Enhancing Calmness and Reducing Stress in the ICU with Lighting

Master Thesis

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ACKNOWLEDGEMENTS

This project has been one of the most meaningful and intense journeys of my academic life. It offered me the opportunity to work on a topic that has the potential to create real impact in one of the most emotionally and physically demanding environments, the ICU.

I would like to start by thanking my chair and mentors for their continuous support, encouragement, and belief in my work.

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There is still so much to discover, and there are a lot of challenges ahead, but I am confident that this project can contribute to the first steps toward a more human-centred ICU.

GRADUATION PROJECT

MSc Integrated Product Design
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EXECUTIVE SUMMARY

The intensive care unit (ICU) is a highly technical and emotionally intense environment that can negatively impact the psychological well-being of patients. Extended exposure to artificial lighting, unfamiliar routines, and the absence of natural day-night cues often disrupt patients' circadian rhythms and emotional stability, contributing to feelings of stress, confusion, and disorientation. This report explores how a lighting intervention can be used to improve the ICU experience from a critically ill patient's perspective.

The project was conducted in collaboration with the Critical Alarms Lab (TU Delft) and Leiden University Medical Center (LUMC). Using a human-centered design approach, the study investigated how environmental lighting could be tailored to support patients' natural biological rhythms, reduce emotional distress, and enhance comfort without interfering with ICU workflows. Observational visits, interviews with healthcare professionals, light measurements, and surveys informed a deep contextual understanding of patient challenges.

A design vision was formed based on vulnarable points identified during the patient journey, especially moments of waking up and preparing for sleep. Co-creation sessions and iterative ideation led to the development of LumoGlaze, a wearable smart goggle, and LumoSync, its mobile control interface. The system uses physiological data, including heart rate and sleep phases (via Fitbit), to adapt lighting dynamically in a way that aligns with the patient's internal rhythm during evening, and a bright light therapy is provided in the morning for two hours.

Prototypes were developed and refined through multiple rounds of testing. The final version was evaluated in a simulated ICU setting with healthy participants. Results showed that users found the system comfortable to wear and the app intuitive to use. While heart rate data showed stable responses across lighting modes, suggesting no strong physiological changes, the system was perceived as safe, non-intrusive, and helpful in creating a more calming environment.

Ultimately, the project demonstrates that patient-centered lighting, when thoughtfully designed, has the potential to become a meaningful, non-pharmacological tool in critical care. LumoGlaze provides a blueprint for how environmental technology can support emotional well-being in the ICU, blending evidence-based light design with human-centered implementation. To further validate its impact, recommendations were made for future studies, including real-world testing in ICU settings, longer-duration physiological monitoring, and deeper exploration of personalized lighting strategies based on patient-specific needs.

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1.
INTRODUCTION

This chapter introduces the assignment, the goal of this project and explains the design approach.

1.1 ASSIGNMENT AND GOAL

This project is centered on improving the emotional and psychological well-being of critically ill patients in Intensive Care Units (ICUs) by addressing environmental design factors, primarily through the development of an adaptive lighting system. Conducted in collaboration with the Critical Alarms Lab (CAL) at the Faculty of Industrial Design Engineering, TU Delft, and the Leiden University Medical Center (LUMC), the project places the patient experience at the core of its exploration.

The main aim is to investigate how lighting in ICU environments can be redesigned to support patients' natural circadian rhythms, reduce environmental stress, and promote a sense of calm and security during their stay. This thesis contributes to that objective by proposing a patient-centered design intervention that directly addresses key environmental stressors found in ICUs, like the absence of natural lighting, as well as the effects of harsh and unnatural lighting conditions.

Using a human-centered design approach, the project will design, prototype, and evaluate a lighting system tailored to the needs of ICU patients, while remaining compatible with the clinical workflow. All experimental work and testing will be carried out within the Faculty of Industrial Design Engineering (IDE) at TU Delft, with the overarching focus on enhancing the daily lived experience of patients in critical care.

1.2 APPROACH

With the support of the Graduation Launchpad elective, I was able to immerse myself in the ICU environment and build a strong foundational understanding of the context. This included two on-site visits to the ICU, where I shadowed nurses and doctors to gain direct insights into their workflows and the daily dynamics of critical care. During these visits, I also conducted basic light measurements to assess the current lighting conditions and began identifying potential environmental stressors.

To further strengthen my contextual understanding, I engaged in conversations with experienced healthcare providers and carried out an extensive literature review focused on patient experiences in ICUs. This exploration culminated in a contextual report, which served as the basis for framing the design challenge from a patient-centered perspective.

To guide the development of a meaningful design intervention, I adopted the Double Diamond design process see Figure 01.

Discover

In the Discover phase, I deepened the literature review, this time focusing specifically on how patients perceive and emotionally respond to the ICU environment. To complement this secondary research, I conducted four in-depth interviews with experienced healthcare professionals (HCPs) and distributed an online questionnaire to HCPs at Leiden University Medical Center (LUMC). The survey received an impressive 39 responses, offering a rich dataset to analyze.

The combination of qualitative (semi-structured interviews) and quantitative (Online survey) insights enabled me to identify recurring themes in patient experiences, particularly the emotional and psychological challenges faced during ICU stays. These findings were instrumental in transitioning into the Define phase, where I could clearly outline the key design focus areas and determine which elements of the ICU experience would be addressed through the design intervention.

Define

Building on the insights gathered during the Discover phase, I analyzed the results from the interviews and survey to identify key emotional pain points experienced by patients in the ICU. A consistent finding was the absence of a supportive sensory environment, with lighting emerging as a critical factor. Inadequate or harsh lighting was frequently linked to discomfort, disorientation, and sleep disruption, all of which negatively impact patients' emotional well-being, often resulting in increased stress, anxiety, and confusion.

To translate these insights into actionable design opportunities, I utilized tools such as empathy mapping and the 5W1H (What, Why, When, Where, Who, and How) framework. These methods helped me to reframe the core problem from a patient-centered perspective and formulate a well-defined design question focused on improving the experience of ICU patients.

To explore potential solutions, I facilitated a co-creation session with six fellow design students. The aim was to generate a diverse range of ideas and perspectives beyond my own, thereby avoiding early fixation on a single concept. Insights from this session were synthesized into two distinct design concepts, each including a preliminary workflow tailored to the ICU context.

These concepts were then presented to my supervisory team, who provided critical feedback. One concept stood out due to its innovative and context-sensitive approach to the identified challenges. As a result, the Define phase concluded with two strong design directions, one of which was selected during the midterm review to move forward into further development.

Develop

With a clear design direction chosen, the project entered the Develop phase, focusing on refining the selected concept into a functional and context-appropriate solution. The main questions at this stage involved how to deliver adaptive lighting in a wearable form and how it could interact with patients' physiological states without interfering with ICU workflows.

To address these questions, further brainstorming and technical exploration were conducted, including a co-creation session with design peers and informal feedback from healthcare professionals. The lighting behavior was informed by circadian lighting research and translated into RGBW light modes for morning and evening use. Simultaneously, component selection began, centered around compact microcontrollers, physiological data integration (via Fitbit API), and interface design using Flutter for real-time control.

Several prototypes were developed and iterated on to test comfort, component layout, and user interaction. Key ergonomic features, such as the nose bridge and strap integration, were progressively improved based on feedback and testing within the design faculty environment.

Deliver

During the Deliver phase, the LumoGlaze system was finalized and evaluated through user testing in a simulated ICU environment. Due to ethical and procedural limitations, real ICU patients could not be involved, so a controlled setup was created to approximate clinical conditions as realistically as possible.

Both low and high-fidelity prototypes were tested, focusing on user comfort, lighting behavior, and system usability. The LumoSync mobile app was also finalized during this stage to enable seamless control and data logging. Eight participants engaged with the system across morning and evening modes, while their feedback and heart rate responses were recorded.

While the physiological data did not reveal strong trends, the system was well-received for its comfort, ease of use, and potential to enhance patient experience. The Deliver phase concluded with the validation of the design intent and formulation of next steps, paving the way for future testing in real ICU contexts and further personalization of the intervention.

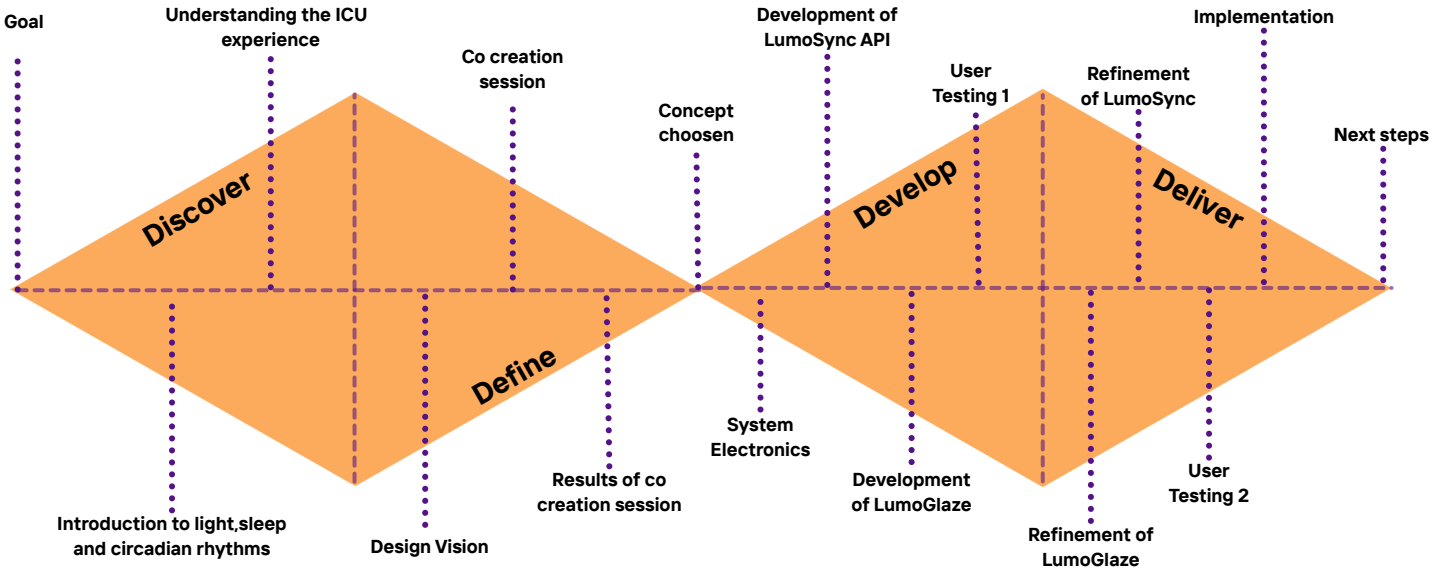


Fig 01: Double Diamond method, design process

2.

LIGHT, SLEEP, AND CIRCADIAN RHYTHMS

This chapter explores the critical relationship between light, sleep, and circadian rhythms within the ICU environment. It examines how light functions as a primary environmental cue that influences the body's internal clock, affecting essential physiological processes such as hormonal regulation, immune response, and the sleep–wake cycle. In critically ill patients, these rhythms are often disrupted due to irregular lighting, noise, and clinical interventions, leading to sleep fragmentation, cognitive impairment, and delayed recovery. By investigating the scientific foundations of circadian biology alongside clinical observations, this chapter aims to highlight the importance of appropriate lighting conditions in supporting patient well-being and improving outcomes in intensive care settings.

2.1 WHY IS LIGHTING IMPORTANT?

Light is a crucial environmental cue that regulates the circadian clock, as we discussed the same in earlier chapter. This regulation occurs through the intrinsically photosensitive retinal ganglion cells (ipRGCs) located in the eye, which transmit light information to the central clock in the suprachiasmatic nucleus (SCN) of the brain. Unlike rods and cones, which mediate visual perception, ipRGCs are sensitive to short-wavelength (blue) light, and their primary function is to regulate circadian rhythms see Figure 02 (Hosseini et al., 2024). The photopigment melanopsin, released by ipRGCs, plays a critical role in this process, helping synchronize the body's internal rhythm with the external cycles of day and night, essential for maintaining a healthy sleep-wake pattern and circadian balance (Engwall et al., 2015).

The relationship between light, circadian rhythms, and overall health has been recognized for over a century. As early as 1912, Florence Nightingale emphasized the importance of light and the natural rhythm of day and night in supporting patient health, a concept that aligns with modern scientific findings. Light serves as a primary environmental cue, or "zeitgeber" which helps regulate the body's circadian clock, ensuring synchronization with the natural light-dark cycle. Bright light exposure during the day, particularly in the morning, enhances circadian amplitude by upregulating clock genes such as PER2 (Period Circadian Regulator 2), which are crucial for aligning the internal circadian rhythm with the solar cycle (Simons et al., 2019; Prin et al., 2023). This synchronization is vital for maintaining healthy biological functions, as disruptions to this cycle can lead to a variety of health complications.

2.2 HOW IS IT CAUSING AN EFFECT ON ICU PATIENTS?

Lighting conditions in intensive care units (ICUs) often deviate significantly from recommended standards, leading to disrupted circadian rhythms, altered melatonin secretion, and poor sleep quality. Studies indicate that nocturnal light levels in ICUs frequently exceed the ideal range of 30–50 lux, with measurements ranging from 3 to 271 lux and averaging 104.1 lux see Figure 03 (Younis et al., 2021). Such excessive light exposure at night suppresses melatonin, a hormone essential for initiating and maintaining sleep, even at low intensities of 30–50 lux. This disruption can fragment sleep, desynchronize circadian rhythms, and adversely impact patient recovery (Younis et al., 2021).

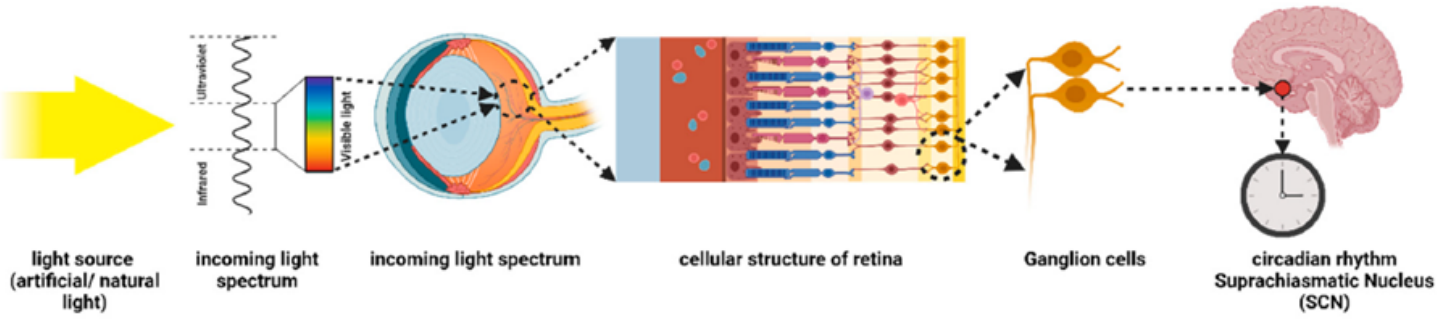


Fig 02: Diagram of the retina photoreceptors (Hosseini et al., 2024)

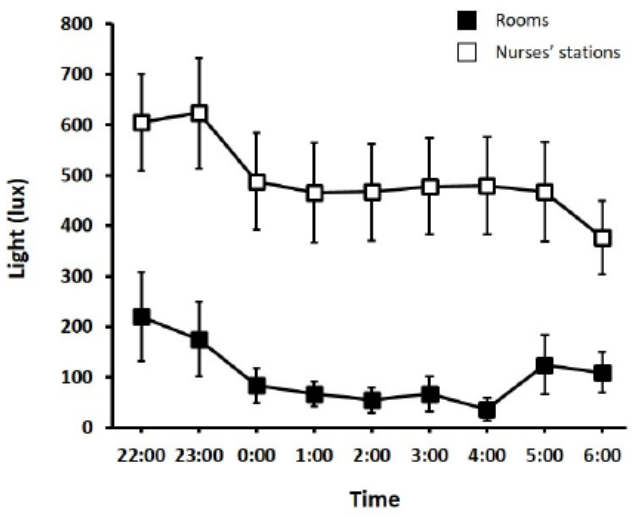


Fig 03: Light levels (lux) in rooms (closed squares) and nurses' stations (open squares) overnight (Martinez et al., 2022).

