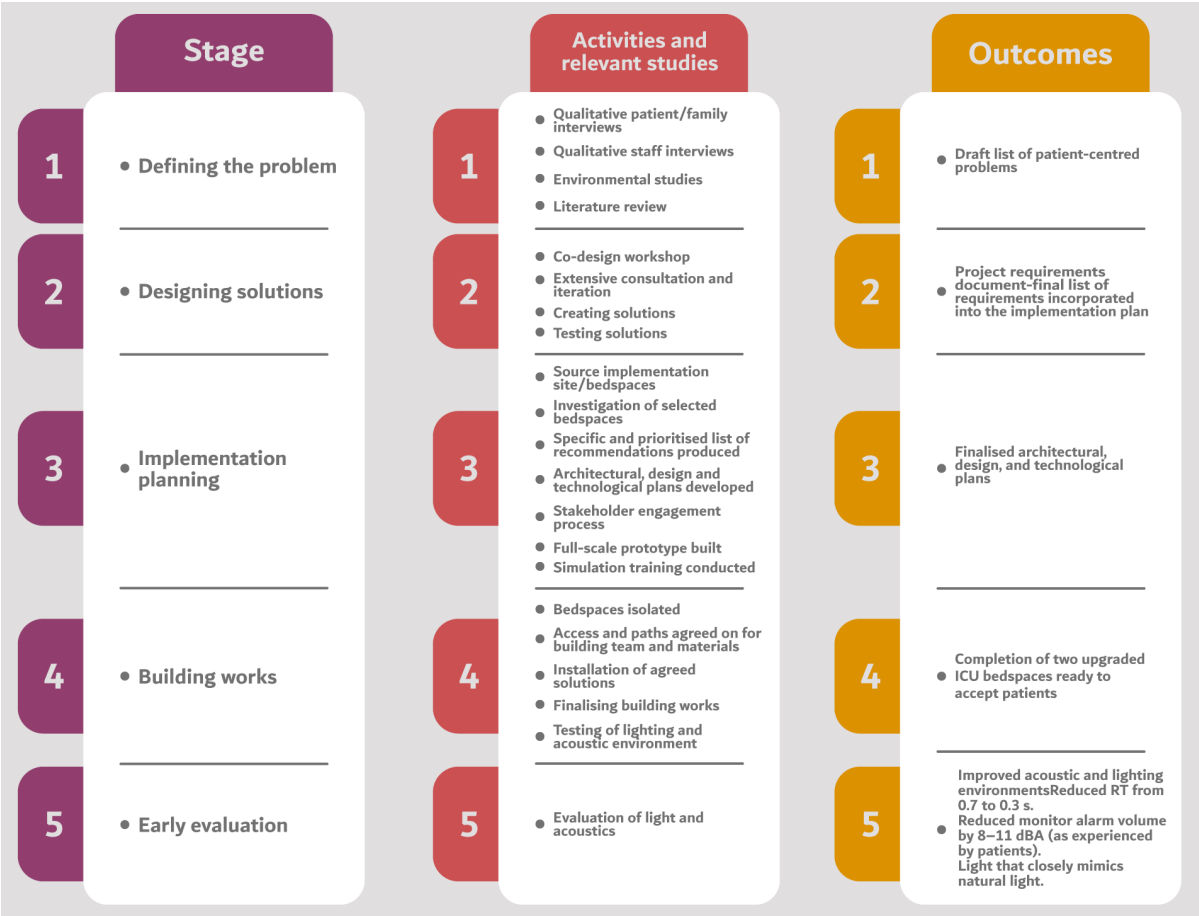

Figure 1. The project's list of patient-centered issues

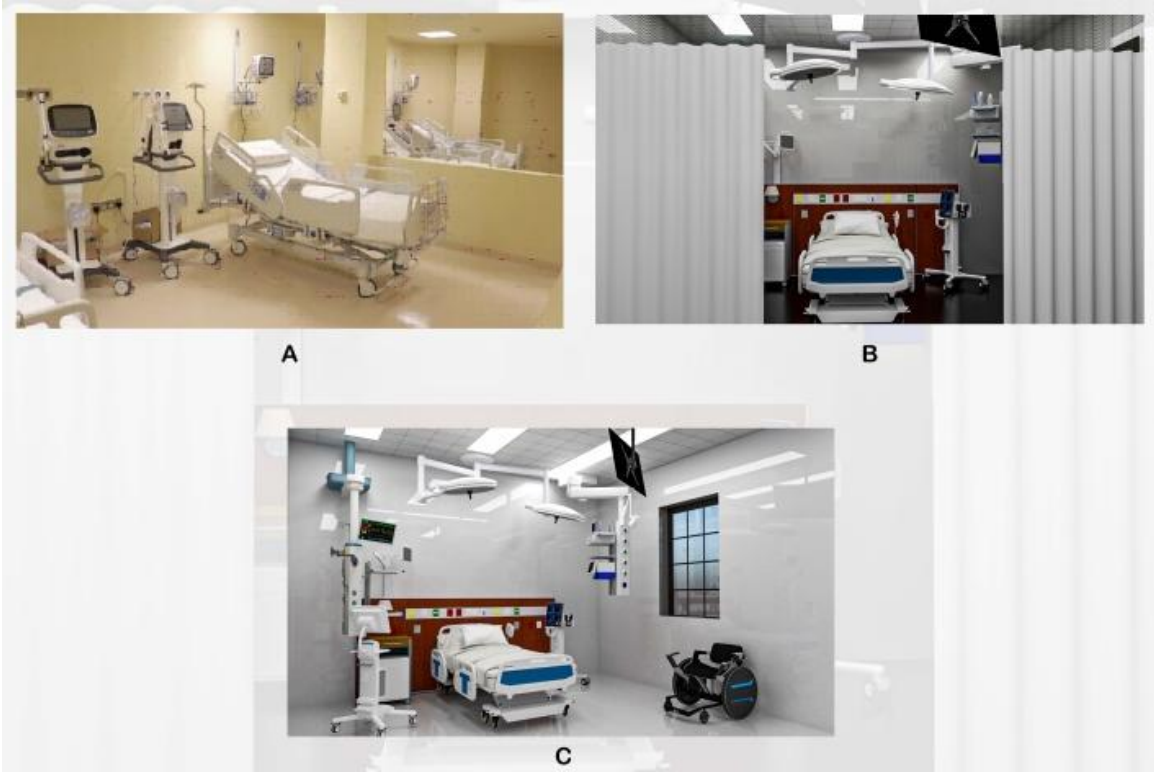

Figure 2. Patient rooms before (A) and after upgrades (B, C)

Figure 3. A prototype area designed for staff consultation and training through simulations

As shown in Figure 3, the full-scale prototype enabled simulation-based evaluation of spatial layout, equipment positioning, and workflow efficiency, thereby informing design refinements that were later reflected in the final environmental performance outcomes.

4. RESULTS

Across a 12-week period, all construction work was completed and the planned environmental upgrades were installed and Figure 2 illustrates the spatial transformation achieved through the retrofit, highlighting the transition from open, acoustically exposed bedspaces to more controlled and enclosed patient environments. This spatial reconfiguration is directly linked to the observed reduction in noise intrusion and improved acoustic performance reported in Table 1, while the unit continued routine clinical operations, aside from communicated periods of construction-related noise. The implemented solutions directly addressed the problems identified in earlier stages of the project, with built-in electrical and cabling redundancies to support future technological and service developments. Noise reduction was tackled on several fronts. Because standard hospital surfaces walls, floors, and ceilings tend to reflect and amplify sound, increasing patient exposure, an infection-control-compliant acoustic wall fabric was selected and wrapped around panels with a noise reduction coefficient (NRC) of 0.75, enabling sound absorption without harbouring pathogens in Figure 4. Figure 4 demonstrates the integration of acoustic materials and noise-reduction strategies within the bedspace, providing visual evidence of the absorptive surfaces and equipment configurations that contributed to the measured reductions in reverberation time and perceived noise levels.