Inappropriate lighting schedules during the night can significantly disrupt the natural light-dark cycle, impairing biological rhythms and circadian alignment. Even brief exposures to light at night have been shown to exacerbate this misalignment, leading to further disturbances in sleep and recovery (Jaiswal et al., 2017). Insufficient daytime lighting in ICUs is another critical factor, with average illuminance levels often below 250 lux, comparable to dim office lighting. This inadequate lighting fails to provide the necessary intensity to maintain or reset circadian rhythms effectively, as observed by Jaiswal et al. (2017) and Danielson et al., (2018).

The issue is particularly acute for elderly patients, who require higher light intensities to achieve proper circadian entrainment and alignment (Jaiswal et al., 2017; Leone et al., 2023).

ICU environments often feature consistently low light levels during the day and bright light at night, disrupting natural circadian alignment. This misalignment contributes to physiological recovery delays, increased fatigue, and reduced restorative slow-wave sleep (SWS), which is critical for healing see Figure 04, Leone et al., 2023; Luther et al., 2018). Furthermore, such lighting conditions are strongly associated with an increased prevalence and duration of delirium in critically ill patients, highlighting the importance of targeted lighting interventions (Luther et al., 2018).

Although ICU patients often have their eyes closed, ambient light can still significantly influence circadian rhythms, emphasizing the role of proper lighting in patient care. Addressing lighting deficiencies by ensuring adequate light levels during the day and reducing light intensity at night may help mitigate the adverse effects of circadian disruption, improving sleep quality and supporting recovery in ICU patients (Leone et al., 2023).

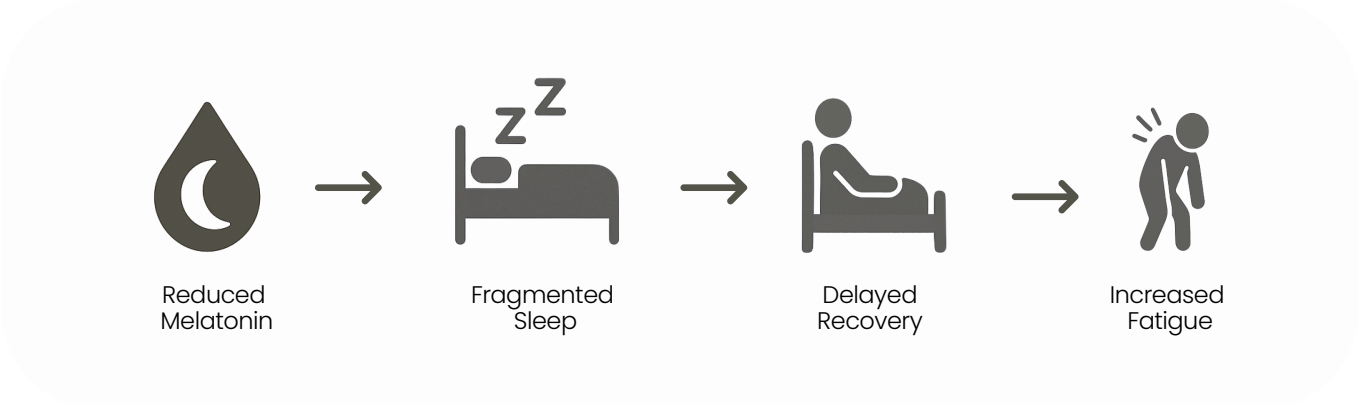


Fig 04: Affects of improper lighting in ICU

2.3 SLEEP IN ICU PATIENTS

Sleep is a fundamental physiological process crucial for immune function, tissue repair, and the regulation of metabolic and hormonal processes (Telias & Wilcox, 2019). In critically ill patients, however, sleep is often significantly disrupted due to the clinical environment and various external factors. Sleep is comprised of stages of NREM (Non-Rapid Eye Movement) and REM (Rapid Eye Movement) sleep. NREM sleep is subdivided into stages N1 to N3, with each stage becoming progressively deeper. A typical sleep cycle consists of approximately three-quarters of NREM sleep, following the routine N1-N2-N3-N2-REM (Van Den Ende, 2025b). In stages N1 and N2, the heart rate, breathing, and brainwaves slow down, muscles relax, and core temperature drops (Perry et al., 2024). Deep sleep in N3, also called 'slow-wave sleep (SWS) is restorative, supporting tissue repair and immune system strengthening while REM sleep supports memory consolidation and emotional stability (Perry et al., 2024). Four to six sleep cycles occur repeatedly, each taking 90 to 120 minutes see Figure 05. In the first half of the night, slow-wave sleep predominates, while REM sleep becomes more prevalent in the latter half (Luetz et al., 2024).

2.4 CIRCADIAN RHYTHMS IN ICU PATIENTS

Circadian rhythms are vital internal physiological processes that regulate key functions, including the sleep-wake cycle, hormone secretion, metabolism, and immune responses. The term "circadian" comes from the Latin words "circa" (about) and "diem" (day) (Hosseini et al., 2024), referring to processes that repeat approximately every 24 hours (Luetz et al., 2024) aligning essential bodily functions with the natural day-night cycle.

The central biological clock that regulates these rhythms is located in the hypothalamic suprachiasmatic nucleus (SCN). Light serves as the primary environmental cue for the synchronization of the circadian system, with intrinsically photosensitive retinal ganglion cells detecting light and transmitting signals to the SCN. These signals help align various physiological functions with the light-dark cycle, supporting the body's adaptation to the natural environment (Hosseini et al., 2024).

In the ICU, maintaining circadian alignment is crucial for supporting patients' recovery and overall well-being. Disruptions to this system, however, can have significant effects on patient health, including compromised sleep quality and increased stress.

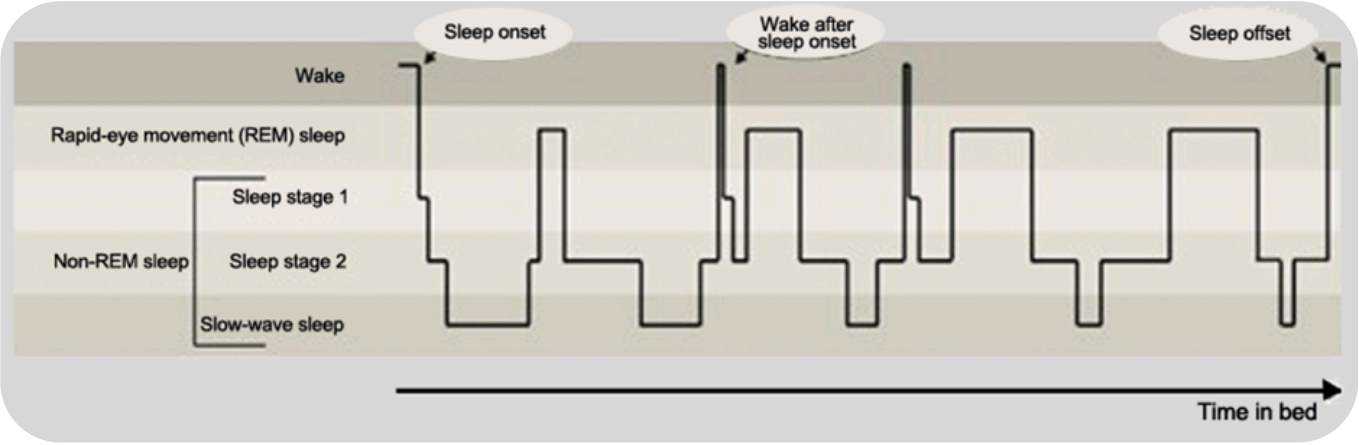


Fig 05: Typical sleep pattern in a healthy young adult (Van Den Ende, 2025b)

2.5 THE EFFECTS OF SLEEP AND CIRCADIAN DISRUPTIONS IN ICU PATIENTS

Sleep and circadian disruptions in ICU patients contribute significantly to a variety of adverse health outcomes, including impaired physical recovery, cognitive dysfunction, and emotional distress. However, the ICU environment, characterized by excessive noise, bright lighting, frequent medical interventions, and the use of sedatives, disrupts these critical sleep stages. These disruptions diminish the time spent in SWS and REM sleep, which are essential for physical and mental recovery. ICU patients often exhibit an inverted sleep-wake cycle see Figure 06, with up to 50% of their sleep occurring during the daytime, further exacerbating circadian misalignment. This misalignment, combined with environmental factors like the absence of natural light and the presence of artificial lighting, increases the risk of complications such as ICU-acquired delirium, delayed recovery, and prolonged fatigue. Disrupted sleep patterns also have long-term consequences, with many ICU patients continuing to experience sleep disorders and cognitive impairments well after discharge (Adell et al., 2021; Luther et al., 2018).

Circadian rhythms, which regulate the sleep-wake cycle, hormone secretion, and immune responses, are particularly vulnerable in the ICU setting. The suprachiasmatic nucleus (SCN) in the hypothalamus controls these rhythms, with light serving as the primary environmental cue. However, in ICU rooms that lack windows or proper light adjustment mechanisms, patients experience misalignment between their internal circadian system and the external environment, which disrupts their ability to synchronize with the natural day-night cycle. This misalignment leads to various negative health effects, including increased anxiety, impaired immune function, and a heightened risk of delirium (Luther et al., 2018). The inability to maintain proper circadian alignment further delays recovery, exacerbating physical and cognitive health challenges. Strategies to mitigate these disruptions, such as reducing artificial lighting at night to allow for natural light exposure and offering patients more control over their environment, are crucial for improving sleep quality and recovery outcomes in critical care settings (Simons et al., 2016).

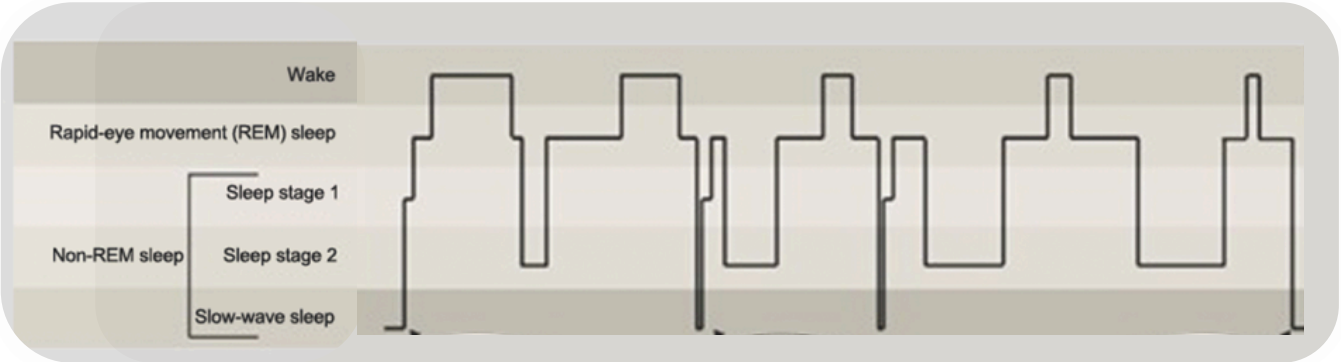


Fig 06: Inverted sleep wake cycle

2.6 CONCLUSION

This chapter has provided a comprehensive overview of how light, sleep, and circadian rhythms intersect to influence patient recovery and well-being in the ICU. It has outlined the physiological foundations of circadian regulation and sleep architecture, emphasizing the detrimental effects of disrupted lighting conditions in critical care settings. The chapter highlights how inappropriate light exposure—both insufficient daylight and excessive nighttime lighting—contributes to circadian misalignment, fragmented sleep, and an increased risk of complications such as delirium and prolonged recovery.

The findings discussed here underline the importance of aligning ICU lighting conditions with natural circadian cycles to support the body's biological needs. By recognizing light as a powerful regulator of both hormonal rhythms and sleep quality, the chapter establishes the foundation for patient-centered lighting strategies in intensive care environments.

3.

UNDERSTANDING THE ICU EXPERIENCE

The previous chapter outlined the critical role of light in regulating circadian rhythms and its effects on ICU patients. Building on these insights, this chapter examines how environmental factors, such as lighting and limited control, are experienced by patients and staff in actual ICU settings. Through direct observations, measurements at Leiden University Medical Centre (LUMC), as well as interviews and surveys with healthcare professionals, this chapter provides a deeper understanding of how these factors impact patient comfort, emotional well-being, and recovery. These findings form the basis for identifying design opportunities addressed in the following chapters.

3.1 MY FIRST EXPERIENCE IN ICU

To deepen my understanding of how an ICU functions and to observe it from an outsider's perspective, I began by gathering firsthand information through direct observation at the Leiden University Medical Centre (LUMC). During my initial visits, I shadowed both an ICU physician and an ICU nurse. These experiences provided a pivotal insight: the ICU environment and patient care are highly personalized, with no two ICUs or ICU patient experiences being exactly alike. Contrary to my preconceived notion of a perpetually chaotic setting due to frequent emergencies, I was struck by the relative quietness of the atmosphere.

However, the atmosphere occasionally shifted to noisiness, especially in the lobby outside the ICU rooms. This area, often bustling with activities such as restocking supplies and conversations among doctors and nurses, especially during breaks or shift changes, was noticeably louder. The central nursing desk often became a hub of noise, with talking and laughter. Additionally, each room is equipped with a microphone placed directly above the patients to relay events to the lobby as a precaution, allowing passing nurses to quickly respond to emergencies.

The lighting arrangement in and around the ICU also varied. The lights near the central desk were on, which could potentially disturb patients near these areas at night. Unlike the lobby lights, which only toggled on or off, the central nurse desk lights were adjustable. The rooms in LUMC are either single or double bedrooms, featuring fluorescent tubes mounted on the wall behind the patient's bed, which are turned on together. Additionally, two warm lights aligned with the patient's bed on the ceiling are seldom used by healthcare professionals. A small night light is supposed to be used during the night, though this practice is not consistently followed by all nurses, who sometimes choose to turn off all lights instead, see Figure 10 for ICU room layout

With the current lighting setup, it is difficult for patients to sleep, as any medical intervention during the night results in all the lights being turned on. This sudden illumination disrupts the patients' sleep cycle, causing them to wake up and negatively affecting their rest and recovery.

Furthermore, LUMC has two wings in the ICU, each with distinct lighting conditions. One wing has access to natural light, while the other does not, earning it the nickname "the dark side" of the building. In the dark side, the windows face the interior of the hospital, preventing patients from experiencing natural daylight. Healthcare professionals mentioned that patients who remain in the ICU for extended periods, especially those in the dark side, are often transferred to the other wing so they can receive natural light. This practice helps prevent patients from feeling completely disconnected from the natural world. Similarly, healthcare providers are also rotated between the dark and light sides of the building to ensure they, too, have exposure to natural light during their shifts.

Fig 07: View of a two-bed ICU room layout as seen from the entrance.

Fig 08: View of an ICU patient bed with active medical equipment.

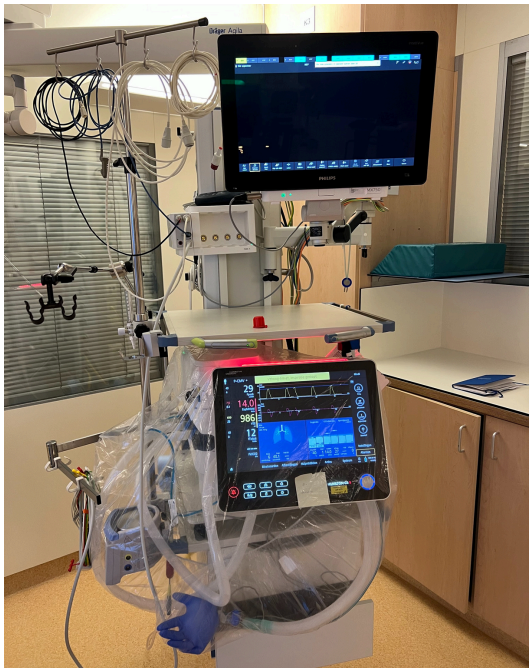


Fig 09: Active ventilator and patient monitor.

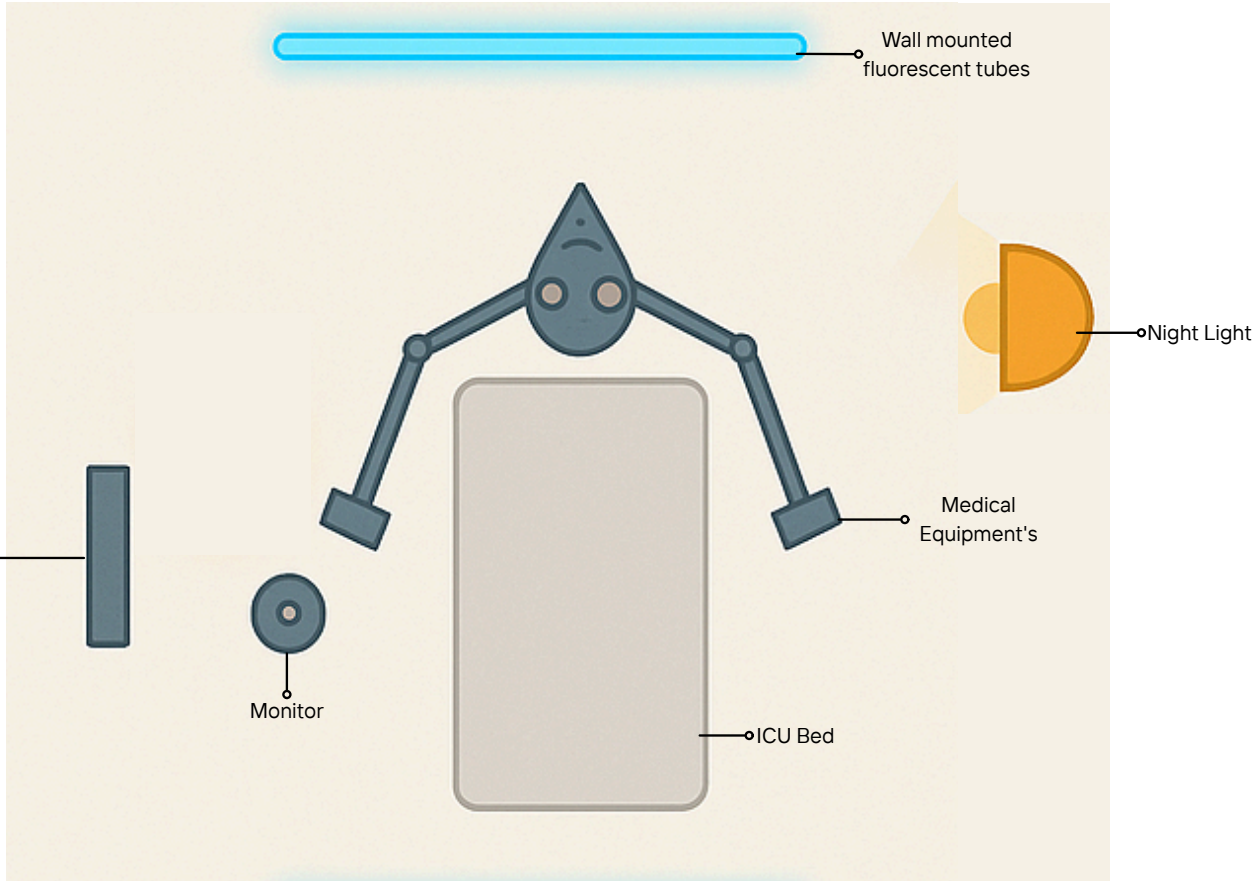


Fig 10: LUMC ICU room layout

3.2 LIGHT MEASUREMENTS IN LUMC

Aim

The aim of this study was to evaluate the lighting conditions within a typical ICU room during evening hours and to understand how light intensity levels vary across space and time in relation to patient zones. Given the critical role of light in regulating circadian rhythms and supporting recovery, this study sought to document and quantify the patterns of ambient and artificial lighting using a standardized measurement method in a simulated ICU setting.

Methodology

The measurement study was conducted in an unoccupied, double patient ICU room on a foggy day. The environment was prepared at 15:00 to reflect a standard ICU lighting setup. Measurements were recorded on January 16th, 2025, starting at 16:00 and continuing hourly until 20:00, capturing light transitions from afternoon through evening.

Due to institutional and ethical constraints, data collection was carried out without patients present. Additionally, lighting transitions typically performed by healthcare professionals, such as dimming or turning off overhead lights at night, were manually simulated by the observers to reflect real-world practice.

Ten specific points were identified within the room based on their relevance to patient interaction, access to natural or artificial light, and proximity to equipment or circulation areas, see Figure 11. Light levels were measured at each point using the cubic method, which involves recording lux values from six directions (top, bottom, left, right, front, and back) at a consistent height of 60 cm above the patient's mattress level, representing the eye level of a patient. The average of the six values was used to represent the effective illumination at each point, allowing for comprehensive spatial comparison.

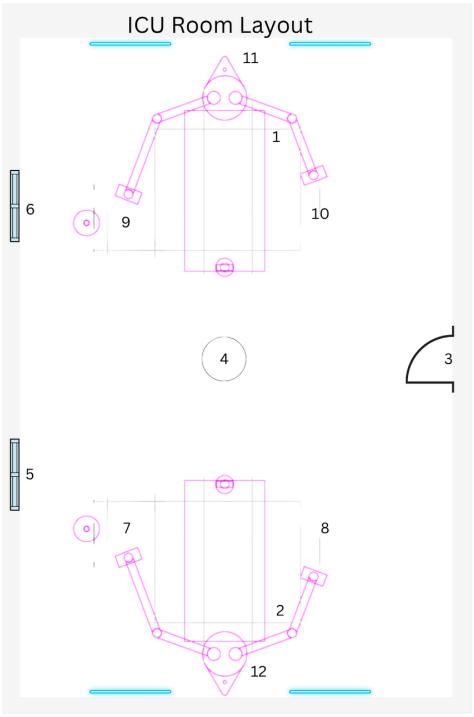


Fig 11: Visualization of ten measurement points on ICU layout

1,2: Measure right above each patient's bed
3: Measure near the room entrance
4: Measure the space between the beds
5,6: Measure near the windows
7,8: Measure near patient 1's equipment
9,10: Measure near patient 2's equipment
11,12: Measure near the light source behind the patient

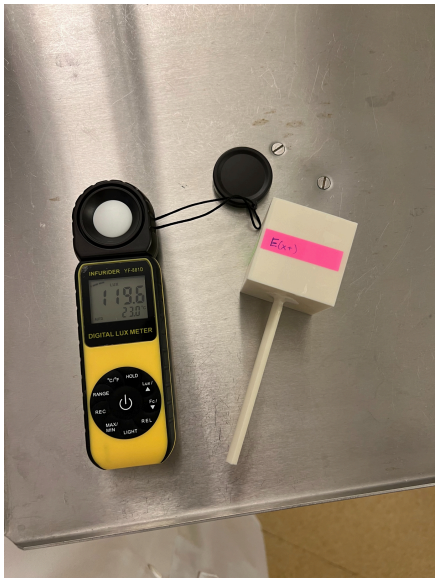


Fig 12: Digital lux meter and cubic reference tool used for illumination measurements.

Tools

Light illuminance was recorded using a digital lux meter (Infurider model), a handheld instrument capable of measuring light intensity in lux across a wide range of conditions see Figure 12. The device was chosen for its high sensitivity, ease of operation, and reliability in capturing low-intensity light levels common in ICU night settings.

Results

The recorded light intensities are presented in Figure 13, showing lux values at each point for five time intervals: 4 PM, 5 PM, 6 PM, 7 PM, and 8 PM.

The results show clear variation in light intensity. Point 6 (near the windows) registered the highest value of 100 lux at 4 PM, followed by Point 2 (92 lux), both of which reflect the combined effect of residual natural daylight and overhead fluorescent lighting. These values declined sharply by 8 PM, reaching as low as 2–3 lux, indicating a transition into nighttime lighting conditions.

Points located near equipment zones or corridors, such as Points 5, 8, and 11, exhibited moderate evening lux levels (~40–43 lux at 6 PM), before reducing to ~3 lux at 8 PM. Meanwhile, interior zones such as Points 1, 3, 4, and 7 showed a more consistent decline and reached low-light conditions sooner.

The lighting transition simulated by the observers resulted in a marked drop in illumination across all zones after 6 PM, with some areas dimmed to near-dark conditions by 8 PM. While this reflected common ICU lighting practice for nighttime, the study's controlled setting without active patient care ensured consistency but may not capture the full variability present in live environments.

Overall, the findings highlight uneven lighting distribution within the ICU space, with sharp contrasts between zones near windows and equipment versus more interior patient areas. These spatial inconsistencies may affect patients' circadian entrainment, especially in rooms with limited access to natural daylight.

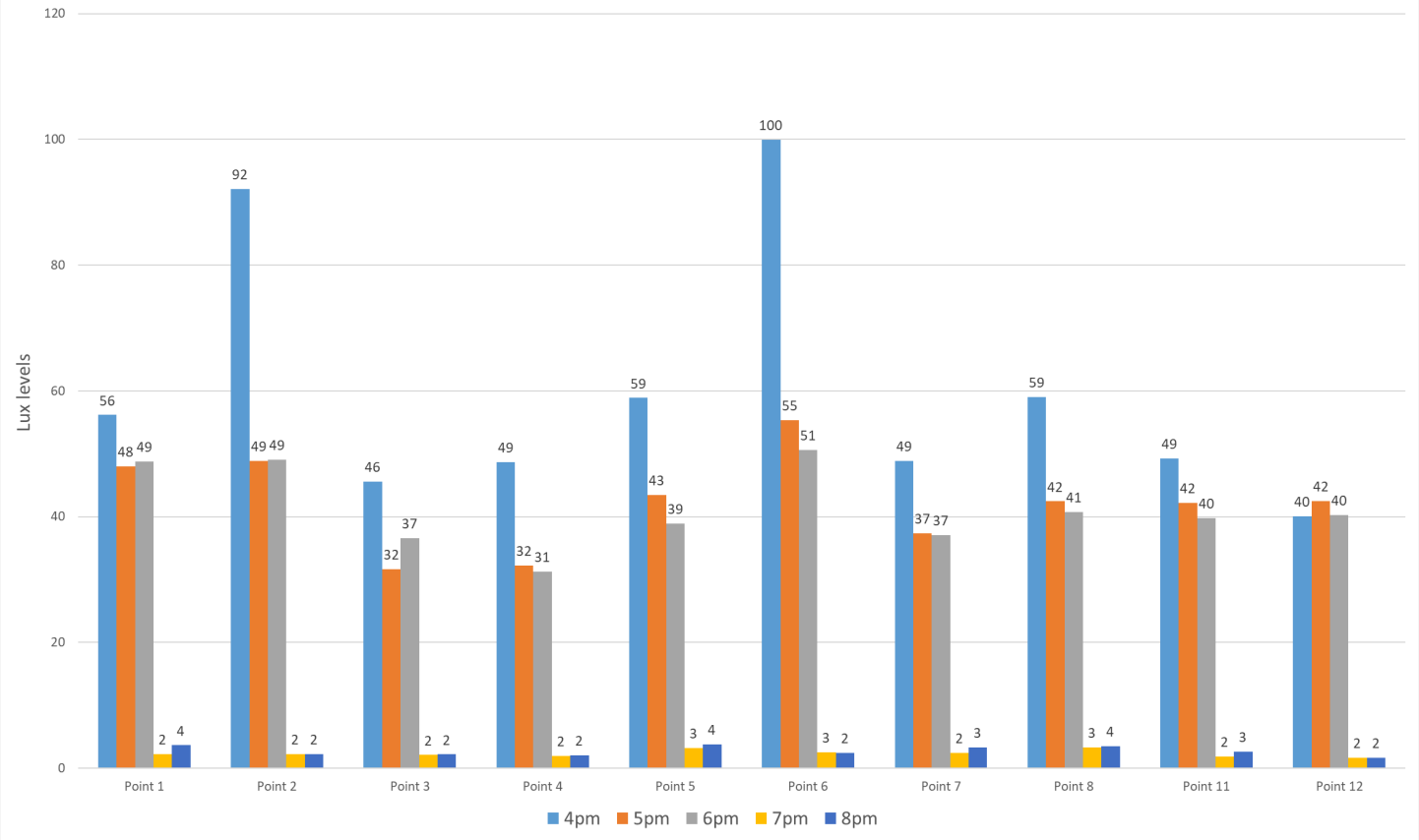


Fig 13: Recorded illumination levels across measured points.

3.3 INTERVIEW WITH HCP

Methodology

To understand the different experiences of patients in the ICU, a qualitative interview study was conducted at Leiden University Medical Centre (LUMC). Four nurses (two male, two female) who regularly interact with ICU patients participated in the study. The participants provided written informed consent after being briefed on the purpose and scope of the research. All interviews were conducted in English, as it was the primary language of the researcher.