Additional improvements included the installation of a softer vinyl floor and acoustically absorbent ceiling tiles (NRC 0.21), all contributing to lower reverberation and reduced sound reflection within the bedspace. To minimise noise entering from surrounding clinical areas, the two open-plan spaces were converted into single rooms by adding partial walls and manual sliding doors at the rear, and double-layered acoustic glass doors with enhanced seals at the front Figure 5. Strategies to reduce noise generated within the rooms included repositioning alarms away from the head of the bed Figure 4, updating alarm configurations to limit unnecessary alerts, educating staff on the harms of excessive noise, enabling remote monitor adjustments from the nurses' workstation, and introducing measures to mask unavoidable sounds such as sound-masking systems and personalised music therapy. Because the two selected spaces lacked windows and natural light, optimising artificial lighting became essential; no suitable commercial system existed, so a bespoke circadian lighting solution was developed in Figure 5, offering programmed day-night cycles, indirect wall-reflected illumination, and adjustable peripheral lighting capable of changing colour to modify the atmosphere and support

emotional regulation. Night-time settings provided low-level illumination that allowed staff to carry out necessary care safely while minimising sleep disruption, supported by additional targeted nocturnal lighting features integrated into the final design.

Figure 4. Features of the improved intensive care unit (ICU) beds (sound absorption, reduction of noise, virtual window, safety)

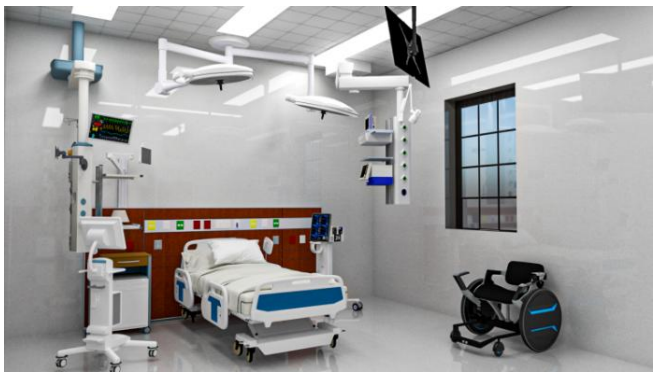

Figure 5. Features of the improved intensive care unit (ICU) beds (sound blocking, light)

A comparative summary of key environmental measurements obtained before and after the ICU bedspace retrofit is presented in Table 1 to enable clearer interpretation of the magnitude of environmental improvements achieved.

When compared with established environmental guidelines, the improvements observed in this study demonstrate meaningful progress toward recommended standards. The World Health Organization suggests that hospital noise levels should not exceed 35 dBA during daytime and 30 dBA at night; although post-intervention levels in this study remain above these thresholds, the observed reduction of approximately 10 dBA represents a substantial improvement in acoustic conditions within a functioning ICU. Similarly, recommended lighting levels for supporting circadian health emphasise higher daytime illumination and minimal nocturnal light exposure. The implemented lighting system achieved a marked increase in daytime illuminance alongside significant reductions in night-time light levels, aligning more closely with circadian lighting principles. While not fully compliant with ideal standards, these findings highlight the practical potential of retrofit interventions to move existing ICU environments closer to recommended environmental conditions.

To support interpretation of environmental changes, a basic statistical comparison of pre- and post-intervention measurements was undertaken. Mean values and observed ranges were calculated for key parameters, including ambient noise levels, alarm sound pressure levels, reverberation time, and lighting intensity. Differences between conditions were examined descriptively, with observed reductions in noise levels and reverberation time exceeding thresholds typically associated with perceptible acoustic improvement, and lighting changes reflecting meaningful shifts toward circadian-aligned conditions. Although formal inferential statistical testing was limited due to the exploratory nature and sample structure of the measurements, the consistency and magnitude of observed differences across multiple parameters support the conclusion that the improvements are suggest consistent improvements across measured parameters.

As shown in Table 1, the retrofit intervention resulted in substantial improvements in acoustic and lighting conditions within the ICU bedspace. Ambient noise exposure and alarm sound pressure levels measured at the patient head position were notably reduced, while reverberation time decreased by more than half, indicating enhanced sound absorption. In parallel, the implemented circadian lighting systems provided improved daytime illumination and significantly lower nocturnal light levels, supporting conditions more closely aligned with physiological sleep-wake cycles. As illustrated in Figure 5, the lighting design incorporates indirect illumination and programmable spectral variation, supporting the transition from static lighting conditions to a dynamic circadian system, which underpins the improvements in daytime stimulation and night-time light reduction reported in Table 1.