The interviews were semi-structured and organized around five core themes:

- Sleep and comfort in the ICU environment
- Patients' inability to distinguish between day and night
- Environmental control and patient autonomy
- Influence of family presence
- Emotional journey of ICU patients

These themes guided the flow of conversation and ensured comprehensive coverage of patient-centered factors. A complete list of interview questions is available in Appendix C.

Findings

Patient Sleep

Most ICU patients face significant challenges in achieving proper rest due to frequent interruptions from medical equipment, such as beeping alarms and infusion pumps. These disruptions, compounded by the inability to adjust lighting, contribute to sleep disturbances. The ICU environment, with its constant noise and lighting issues, creates an atmosphere that is far from conducive to restful sleep. Although nurses attempt to manage lighting and sound levels, these efforts are often limited by the need for adequate illumination during medical procedures.

Additionally, the lack of control over the lighting in ICU rooms further impacts patients' ability to rest. While some nurses strive to adjust lighting for better sleep conditions, this is not always feasible due to the necessary lighting required for medical tasks. The current lighting system, which lacks sufficient flexibility, significantly affects patient comfort and disrupts their sleep cycle.

> *"Patients often claim they slept well, but if you observe them during night shifts, they're often awake. It's difficult to get a full night's rest in the ICU due to the constant beeping and lighting." – Nurse 3*

> *"Patients don't have control over the lighting, and this often affects their sleep. The light in the ICU is either on or off, and there is no option to adjust it to a lower setting." – Nurse 4*

Patients' Inability to Distinguish Between Day and Night

Nurses consistently reported that ICU patients often struggle to differentiate between day and night, which contributes significantly to psychological distress and disrupted sleep cycles. This difficulty primarily stems from the lack of natural light exposure and the constant presence of artificial lighting within the ICU environment. The absence of normal circadian cues affects patients' ability to orient themselves, resulting in confusion about rest and activity periods.

Nurse 1 emphasized the disorienting effect of continuous artificial lighting:

> *"Patients in the ICU often don't know if it's day or night because there's no natural light. They are confused about when it's time to rest or be active."*

This disruption of normal sleep-wake rhythms further exacerbates emotional and physical strain, contributing to anxiety and restlessness. Nurses observed that without clear external cues indicating the passage of time, patients may struggle to relax or feel grounded.

Nurse 2 further highlighted the impact on patients' sense of connection with the outside world:

> *"Without the daylight or night to signal the passing of time, patients can feel disoriented and isolated, unable to ground themselves in the normal rhythms of the day."*

The inability to distinguish between day and night therefore plays a critical role in the emotional challenges faced by ICU patients. Implementing more natural and adaptable lighting solutions may help re-establish patients' sense of time, potentially supporting emotional stability and recovery.

Control Over Environment:

Patients in the ICU often experience a sense of disempowerment, as the environment strips them of control over even the most basic aspects of their surroundings. Providing patients with some control over their environment, such as adjusting the lighting or sound, can significantly enhance their comfort and overall mental well-being. Offering this autonomy helps reduce feelings of helplessness and promotes greater psychological stability.

The ICU environment, combined with the loss of independence and physical strength, can lead to feelings of disconnection, depression, and isolation. Patients frequently miss their regular routines, and the lack of control over key aspects of their environment exacerbates these emotions. Long-term ICU patients, in particular, often feel disconnected and depressed due to the loss of their independence. The inability to control their environment further amplifies these feelings.

> *"Patients feel more comfortable when they have some control over their environment, like adjusting the lighting or choosing the sounds in their room. It gives them a sense of autonomy, which is crucial for their mental state." – Nurse 4*

> *"The longer a patient stays in ICU, the more they feel disconnected from their normal life. They can't move or even watch TV without help, and that isolation makes them depressed." – Nurse 1*

The Role of Family

Nurses consistently identified family presence as a critical factor in reducing isolation and emotional distress for ICU patients. Patients who have family members present tend to feel more at ease and demonstrate better psychological recovery. The emotional support provided by family members plays a significant role in alleviating anxiety and helping patients cope with the stress of their ICU experience. Additionally, the familiar presence of family creates a sense of connection, offering reassurance to patients during an otherwise challenging and isolating time.

In contrast, for patients who do not have family nearby, nurses observed that loneliness often leads to increased depression and anxiety, which hinders emotional recovery. The absence of family support exacerbates feelings of isolation, making it more difficult for patients to maintain a positive outlook and recover emotionally. Family involvement, therefore, is crucial for maintaining patient morale and promoting psychological well-being throughout their ICU stay.

> *"Having family around can significantly ease the patient's emotional burden. It's comforting for them to hear familiar voices or have family members near, which makes them feel less isolated." – Nurse 2*

"Without family, patients often feel very lonely. Even with all the medical care, the emotional support they need can only come from those close to them." – Nurse 3

Patient's Emotions and Journey in the ICU:

The ICU presents a complex environment where patients undergo significant emotional fluctuations in response to both their clinical condition and the surrounding atmosphere. To better understand and represent these nuanced emotional shifts, healthcare professionals were introduced to visual tools such as the PrEmo character stills, developed by Desmet et al. (2016) see Figure 14. This expressive framework features 14 animated characters that illustrate a wide spectrum of emotions, serving as a starting point for discussing patient experiences in a more tangible and relatable manner.

The result of this approach was the development of a Patient Emotional Journey Map, a visualization that captures the emotional states of ICU patients across different moments of a typical day. This map was built upon the qualitative feedback provided by ICU nurses. While the PrEmo tool helped initiate discussion, participants often preferred to describe patients' emotions in their own words, highlighting the individuality and fluidity of emotional responses in ICU care.

From these conversations, a clear pattern of emotional disruption emerged. Patients commonly experience emotional turbulence upon awakening from sedation, especially post-surgery. Disorientation, physical discomfort, and the stark realization of their medical condition can make this moment particularly distressing. Nurses emphasized that patients frequently express fear and a sense of helplessness during these transitions, which can significantly burden their psychological recovery.

"Waking up from surgery can be a very isolating and frightening experience, especially because of the medication, thirst, and the disorientation from sedation." – Nurse 1

"The moment that they realize how sick they are... that's the time that people are thinking a lot and becoming anxious and sad." – Nurse 2, Nurse 3

Fig 14: PrEmo character stills—an expressive framework

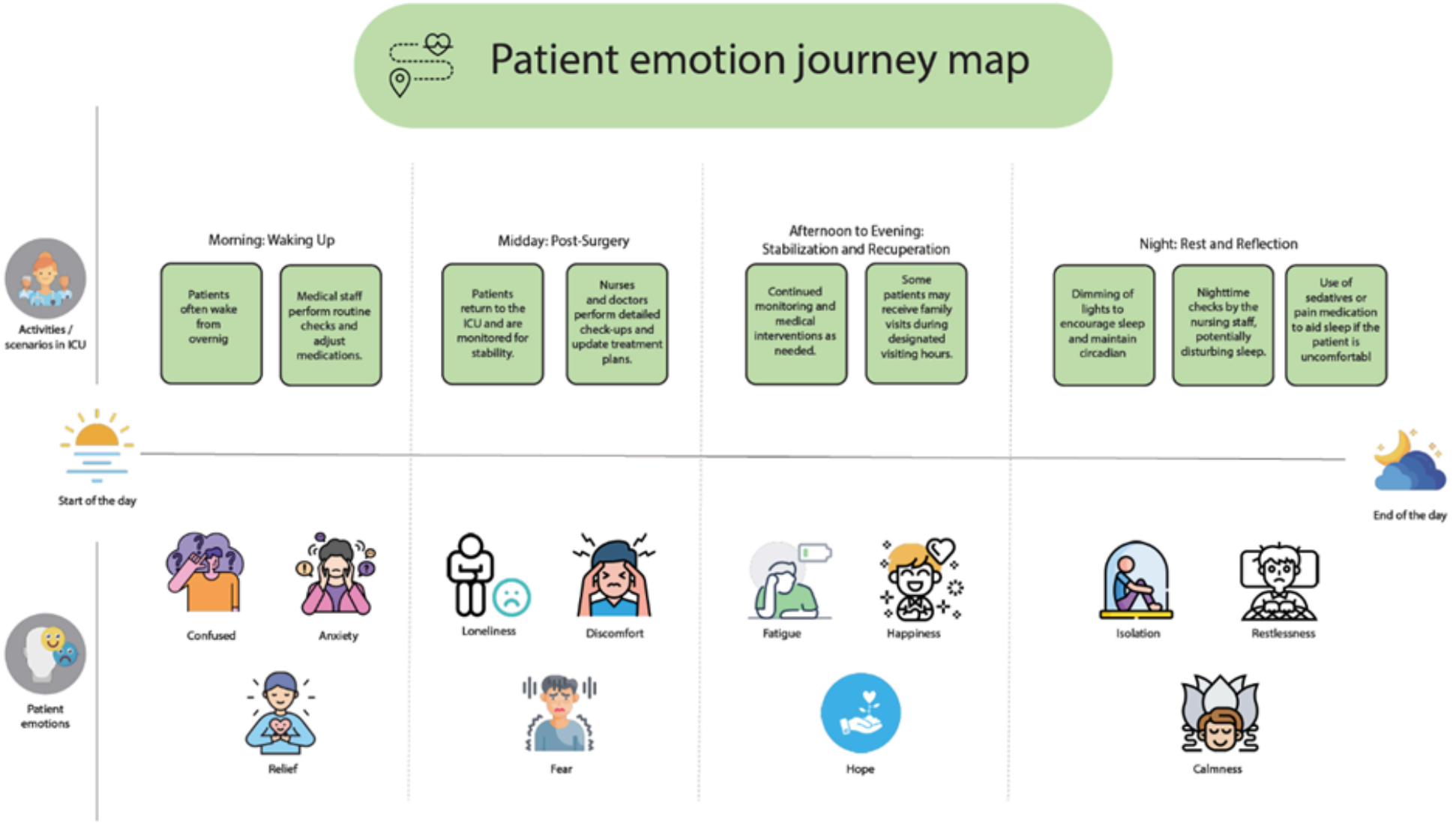


Fig 15 : Overall emotional journey of ICU patients

Prolonged ICU stays further amplify feelings of anxiety and depression. The lack of control over one's environment, continuous exposure to medical interventions, and separation from loved ones can gradually erode emotional resilience. Despite these challenges, nurses observed a dynamic progression in patients' emotions from fear and anxiety to brief moments of hope and reassurance, particularly when signs of recovery appear or meaningful social interactions occur. To comprehensively understand patients' experiences and the factors influencing their emotional states, each phase of the day morning, midday, afternoon to evening, and nighttime, will be discussed individually and in detail in the following sections.

Morning: Waking Up

The morning phase in the ICU marks a critical transition point for patients as they typically awaken from overnight sedation or sleep. This period is characterized by medical staff performing routine checks, monitoring vital signs, and adjusting medications as required. The emotional experience of patients during this phase can vary significantly, with confusion and anxiety frequently observed due to lingering effects of sedation and the unfamiliar clinical environment upon awakening.

Patients commonly express feelings of confusion immediately after waking, primarily due to disorientation and uncertainty regarding their surroundings. This confusion is amplified by the absence of clear cues signaling the start of the day, such as natural light or familiar routines, leading to heightened anxiety. Patients may feel overwhelmed by their inability to clearly recall their circumstances or the events leading to their ICU stay, intensifying their sense of vulnerability. These experiences align with findings by (Latour et al., 2022), who report that ICU survivors often recall their ICU stay with varying degrees of clarity and that disorientation, combined with sleep deprivation, can contribute to anxiety and mood disturbances.

Similarly, Johansson et al. (2012) found that patients waking in a quiet room without identifiable sensory cues described moments of fear and disorientation, sometimes feeling isolated and abandoned. However, despite these distressing experiences, some patients also report moments of relief, particularly when comforted by the presence of medical staff or through reassuring interactions that clarify their situation. Reassurance and empathy from caregivers have been shown to alleviate confusion and fear, offering a crucial emotional anchor to help patients navigate the initial hours of the day (Johansson et al., 2012; Latour et al., 2022), see Figure 16.

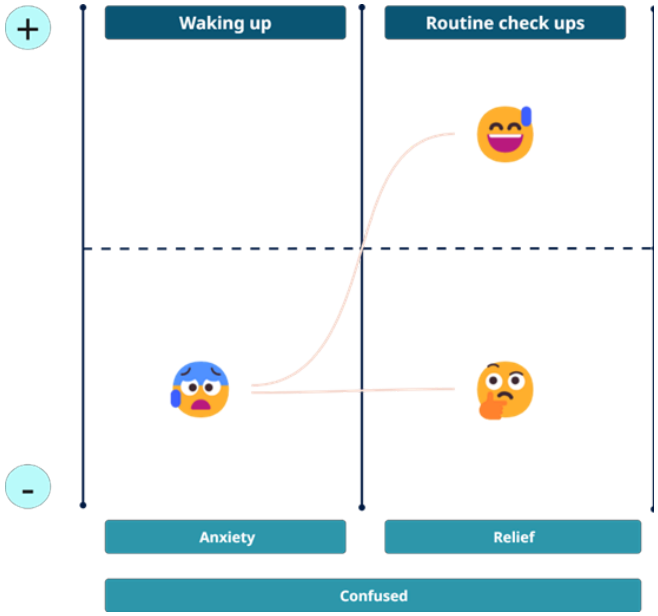


Fig 16: Emotional Responses Reported During Morning Hours

Midday: Post-Surgery

The midday phase in the ICU typically involves patients returning from surgery, a period requiring careful monitoring and stabilization by healthcare professionals. During this time, nurses and doctors perform thorough evaluations, continuously updating and adjusting treatment plans based on patient conditions. This intensive monitoring is crucial for ensuring patient stability and successful recovery. Emotionally, however, this stage often presents significant challenges for patients. Feelings of loneliness frequently emerge as patients find themselves separated from their families, facing an unfamiliar and clinical environment without the emotional support of loved ones. Latour et al. (2022) emphasize that such isolation, combined with the stress of an unfamiliar environment and physical discomfort, significantly increases emotional vulnerability, especially during the immediate post-surgical period.

In addition to loneliness, patients commonly experience pronounced discomfort, resulting from post-surgical pain, the side effects of medications, or physical restrictions imposed by their medical conditions. Fear is another prominent emotion during this period. Patients may fear their current medical status, uncertainty about their future health outcomes, or potential complications. This fear is often amplified by the clinical atmosphere and the presence of continuous medical interventions. Supporting this, Johansson et al. (2012) found that unfamiliar technical sounds and nearby medical procedures, such as emergency treatments or surgical interventions performed on neighbouring patients, contributed to intense emotional distress, fear, and helplessness. These environmental and sensory stressors can significantly impact the emotional state of ICU patients during the post-operative phase, see Figure 17.

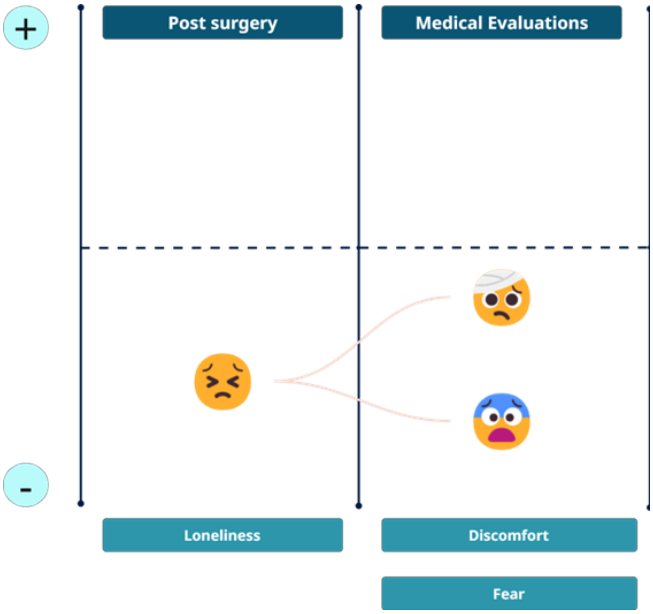


Fig 17: Emotional Responses Reported During Midday

Afternoon to Evening: Stabilization and Recovery

The afternoon to evening phase in the ICU is characterized by ongoing stabilization, careful recuperation, and continuous medical monitoring. During this period, healthcare professionals conduct necessary medical interventions to ensure the patient's condition remains stable and progresses positively. Additionally, this time frame often includes designated visiting hours, allowing family members or loved ones to visit and support the patients.

Patients frequently experience fatigue during this phase, as the cumulative effects of medical procedures, continuous monitoring, and overall stress from their ICU stay become apparent. This fatigue can significantly impact their emotional resilience, making them vulnerable to stress and feelings of exhaustion. Boulanger & McWilliams (2020) note that during the recovery phase, physical exhaustion often leads to emotional fragility, with patients becoming more sensitive to stressors. However, they also highlight that small signs of progress or reassuring interactions with staff can serve as powerful emotional reinforcements.

Despite the challenges, this period also introduces positive emotional experiences, particularly happiness and hope. Visits from family members or loved ones significantly uplift patients, providing emotional reassurance, comfort, and a vital sense of connection to their life outside the ICU. These visits often lead to increased happiness, significantly improving patients' morale and mental well-being. Latour et al. (2022) support this, noting that family-centered interventions are associated with reduced anxiety, lower PTSD-related symptoms, and greater emotional comfort. Moreover, continuous progress in recovery and positive, empathetic interactions with medical staff foster hope for improvement and eventual discharge. These positive emotional responses, triggered by both medical progress and meaningful human connection, offer relief and optimism, which are crucial in supporting patients' emotional strength and psychological recovery during their ICU stay, see Figure 18.

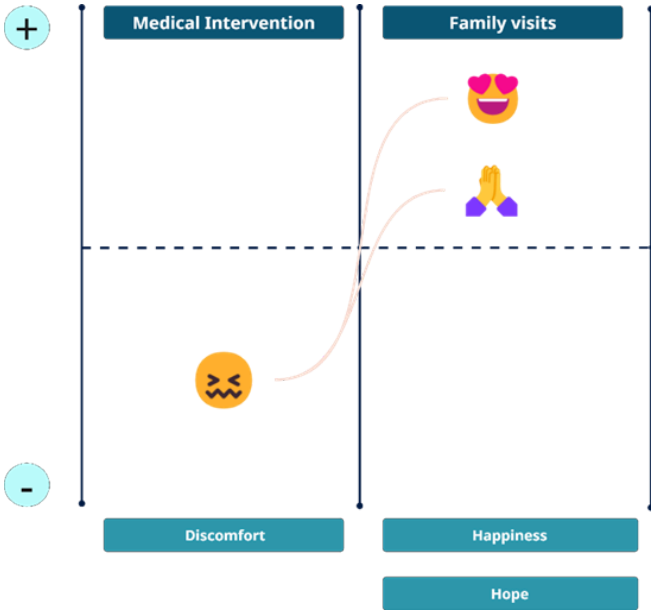


Fig 18: Emotional Responses Reported During Noon

Night: Rest and Reflection

The night phase in the ICU is intended to be a period of rest and physiological recovery, where efforts are made to support sleep and circadian regulation. Common practices during this time include dimming the lights to create a more conducive environment for rest and, when necessary, administering sedatives or pain medication to aid sleep. Despite these efforts, the goal of restful sleep is often challenged by ongoing medical routines, such as nighttime checks by the nursing staff, which may unintentionally disrupt the patient's sleep cycle.

Emotionally, this phase presents a complex landscape. Patients often experience a heightened sense of isolation during the night. The quietness of the ward, limited interaction, and absence of familiar faces can intensify feelings of loneliness and disconnection. The reduced stimulation, although intended to promote calm, may instead leave patients alone with their thoughts, amplifying emotional sensitivity.

Johansson et al. (2012) found that some patients described the nighttime silence as unsettling and even frightening, particularly when they were unable to communicate due to sedation or intubation. Others reported that this silence led to feelings of abandonment, especially when they were awake and alone.

Restlessness is also a frequent emotional response during this time. The inability to fall or stay asleep—due to discomfort, hospital noise, or internal stress—can generate frustration and emotional exhaustion. Johansson et al. (2012) further noted that persistent disturbances from alarms, technical equipment, and medical activity frequently interfered with patients' rest, thereby negatively impacting both emotional and physical recovery. For some, this restlessness accumulated over time, making the night a particularly difficult period in extended ICU stays.

Nonetheless, when pain is well-managed and external stimuli are minimized, the quieter nighttime atmosphere can offer moments of peace. The dimmed lighting and relative reduction in activity may allow some patients to experience a sense of calmness and mental relief. These rare, restful moments can help patients recharge both mentally and physically, supporting their overall emotional resilience and healing process, see Figure 19.

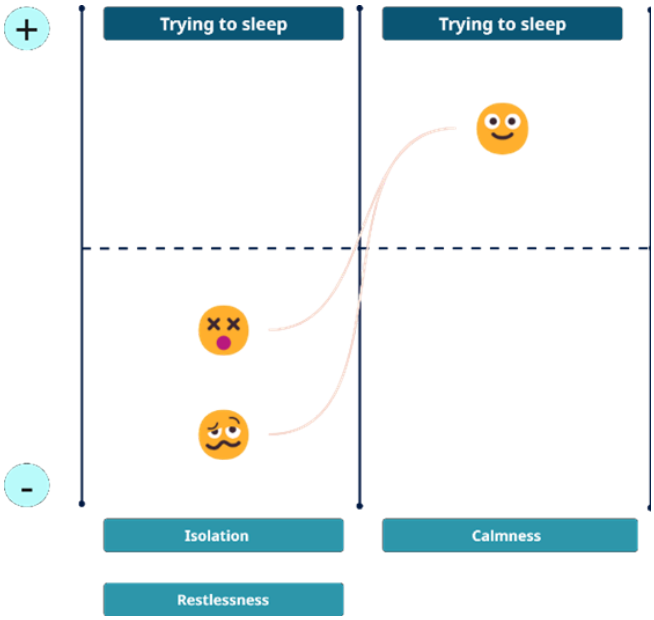


Fig 19: Emotional Responses Reported During Night

3.4 ONLINE SURVEY

To complement the insights gathered from in-depth interviews and broaden the understanding of patient experiences in the ICU, an online survey was conducted targeting healthcare professionals (HCPs) at Leiden University Medical Centre (LUMC). This method was selected due to time constraints that limited participation in interviews, offering a quicker and more flexible alternative for collecting feedback.

The survey, designed to take 5–7 minutes, consisted of multiple-choice and Likert-scale questions prepared by the researcher and it was distributed across the ICU staff. The survey was built on Qualtrics. The main themes explored through the survey are summarized below, while the complete list of survey questions is provided in Appendix D.

- Perceived impact of lighting on patient well-being
- Suggested environmental improvements
- Perceived timing of patient vulnerability
- Control and autonomy in environmental adjustments

A total of 39 respondents completed the survey. The group included 38 nurses and 1 doctor, with 27 female, 10 male, and 2 neutral-gender participants, see Figure 20. The average professional experience among respondents was 16 years, ensuring well-informed and diverse perspectives.

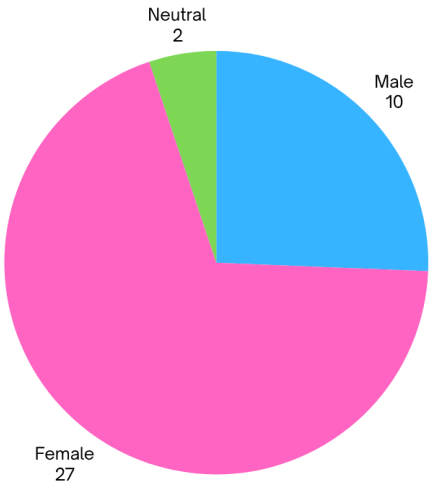


Fig 20: Demographics of survey respondents

Results

Patients' Experiences with Lighting Conditions in ICU Rooms

Participants were asked whether patients seem to experience discomfort or difficulty sleeping due to lighting conditions. Out of 39 participants, 20 selected *Somewhat agree*, 9 selected *Neither agree nor disagree*, 7 selected *Strongly agree*, and 3 selected *Somewhat disagree*, while no participants selected *Strongly disagree*. The results of the user responses are illustrated in Figure 21.

The descriptive statistics of the responses were as follows: Mean = 3.79, Median = 4, and Standard Deviation (SD) = 0.82.

These results indicate that the majority of participants perceived lighting conditions as potentially contributing to discomfort or difficulty sleeping for patients.

Participants were asked about the impact of lighting on patients' mood. Out of 39 participants, 16 selected *Neither agree nor disagree*, 13 selected *Somewhat disagree*, 8 selected *Somewhat agree*, 2 selected *Strongly disagree*, and no participants selected *Strongly agree*. The results of the user responses are illustrated in Figure 22.

The descriptive statistics of the responses were as follows: Mean = 2.77, Median = 3, and Standard Deviation (SD) = 0.83.

This suggests that while lighting may not have a strong visible effect on mood for most patients, it still plays a role in their emotional experience.

Participants were asked about the restlessness or agitation caused by lighting conditions. Out of 39 participants, 24 selected *Neither agree nor disagree*, 8 selected *Somewhat agree*, 6 selected *Somewhat disagree*, 1 selected *Strongly agree*, and no participants selected *Strongly disagree*. The results of the user responses are illustrated in Figure 23.

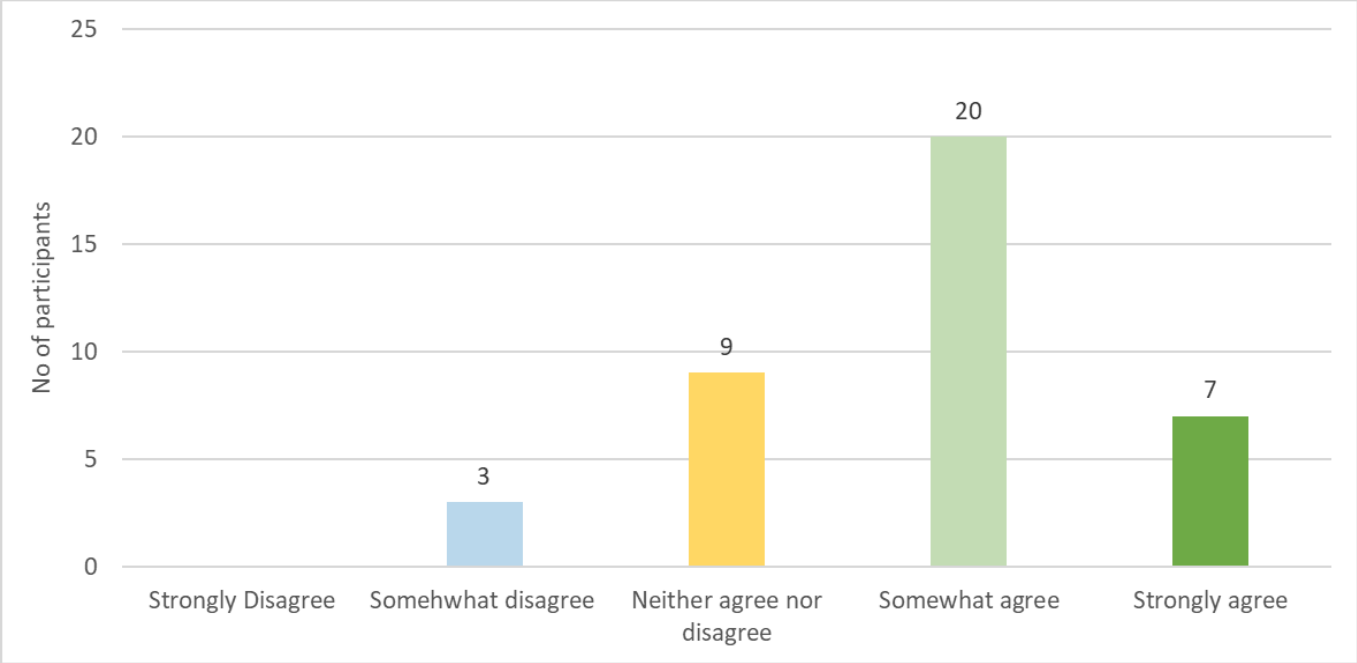
The descriptive statistics of the responses were as follows: Mean = 3.10, Median = 3, and Standard Deviation (SD) = 0.67.

These results indicate that participants were generally neutral regarding the extent to which lighting conditions caused restlessness or agitation, with a small proportion reporting mild agreement or disagreement.

Participants were asked about patients' sense of calmness or relaxation. Out of 39 participants, 25 selected Neither agree nor disagree, 9 selected Somewhat disagree, 4 selected Somewhat agree, 1 selected Strongly disagree, and no participants selected Strongly agree. The results of the user responses are illustrated in Figure 24.