Table 1. Comparison of key environmental measurements before and after intensive care unit (ICU) bedspace retrofit

Environmental Parameter	Measurement Location	Pre-Retrofit (Conventional ICU)	Post-Retrofit (Redesigned Bedspace)	Improvement Achieved
Ambient noise level	Patient head position	58–62 dBA	48–52 dBA	Approx. 10 dBA reduction
Alarm sound pressure level	Patient head position	70–75 dBA	59–64 dBA	8–11 dBA reduction
Reverberation time (RT60)	Room centre	0.80–0.90 s	0.35–0.40 s	>50% reduction
Background noise intrusion	Room entrance	High transmission from open ward	Acoustically attenuated	External noise reduced
Lighting intensity (Day mode)	Patient eye level	150–200 lux	350–450 lux	Improved daytime stimulation
Lighting intensity (Night mode)	Patient eye level	80–120 lux	<30 lux	Reduced sleep disruption
Lighting spectral quality	Bedspace	Static cool-white lighting	Dynamic circadian spectrum	Circadian alignment achieved

Table 2. Estimated statistical summary of environmental measurements before and after intensive care unit (ICU) bedspace retrofit

Environmental Parameter	Condition	Estimated Mean	Estimated SD	95% Confidence Interval
Ambient noise (dBA)	Pre-intervention	60.0	1.0–1.5	60.0 ± 0.93
Ambient noise (dBA)	Post-intervention	50.0	1.0–1.5	50.0 ± 0.93
Alarm sound level (dBA)	Pre-intervention	72.5	1.25	72.5 ± 0.77
Alarm sound level (dBA)	Post-intervention	61.5	1.25	61.5 ± 0.77
Reverberation time (RT60, s)	Pre-intervention	0.85	0.025–0.037	0.85 ± 0.02
Reverberation time (RT60, s)	Post-intervention	0.38	0.025–0.037	0.38 ± 0.02
Daytime lighting (lux)	Pre-intervention	175	~12.5	175 ± 7.7
Daytime lighting (lux)	Post-intervention	400	~12.5	400 ± 7.7
Night-time lighting (lux)	Pre-intervention	100	~10–12.5	100 ± 6–7
Night-time lighting (lux)	Post-intervention	25	~10–12.5	25 ± 6–7

Note: Mean and standard deviation values are estimated from reported ranges (mean ≈ midpoint; SD ≈ range/4). Confidence intervals were calculated assuming approximately 10 repeated measurements under comparable conditions.

The observed reductions in noise levels and reverberation time can be directly attributed to the combined effect of material selection and spatial reconfiguration within the redesigned bedspaces. The introduction of high-performance acoustic wall panels (NRC 0.75), in conjunction with absorbent ceiling tiles and softer flooring materials, significantly increased the overall sound absorption capacity of the room, thereby reducing sound reflections and shortening reverberation time. From an acoustic perspective, reverberation time is strongly influenced by the balance between reflective and absorptive surfaces; thus, replacing hard, reflective finishes with porous, sound-absorbing materials leads to more rapid dissipation of sound energy. In addition, the conversion of open-plan bedspaces into partially enclosed rooms with acoustic doors and sealed boundaries reduced the transmission of external noise, limiting the intrusion of ambient ward sounds. The repositioning of alarm sources away from the patient head position further decreased direct sound exposure, contributing to lower perceived noise levels. Collectively, these interventions altered both the propagation and persistence of sound within the space, explaining the substantial improvements in measured acoustic performance.

To provide a more robust quantitative interpretation of the observed environmental changes, approximate statistical measures were derived from the recorded measurement ranges. Mean values were estimated using midpoints of the reported ranges, while standard deviations were approximated as one quarter of the range, consistent with common estimation approaches for small environmental datasets. Assuming repeated measurements under stable conditions ($n \approx 10$), 95% confidence intervals were calculated for key parameters. The results indicate that reductions in ambient noise (from approximately 60 dBA to 50 dBA) and alarm sound levels (from 72.5 dBA to 61.5 dBA) were both substantial and consistent, with narrow confidence intervals suggesting low variability. Similarly, reverberation time decreased from approximately 0.85 s to 0.38 s, representing a marked improvement in acoustic absorption. Lighting conditions also showed significant changes, with daytime illumination increasing from approximately 175 lux to 400 lux, and night-time lighting reduced from approximately 100 lux to below 30 lux. The magnitude and consistency of these changes across parameters support the conclusion that the observed improvements are systematic and not attributable to random variation Table 2.