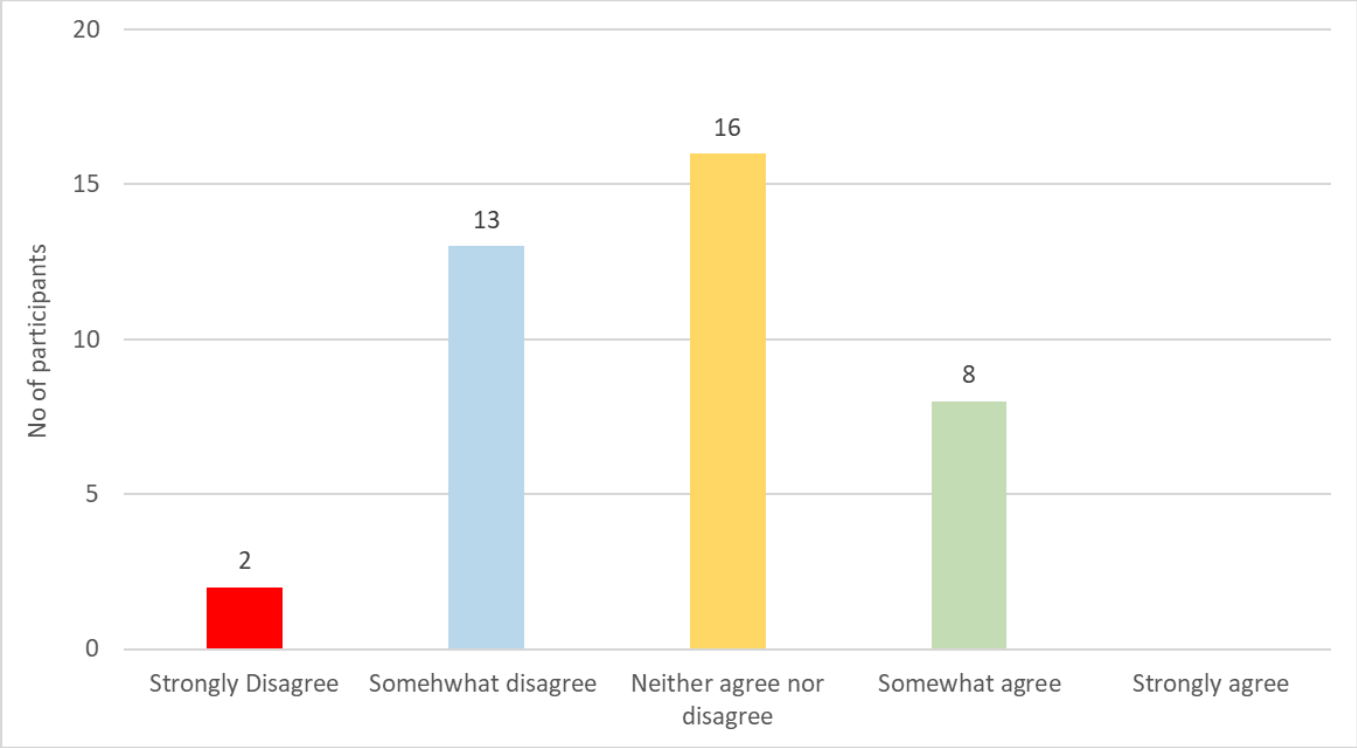
The descriptive statistics of the responses were as follows: Mean = 2.82, Median = 3, and Standard Deviation (SD) = 0.63.

These results suggest that participants were generally neutral regarding the extent to which lighting contributed to a sense of calmness or relaxation, with a small proportion reporting mild disagreement or agreement.



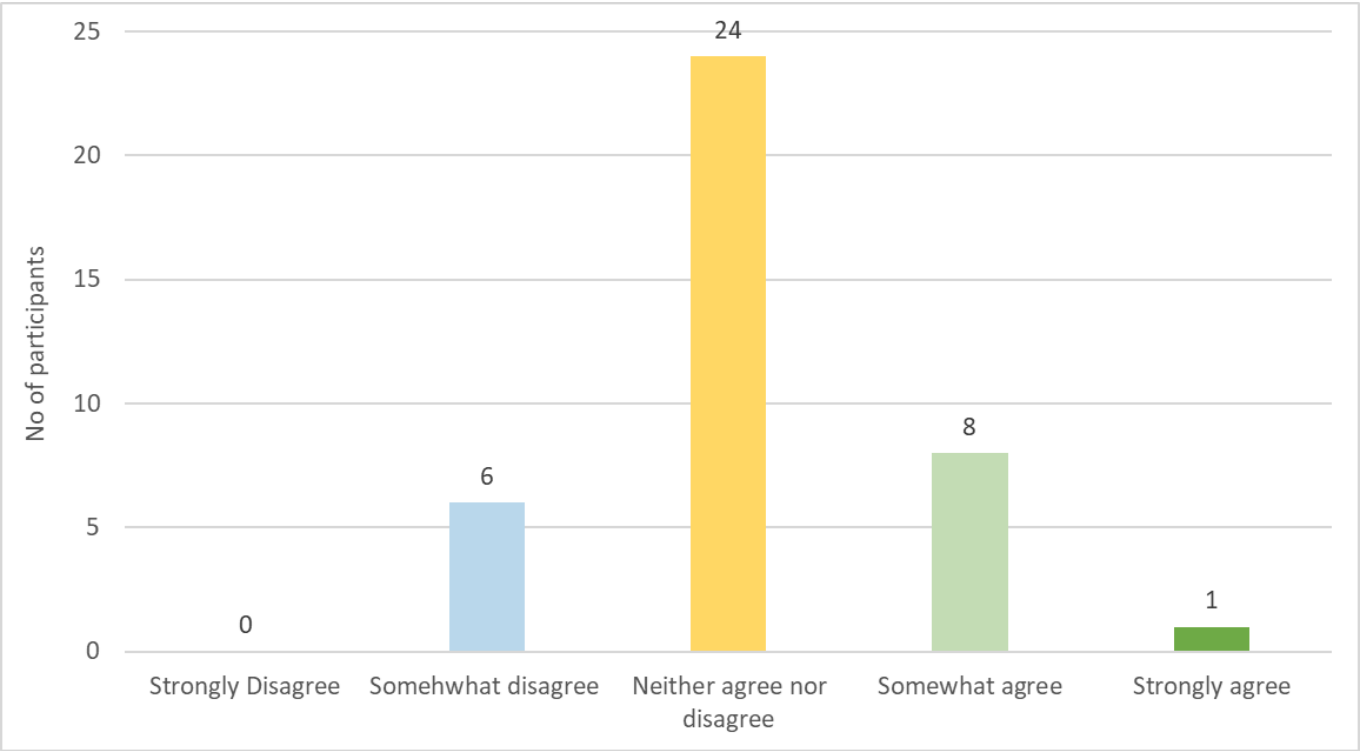
Patients seem to experience discomfort or difficulty sleeping due to lighting conditions.

Fig 21: Results of patients experience discomfort or difficult sleeping due to lighting conditions



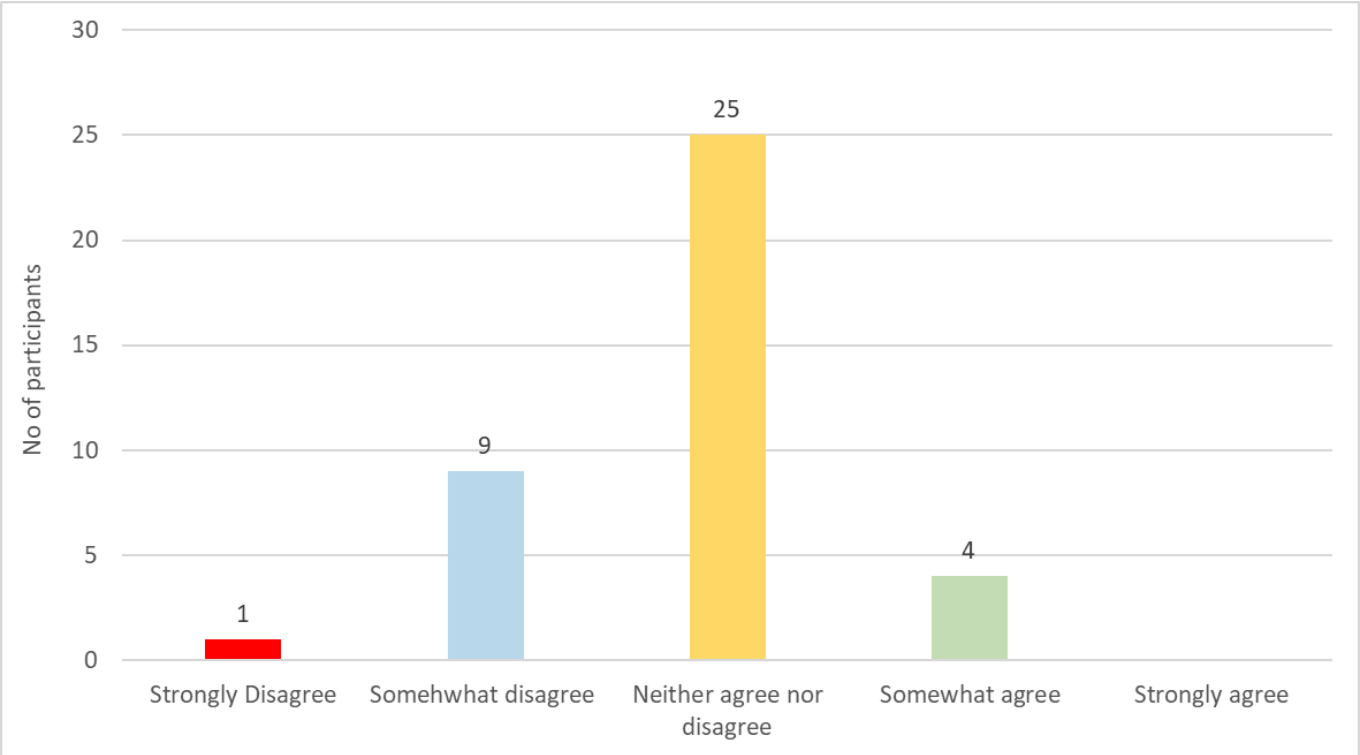
Patients show no noticeable change in mood due to lighting conditions.

Fig 22: Results of impact of lighting on patients' mood



Patients often appear agitated or restless under current lighting conditions.

Fig 23: Results of restlessness or agitation caused by lighting conditions



Patients appear more calm and relaxed under current lighting conditions.

Fig 24: Results of patients' sense of calmness or relaxation

Overall, the majority of healthcare professionals reported a neutral experience regarding lighting conditions and their impact on patient mood and emotions. However, these results also suggest that there is room for improvement. By optimizing lighting conditions to cater to the natural rhythms of patients, such as introducing adjustable lighting or more dynamic systems that better align with circadian rhythms, the ICU experience could potentially be transformed from a neutral emotional state to one where patients feel calmer and more relaxed. This change could significantly improve their emotional well-being and overall recovery process.

Patients' Sensitivity or Vulnerability at Specific Times during a Nurse's Shift

Participants were asked to indicate situations in which they believed lighting interventions could be most beneficial in ICU settings. Since multiple selections were allowed, the total count reflects the number of times each option was selected across all participants. The most frequently selected situation was "*After waking up"* from sedation (n = 38), followed by *"During night-time or early morning hours"* (n = 37), *"When experiencing pain or discomfort"* (n = 34), and During moments of "*isolation or loneliness"* (n = 33). Other commonly selected situations included before or after medical procedures (e.g., intubation, injections, catheterization) (n = 26), when receiving distressing medical news (n = 22), during "*caregiving activities"* (e.g., bathing, dressing changes, repositioning) (n = 20), and During "shift changes or handovers" (n = 15). The least frequently selected situation was when family members leave after visiting hours (n = 7) see Figure 25.

These results suggest that participants identified multiple key moments during the ICU stay where tailored lighting interventions could potentially improve patient comfort, emotional regulation, and overall well-being, particularly in relation to recovery from sedation, pain management, sleep–wake regulation, and emotional distress.

Potential New Lighting Interventions to Improve Patient Comfort in the ICU

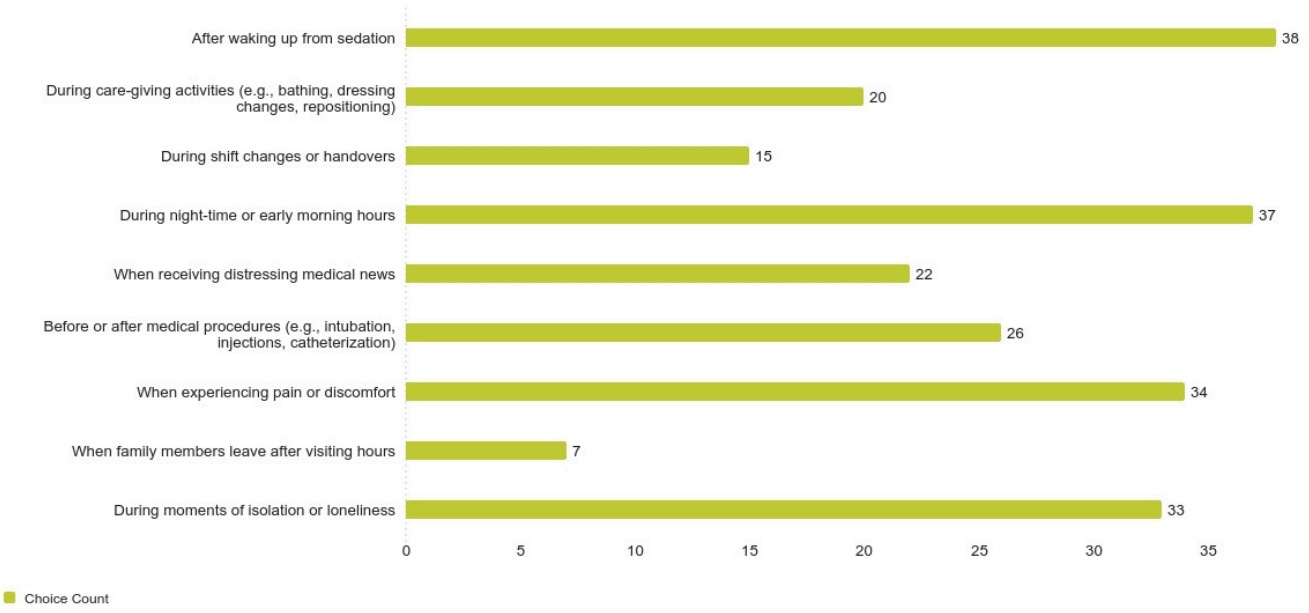
The survey results reveal several key suggestions for improving patient comfort through lighting interventions in the ICU. The most frequently mentioned improvement was *dynamic lighting synchronized with nature's time*, cited by 15 respondents.

This approach emphasizes aligning the artificial lighting system with patients' natural circadian rhythms, adjusting both light intensity and color temperature to mimic the natural progression of daylight. Such synchronization is expected to support patients' sleep-wake cycles, promote better rest, and contribute to improved recovery by providing a lighting environment that is more natural and less disruptive.

In addition, light dimming features were highlighted by 7 respondents, indicating the importance of enabling gradual adjustments to lighting intensity. This capability would allow for softer transitions, particularly during nighttime, helping patients rest more comfortably without being exposed to harsh, bright illumination.

A group of respondents also suggested different correlated color temperature (CCT) during the day and darker lighting at night (6 respondents). This approach involves maintaining brighter, stimulating lighting during daytime hours to promote alertness and switching to dimmer, warmer lighting in the evening to foster relaxation and prepare for sleep.

Lastly, architectural changes were suggested by 3 respondents, referring to potential structural modifications that could enhance natural light exposure or improve the simulation of daylight through artificial means. Additionally, 10 responses were grouped under others, capturing a variety of miscellaneous suggestions that did not fall into the primary categories identified.



Specific times during a nurse shift when patients seemed sensitive or vulnerable

Fig 25: Results of Patients' Sensitivity or Vulnerability at Specific Times during a Nurse's Shift.