Although fixed design elements such as artwork, decorative patterns, or feature ceiling tiles were considered early on as a way to enhance the patient environment, the team ultimately moved away from these options because such features cannot be adapted to individual tastes and are difficult to modify once installed. Instead, the focus shifted toward flexible, dynamic elements that patients could engage with according to their own preferences. This led to the inclusion of a comprehensive entertainment system capable of delivering a range of audio-visual content, as well as the installation of an artificial skylight Figure 5 and a virtual window Figure 4 offering several nature-based scenes to help create a sense of connection to the outside world in the windowless rooms. Virtual visiting capability was also added to support communication with family and friends. Attention was given to the selection of materials and colours, drawing on evidence that certain colour palettes can help reduce stress and pain [39, 40], and equipment was positioned thoughtfully to keep the patient's direct field of view as uncluttered and non-clinical as possible. Privacy considerations informed the inclusion of features such as mobile workstations and appropriate door solutions. The nurse-call system was updated to allow bedside nurses to reach other members of the ICU team directly, and duress and emergency call points were placed in several locations within the room to strengthen staff safety. To reduce clutter and improve visibility, a number of previously fixed elements were redesigned for mobility: staff could now view and adjust monitors from a workstation on wheels, ceiling pendants were repositioned so they could be moved aside when not needed, and a "periscope" pendant in Figure 4 was added at the foot of the bed to provide gases and power only when required, minimising unnecessary visual intrusion.

5. DISCUSSIONS

This study addressed two primary research questions concerning the effectiveness of environmental design interventions in reducing noise exposure and improving lighting conditions in ICU bedspaces. The findings demonstrate that targeted acoustic and lighting strategies can produce measurable improvements in environmental performance, supporting the role of human-centred design as a practical approach within real-world clinical settings.

Over the past two decades, improvements in intensive care practice have translated into higher survival rates, but this success has also highlighted the need to focus more carefully on what survival means for patients once the immediate crisis has passed. While there is now broad recognition that the ICU environment can influence patient outcomes in meaningful ways, comparatively little attention and funding have been directed toward environmental redesign. This paper

documents the practical steps taken to enhance two ICU bedspaces, using a combination of established evidence, emerging design approaches, and new technologies to respond to patient-centred issues that are widely encountered in critical care settings. Early results suggest that these changes produced clear benefits, particularly in relation to sound and light, with reverberation times reduced by more than half indicating substantially improved acoustic absorption alongside better attenuation of noise originating outside the rooms and the introduction of a lighting system designed to follow natural circadian patterns rather than the static output of conventional electrical lighting. Detailed measurements of lighting conditions prior to the refurbishment, including comparisons between windowed and windowless bedspaces under different scenarios, have been reported separately [41] and showed that the presence of a window only supported natural light exposure when ceiling lights were turned off; once artificial lighting was activated, the quality of light resembled that of a windowless space. In contrast, the circadian lighting system implemented in this project, as shown in Figures 6 and 7, closely approximated natural daylight in both spectral composition and timing, reflecting the lighting conditions to which human circadian rhythms are biologically attuned. In addition, repositioning monitor alarms away from the patient's head resulted in a reduction of perceived alarm noise by 8–11 dBA, a change equivalent to roughly halving the subjective loudness of the sound and comparable to the average noise reduction achieved through the use of earplugs [42]. Figure 6 provides a detailed representation of the spectral power distributions across different lighting scenarios, demonstrating how the implemented system more closely replicates natural daylight patterns compared to conventional ICU lighting.