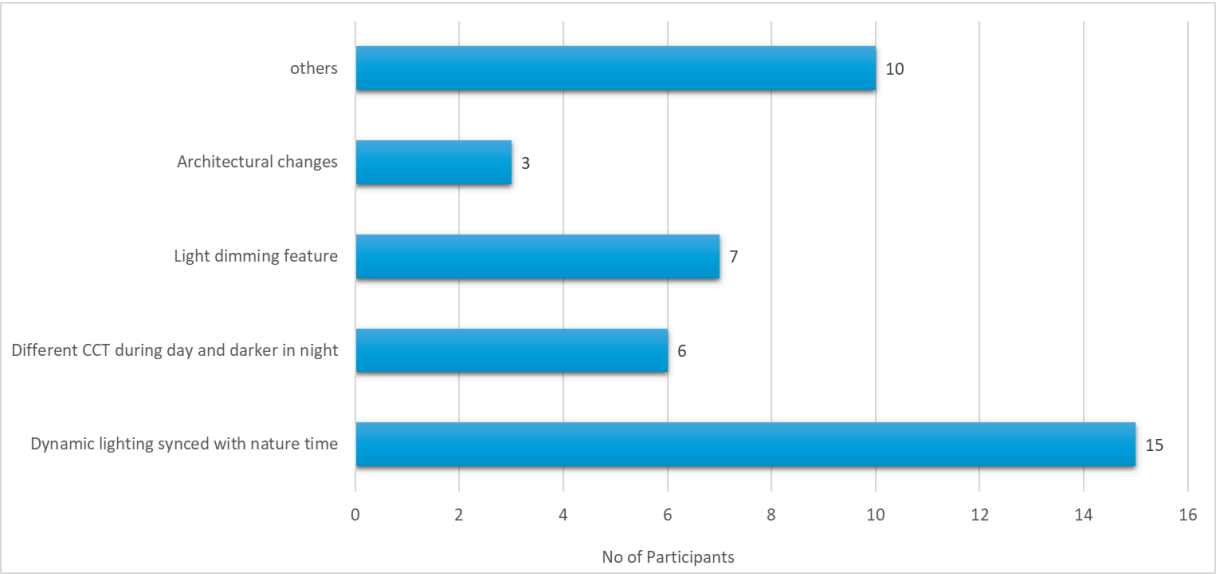
Collectively, these results indicate that dynamic, adaptive lighting solutions—particularly those that reflect natural light cycles—are perceived as highly valuable for enhancing patient comfort and supporting their physiological needs in the ICU environment. The results of the user responses are illustrated in Figure 26.

Control Over Lighting Intervention

The survey results on who should have the ability to control the potential lighting intervention in the ICU indicate that the majority of respondents believe both patients and staff should have the ability to adjust the lighting. This was the most popular choice, with 27 respondents selecting this option. The idea of providing both patients and staff with control aligns with enhancing patient comfort while ensuring that healthcare professionals can make necessary adjustments for medical procedures.

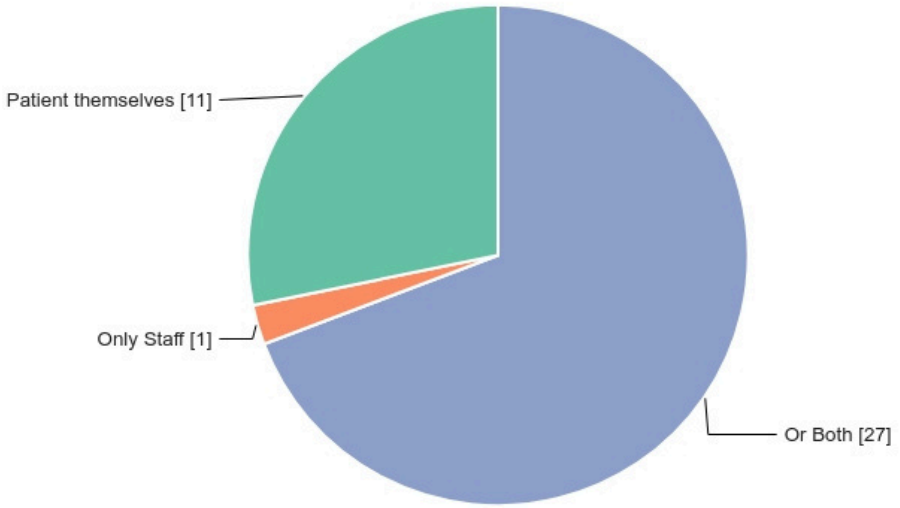
A smaller portion of respondents (11) felt that patients themselves should have the ability to control the lighting. This suggests that empowering patients with some control over their environment could contribute positively to their emotional well-being, as patients often experience a lack of autonomy in the ICU. Only 1 respondent indicated that only staff should have control over the lighting. This option highlights the importance of medical oversight in certain situations but is less favoured compared to shared control between patients and staff, see Figure 27.

The data suggests that the most effective approach would be a system that allows both patients and staff to adjust the lighting, providing flexibility and enhancing the overall ICU experience for patients while maintaining necessary medical oversight.



What could be the potential new lighting intervention.

Fig 26: Results of Potential New Lighting Interventions to Improve Patient Comfort in the ICU



Who should have the ability to control this potential lighting intervention?

Fig 27: Results of Control Over Lighting Intervention

The framework shown in Figure 28 represents the overall results derived from the interviews and surveys conducted with healthcare professionals regarding the factors affecting sleep in ICU patients. It highlights the key areas of Environmental Factors, Routine Care, and Emotions, all of which contribute to the sleep disturbances and overall well-being of patients in the ICU.

3.5 CONCLUSION: PROBLEM STATEMENT

Insights gathered from the interviews and online survey provided valuable clarity about the emotional experiences and environmental challenges faced by patients in the ICU. Findings showed that the current patient experience tends to be emotionally neutral or even negative, primarily driven by certain aspects of their environment. Patients were observed to be particularly vulnerable upon waking from sedation, a moment characterized by fear, anxiety, and significant disorientation. The transition from sedation not only leaves patients physically uncomfortable due to sensations like thirst, dry mouth, or pain, but also emotionally fragile due to the uncertainty about their surroundings.

An important theme identified was patients' pronounced lack of control over their environment. Nurses frequently emphasized that patients' inability to adjust basic elements such as lighting or sound significantly contributes to feelings of helplessness and emotional distress. This limited autonomy greatly affects the psychological well-being of patients, intensifying their emotional vulnerability and reinforcing their dependence on medical staff and equipment.

Additionally, patients in the ICU often struggle with differentiating day from night due to insufficient natural light and the continuous presence of artificial lighting. This disrupts their natural circadian rhythms, resulting in disrupted sleep patterns and increasing feelings of discomfort and confusion. Such misalignment severely affects their recovery process and exacerbates their emotional struggles.

To foster a more positive ICU experience, it is crucial to address these identified environmental stressors. Specifically, providing patients with greater control over their immediate surroundings, especially regarding adjustable lighting systems aligned with natural daylight cycles, could significantly alleviate feelings of fear, anxiety, and helplessness.

Based on these insights, the following problem statement has been formulated:

"ICU patients require an environment that reduces emotional distress by providing a sense of control, comfort, and clear day-night orientation, thereby reducing feelings of anxiety, fear, loneliness, and disorientation during their ICU stay."

In the following chapters, we will delve deeper into patient emotions, informing our approach to addressing this problem and creating effective design solutions for an enhanced patient experience.

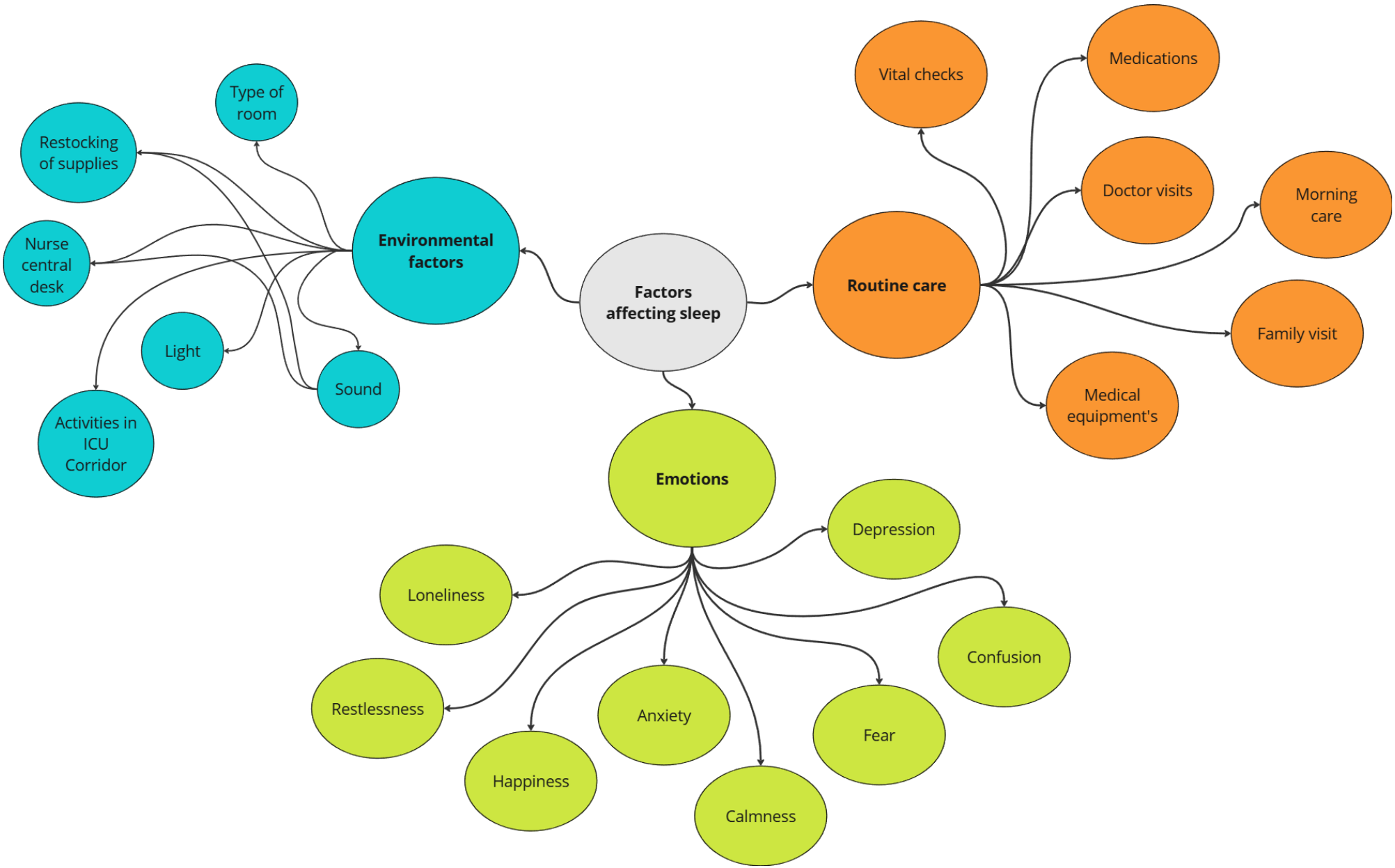


Fig 28: Framework Illustrating Key Insights from Interviews and Surveys

4.

DESIGN VISION

This chapter brings together the conceptual groundwork and creative ideation that informed the developme-nt of a patient-centered intervention for ICU environments. It first outlines a clear design vision derived from contextual insights, emphasizing the psychological and environmental challenges faced by patients. Using a structured 5W1H approach, key design questions and criteria were defined to ensure the intervention aligns with real needs, such as restoring circadian rhythms, enhancing emotional comfort, and promoting patient autonomy.

The chapter then transitions into the ideation phase, employing co-creation techniques with fellow design students to generate and refine solution concepts. This collaborative and iterative process explored a wide range of possibilities, which were then filtered and evaluated using a feasibility-impact matrix. Ultimately, two promising directions emerged: the Collapsible Light Module and the Smart Goggles, each addressing all aspects of the identified design criteria. These outcomes set the foundation for further development and prototyping.

4.1 5W AND 1H

In the intensive care unit (ICU), patients face unique environmental challenges that can significantly impact their recovery and psychological well-being. To systematically address these issues, I have employed the 5W and 1H method—What, Why, When, and How—to thoroughly analyse the problem and develop targeted interventions. This method helps in identifying the key factors contributing to the patient's stress and isolation, understanding the critical times when interventions are most needed, and formulating strategic questions that lead to innovative design solutions.

What?

Our analysis in Chapter 4 on the ICU environment revealed several factors contributing to negative psychological stress among patients. Notably, the absence of natural light makes it difficult for patients to distinguish between day and night, severing their connection to the natural world. Healthcare professionals also report that patients cannot currently control basic environmental conditions, such as lighting, within their rooms.
In response to these challenges, our initiative aims to foster a connection to nature, enhance positive emotional responses, and provide patients with the ability to exert control over their environment.

Why?

Interventions are essential for ICU patients to either help them escape from their state of isolation or prevent them from delving further into it. The continuous experience of negative emotions such as frustration, loneliness, discomfort, shame, panic, and confusion significantly challenges their ability to stay positive. This not only undermines psychological well-being, leading to heightened anxiety and depression, but also extends hospital stays. Addressing these emotional and psychological stresses is critical not only for the mental and emotional health of the patients but also for reducing the overall time they spend in recovery in the ICU.

When?

Stress typically emerges when patients begin to regain consciousness as sedation is tapered off. At this point, patients often find themselves disoriented, not fully aware of their surroundings. This issue is exacerbated by the absence of familiar faces immediately after awakening, which can profoundly impact their mental state. Additionally, inadequate lighting throughout the day further complicates their ability to orient themselves and maintain a connection with the natural day-night cycle, adding to their stress and disorientation. In response to these challenges, it was decided to facilitate a smoother transition for patients waking in the morning or preparing to sleep in the evening. This involves using lighting stimuli designed to evoke positive responses and promote restful sleep.

How?

Taking into consideration the various challenges identified, a pivotal design question was formulated:

"How can we design an interactive system that enhances calmness, reduces emotional stress, and creates restorative environments that align with the Circadian rhythm of ICU patients?"

This question guides the development of solutions that aim to realign patients' biological clocks with their environment, enhancing their recovery process. It serves as a foundation for the subsequent steps in the design process, including the generation of ideas and the validation of proposed solutions, to ensure they effectively support the well-being of ICU patients.

4.2 CRITERIA TO BE FULFILLED

In designing environments conducive to recovery, especially in the intensive care unit (ICU), it is essential to prioritize specific criteria that address the unique needs of patients. These criteria are developed to combat the inherent stressors of the ICU setting and to foster a healing atmosphere that can significantly influence patient outcomes. The following criteria focus on reducing psychological stress, connecting patients to their surroundings in meaningful ways, and giving them control over their environment. Each criterion is designed with the goal of transforming the ICU into a space where patients can recover more effectively and comfortably. By addressing these fundamental needs, our design solutions aim to enhance the overall well-being of patients, facilitating a faster and more pleasant recovery process. The subsequent sections will delve into each criterion in detail, outlining how they contribute to our overarching goal of improving patient care in critical environments.