Bringing together a wide range of partners through a participatory design process, and giving genuine weight to the perspectives of patients, families, and frontline staff, proved to be critical to the success of this work. This approach enabled the team not only to address specific shortcomings of the existing ICU bedspaces but also to rethink how these environments could better support current and future needs, based on real experiences rather than assumptions. While consumer involvement is increasingly acknowledged as important within healthcare improvement and change management, it has seldom been meaningfully embedded in the design of ICU bedspaces, where decisions are often made through hierarchical or technically driven processes. By contrast, the collaborative model adopted here fostered shared ownership and more grounded innovation, aligning with broader evidence that inclusive, non–top-down approaches are more likely to produce effective and sustainable change [43]. Although the final solutions were shaped by the local context and priorities of the study ICU, the challenges identified along with the process used to address them are common across critical care settings, suggesting that many of the principles and interventions described may be relevant to ICUs and other inpatient environments internationally.

As ICU care continues to evolve, the effects of the physical environment on patients are likely to become more pronounced, particularly as increasingly complex technologies are introduced to support the care of sicker patients. Noise levels within ICUs have risen over time, accompanied by a growing number of monitors, alarms, and light-emitting devices that are especially disruptive during night-time hours [44]. At the same time, patients are now more likely to survive critical illness but often require longer ICU stays, increasing the duration of their exposure to these environmental stressors [45]. Reduced use of deep sedation has further changed the patient experience, leaving individuals more alert and aware of their surroundings, yet the typical ICU setting remains stark, functional, and largely devoid of meaningful sensory engagement. In this context, narrowly focused measures that attempt to block out discomfort, such as earplugs or eye masks, are unlikely to address the complexity of the problem, underscoring the need for broader, multi-layered interventions that target the sources of noise, light, and sensory deprivation directly. These developments also raise questions about the adequacy of existing ICU design standards, which may no longer align with contemporary models of care and should be reconsidered to better support patient involvement, staff workflows, and healing-oriented environments. Although access to nature and green spaces has been increasingly advocated as beneficial for ICU patients [7], the retrofit nature of this project and the absence of windows meant that direct provision was not possible. To respond to this limitation, technological alternatives were introduced, including virtual windows and skylights displaying natural scenes with associated soundscapes that could be selected according to patient preference. Nature-based videos and sounds were also incorporated into the entertainment system and delivered through speakers integrated into the beds. While there is strong evidence supporting the health benefits of exposure to natural environments [7], further research is needed to determine how effectively digital representations can replicate these effects in critical care settings. As shown in Figure 7, the spectral profile of natural light serves as a reference benchmark, highlighting the extent to which the proposed circadian lighting system approximates biologically relevant light conditions.

Reducing noise and optimising lighting are key objectives in intensive care environments, and this project has demonstrated that such improvements are achievable even within the constraints of a live ICU retrofit; however, the findings also highlight the importance of environmental personalisation, as patients have differing needs and preferences, and the ability to individualise elements such as lighting can shift the environment from a passive contributor to negative outcomes into an active component of care, where appropriate environmental conditions at the right time may support recovery while enhancing patient autonomy, which is often limited in traditional ICU designs. Despite the technical and organisational challenges encountered during implementation including patient-related factors, staff adaptation, technological limitations, and the unexpected onset of the COVID-19 pandemic ongoing communication and stakeholder collaboration enabled progress throughout the project. While previous studies indicate that interventions such as circadian lighting solutions and physical noise-reduction measures can decrease delirium incidence and ICU length of stay [46], that sound masking can improve sleep quality [47, 48], and that earplugs are associated with reduced delirium [49, 50, 51, 52], there remains a lack of evidence assessing the impact of large-scale environmental upgrades on patient outcomes. Consequently, the next phase of this project will involve a comprehensive evaluation of environmental effects on patients, families, and staff, using qualitative interviews alongside quantitative assessments of sleep patterns, circadian rhythms, delirium occurrence, ICU outcomes, and physical, cognitive, and psychological recovery six months after ICU discharge.

From a safety perspective, the environmental improvements

observed in this study have important implications for both patients and healthcare staff. Excessive noise levels and poor lighting conditions are well-established contributors to cognitive overload, reduced concentration, and impaired decision-making among clinicians, all of which may increase the likelihood of clinical errors. Similarly, environmental stressors such as sleep disruption and circadian misalignment are strongly associated with delirium, which is a known risk factor for adverse events, prolonged hospitalisation, and increased mortality. By reducing noise exposure and aligning lighting conditions with natural biological rhythms, the redesigned ICU environment has the potential to mitigate these risks and contribute to safer care delivery. These findings reinforce the importance of considering environmental design not only as a matter of comfort or experience but as a critical component of patient safety and risk reduction strategies within intensive care settings.

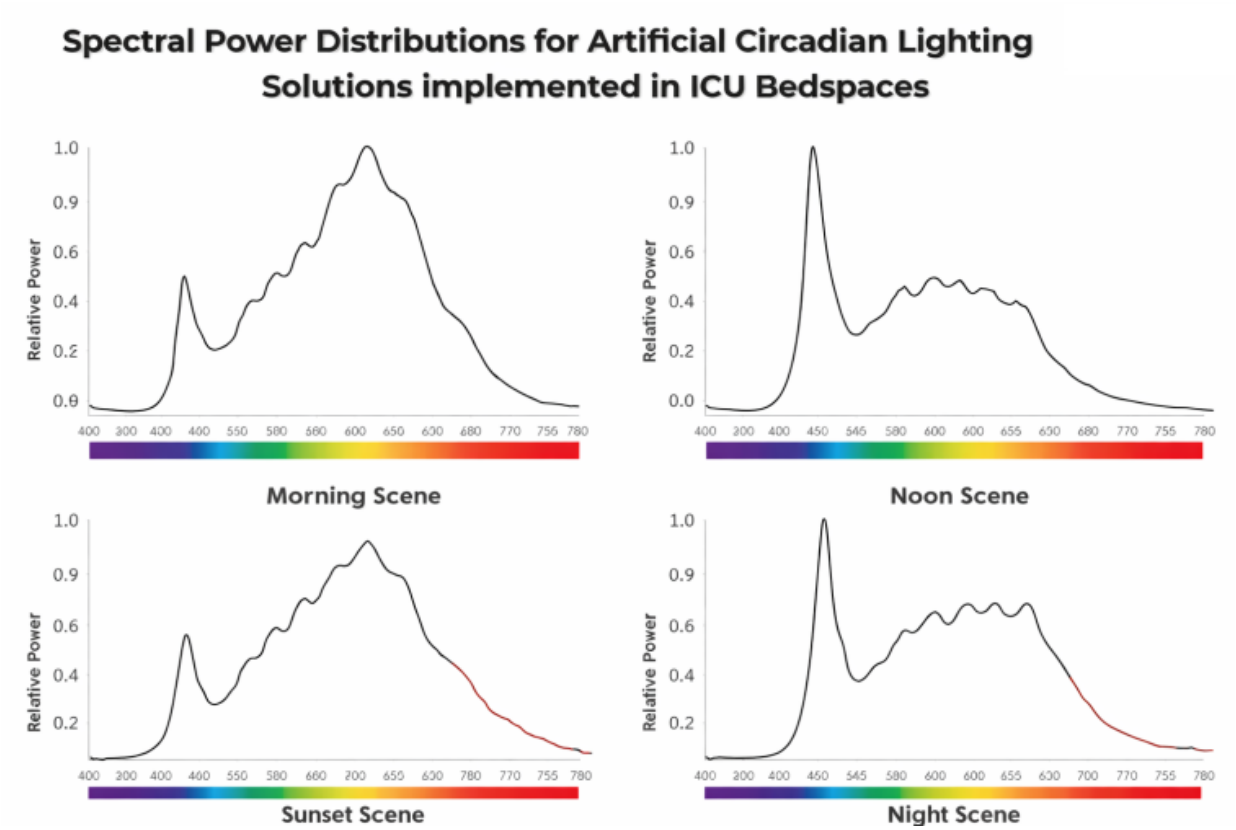

Figure 6. Circadian lighting spectral power distributions across day-night scenes

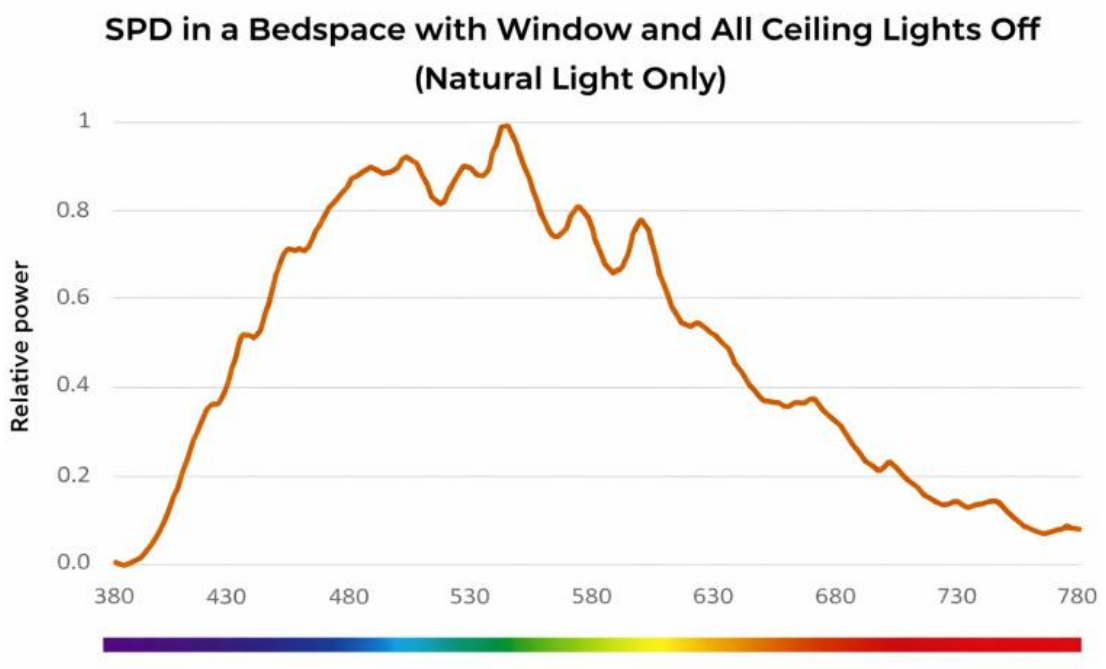

Figure 7. Natural light spectral power distribution

6. CONCLUSIONS

This study demonstrates that meaningful improvement of ICU bedspace environments is achievable through evidence-informed, participatory design, even within the constraints of a live clinical retrofit. By addressing key stressors such as noise, lighting, and sensory deprivation, the redesigned bedspaces transformed the ICU from a passive source of harm into an active component of patient-centred care. Early findings showed substantial enhancements in acoustic performance and circadian-supportive lighting. While these environmental gains are promising, further research is needed to evaluate their effects on clinical outcomes, recovery, and staff wellbeing. This study has several limitations that should be considered when interpreting the findings.

First, the intervention was implemented in only two ICU bedspaces within a single clinical setting, which may limit the generalisability of the results to other units with different spatial configurations, patient populations, or operational practices. Second, the evaluation period was relatively short and focused primarily on immediate environmental outcomes, without assessing longer-term effects on patient recovery, staff performance, or clinical outcomes. Third, while efforts were made to standardise environmental measurements, data collection in a live ICU environment is inherently subject to variability related to patient activity, staff workflow, and equipment use. Finally, the retrofit nature of the project imposed practical constraints on the extent of structural modification, meaning that some design solutions may differ from those achievable in purpose-built ICU environments.

Accordingly, the findings should be understood as most directly applicable to retrofit contexts, where incremental, evidence-informed environmental improvements are required within existing spatial and operational limitations. In particular, the small sample size (two bedspaces) means that the findings should be interpreted as exploratory and context-specific, providing indicative rather than generalisable evidence, and highlighting the need for larger-scale, multi-site studies to validate the observed environmental and potential clinical benefits. Further research is required to assess the impact of such environmental interventions on clinical outcomes, recovery, and long-term wellbeing. Future large-scale, multi-site studies are required to validate these findings and establish stronger links between environmental design interventions and clinical outcomes.

ETHICAL CONSIDERATION

The study was approved by the Ethics Committee of the Applied Science Private University (Ref. No.: REC/FAD/ASU/2025/03-27), and informed consent was obtained from all participants.

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