Criterion 1: Reduce emotional stress and enhance calmness

A fundamental criterion for my design solutions in the ICU is to reduce emotional stress and enhance calmness among patients significantly. This objective addresses the direct impact that a stressful and chaotic environment can have on patient recovery. Stress reduction is aimed at alleviating common negative emotions experienced by ICU patients, such as anxiety, confusion, and depression, which can impede the healing process. Simultaneously, enhancing calmness involves creating an environment that supports relaxation and mental peace, helping patients to maintain a positive mindset crucial for recovery. This criterion is crucial for developing interventions that provide comfort to patients in their vulnerable states and step up their recovery by nurturing a peaceful and supportive environment.

Criterion 2: Provide day-night orientation

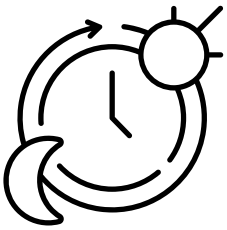
The second essential criterion is to provide day-night orientation for patients. This connection is crucial in helping patients maintain a sense of orientation, which is disrupted in the ICU environment. By integrating elements that allow patients to perceive the passage of time and feel a connection to a specific place, we can significantly reduce feelings of disorientation and alienation. This may involve the use of artificial lighting to mimic the day-night cycle, and visual cues that reflect the outside world, enhancing patients' awareness and helping them stay grounded. Establishing this connection is key to improving patient well-being by fostering a more familiar and less disconcerting environment.

Criterion 3: Control Over the Environment

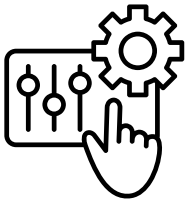
Granting patients control over their environment is a critical criterion for our ICU design solutions. Empowering patients with the ability to adjust their surroundings according to their preferences plays a significant role in enhancing their comfort and autonomy, which can help tailor the environment to suit individual needs and preferences. Providing such control helps mitigate feelings of helplessness and fosters a sense of normalcy and personal space within the clinical setting. Enabling patients to influence their environment not only improves their comfort but also positively impacts their mental health and overall recovery process.

See Figure 29 for a visual representation of the three criteria.

Reduce emotional stress and enhance calmness



Provide day-night orientation



Control over the environment

Fig 29: Three criteria's to be fulfilled by future intervention

4.3 CO-CREATION SESSION

Brainstorm

The next phase involved a brainstorming session, utilizing the collective creativity and diverse perspectives of design students from various specializations within Industrial Design Engineering. This session, rooted in collaborative principles, was guided by methodologies from Katrina Heijne's "Road Map for Creative Problem-Solving Techniques" (Heijne & Van Der Meer, 2019).

We gathered six participants—four males and two females—with an average age of 23. Their academic focuses were distributed among three tracks: three in Integrated Product Design, two in Design for Interaction, and one in Strategic Product Design. The session was structured around two main phases: Idea Finding and Solution Finding, each comprising three stages: Diverging, Reverging, and Converging. Each stage lasted approximately 20 minutes, ensuring a thorough exploration and refinement of ideas.

The session kicked off with a brief introduction by me, where I set the context by presenting my findings and the central problem statement. Following a concise 10-minute Q&A period, the participants gained a clear understanding of the issues at hand and were eager to begin the creative process. A co-facilitator, also a design student, helped in steering the session, ensuring that the collaborative efforts were both productive and insightful.

Fig 30: Participants performing brainwriting activity

Fig 31: Participants clustering the ideas into different categories

First Diamond Phase: Idea Finding Summary

The initial phase of idea finding in our co-creation session was brain writing, where we unleashed a wealth of creative proposals, grouped into several thematic clusters: "Nurse/Medical Staff, Visuals, Sensual/Time, AI, Nature, and Who's in Control?". Participants explored a wide range of innovative solutions aimed at enhancing the ICU environment and patient experience. Ideas spanned from integrating advanced technologies for better patient-staff communication and personalized care to incorporating natural and sensory elements that promote relaxation and well-being. The theme of patient autonomy was also prominent, with many suggestions focused on empowering patients to control their environmental settings. This phase was marked by a vibrant exchange of concepts, where the goal was to generate a diverse set of ideas, setting the stage for further refinement in subsequent stages of the brainstorming process. See Figure 32 for the final results from the Hits and dots which is the last step of the first diamond phase.

Transition to Second Diamond: Selection and Refinement

After completing the first diamond phase of idea finding, participants took a well-deserved 10-minute coffee break. This pause not only gave everyone a chance to refresh and regroup but also provided me, as the problem owner, with an opportunity to review the plethora of ideas generated. During this break, I carefully sifted through the diverse ideas, selecting those that were particularly intriguing and held potential for practical implementation. These selected ideas were then communicated to the co-facilitator, who prepared to integrate them into the next phase of the session.

The selected ideas, representative of the initial brainstorming clusters, were chosen based on their innovative approach to solving the identified problems and their feasibility within the ICU environment. This selection process was crucial as it ensured that the subsequent diamond, focused on solution finding, was grounded in the most promising concepts, ready for further exploration and refinement. See Figure 33 for a visual representation of the selected ideas from each cluster.

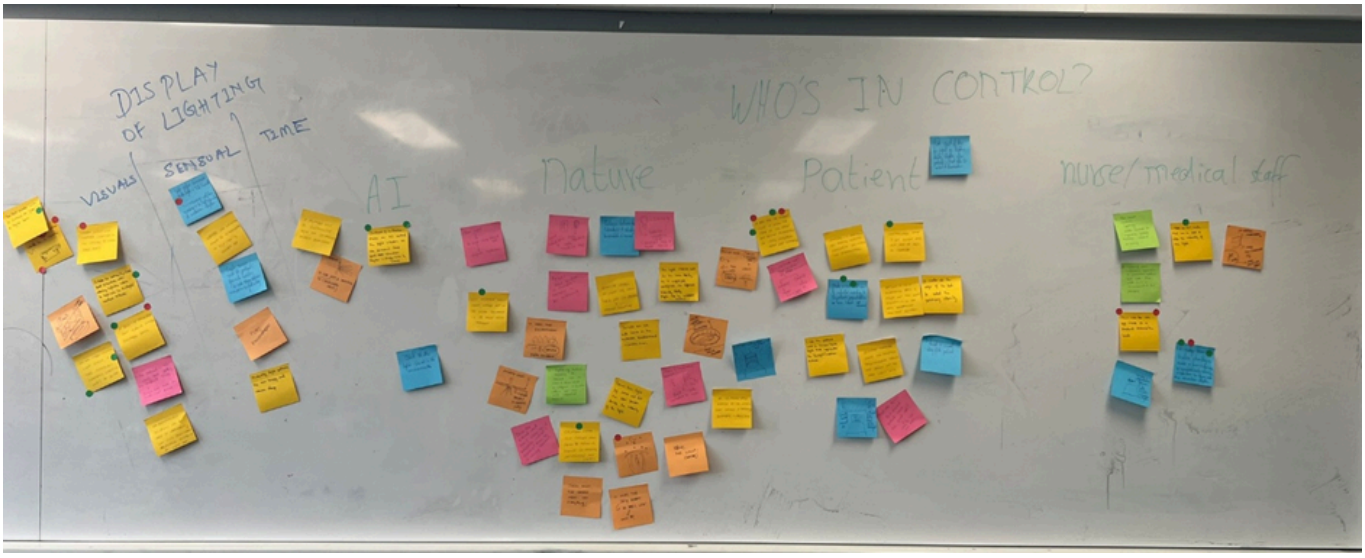


Fig 32: Final results after Hits or dots activity.

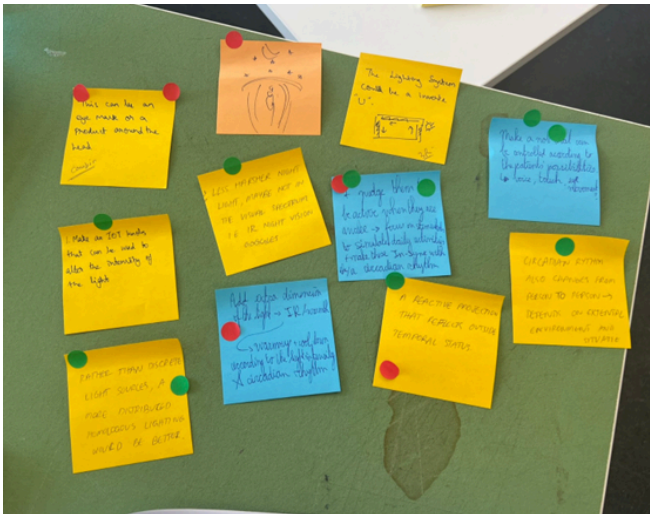


Fig 33: Selected ideas from each cluster for next diamond

Second Diamond Phase: Refinement and Evaluation

The second diamond phase of our design process began with an expansive dive into the ideas generated during the first phase. Participants were tasked with formulating questions that challenged the status quo and explored new possibilities, as depicted in the first image. This step was crucial for diverging thought processes and expanding the scope of potential solutions.

After this initial divergence, the focus shifted towards aligning the generated ideas with the predetermined criteria that had been discussed in previous chapters. As shown in the second image, each idea was evaluated to determine how well it addressed the core objectives of reducing psychological stress, providing a connection to time and place, and allowing control over the environment. This alignment ensured that the solutions not only were innovative but also met the specific needs of ICU patients.

The final step in this phase involved placing the ideas on a 2x2 matrix. This matrix categorized the ideas based on their potential impact on patient outcomes and their feasibility for implementation. The axes ranged from low to high impact and low to high feasibility, allowing us to prioritize ideas that were both impactful and realistically achievable. This strategic placement helped in making informed decisions about which concepts to develop further, ensuring that the most promising solutions were carried forward into the next stages of the design process.

This evaluation phase was critical in ensuring that the ideas not only fostered creativity but were also practical and aligned with the essential goals of enhancing the ICU environment for better patient care. See Figure 34 for the results of the second diamond phase.

4.4 GENERAL WORKFLOW OF THE SYSTEM

The designed system aims to integrate seamlessly into the ICU environment, providing a foundational workflow for enhancing patient care through adaptive lighting. This workflow serves as the basis for any specific concepts such as the Collapsible Light Module System, ensuring that each feature builds upon a standardized operational structure.

System Activation:
The operation begins with the activation of the system via the main power button, setting the stage for subsequent functionalities.

Lighting Initiation:
Once the system is activated, the lighting is initiated by pressing a secondary button, which engages the light features.

Data Integration and Synchronization:
Simultaneously, the system syncs with data from the patient's Fitbit, which includes vital health metrics like heart rate and time-based data. This synchronization is critical for tailoring the lighting adjustments to the patient's natural rhythms and current health needs.

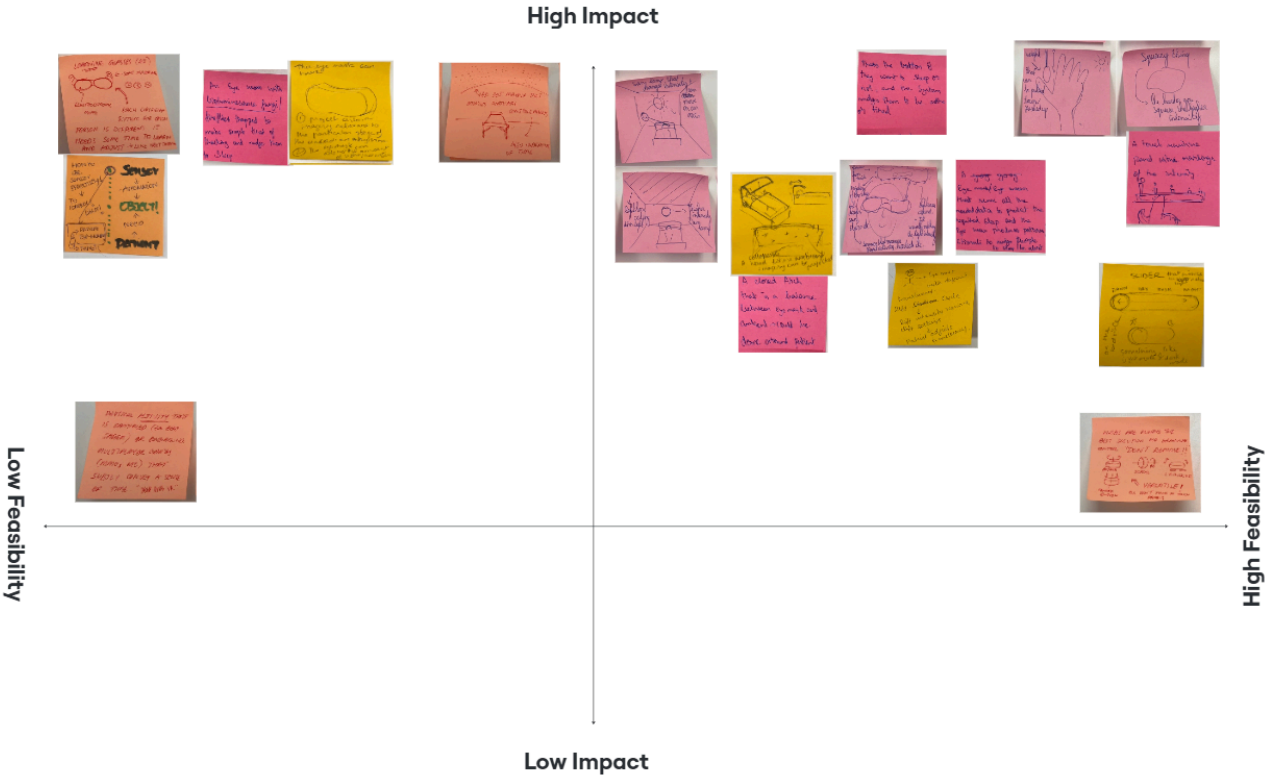


Fig 34: Selected ideas placed on the axes during sequencing activity

Lighting Adjustment Phases:

- Morning Lighting: To simulate a natural sunrise, the system delivers bright light for two hours in the morning (>1000 lux, CCT 6000–7000K) to help reset the patient's internal clock and support circadian alignment (Simons et al., 2019; Prin et al., 2023).
- Evening Lighting: In the evening, the system gradually dims the light to below 50 lux in the final hour, using a warm CCT of 2700–3000K, to gently prepare the patient for sleep and support natural wind-down processes (Nie et al., 2024; Vethe et al., 2021).

Control Features:

- Healthcare Provider Control: Healthcare providers have the ability to manually adjust the lighting intensity at any time through control knobs, allowing for immediate customization based on clinical observations and patient requirements.
- Patient Control: Patients themselves can adjust the intensity of the lighting via user-friendly mechanisms, such as squishy toys, which they can manipulate to change settings. This feature provides patients with control over their environment, promoting autonomy and involvement in their own care process.

Manual Overrides and Adjustments:

The system allows for manual overrides during the day, where both patients and healthcare providers can make immediate adjustments to the lighting based on specific needs or preferences.

This foundational workflow guarantees that each component of the lighting system is geared towards improving patient comfort and advancing health outcomes. It lays the groundwork for specialized implementations that further tailor the patient experience within the ICU.

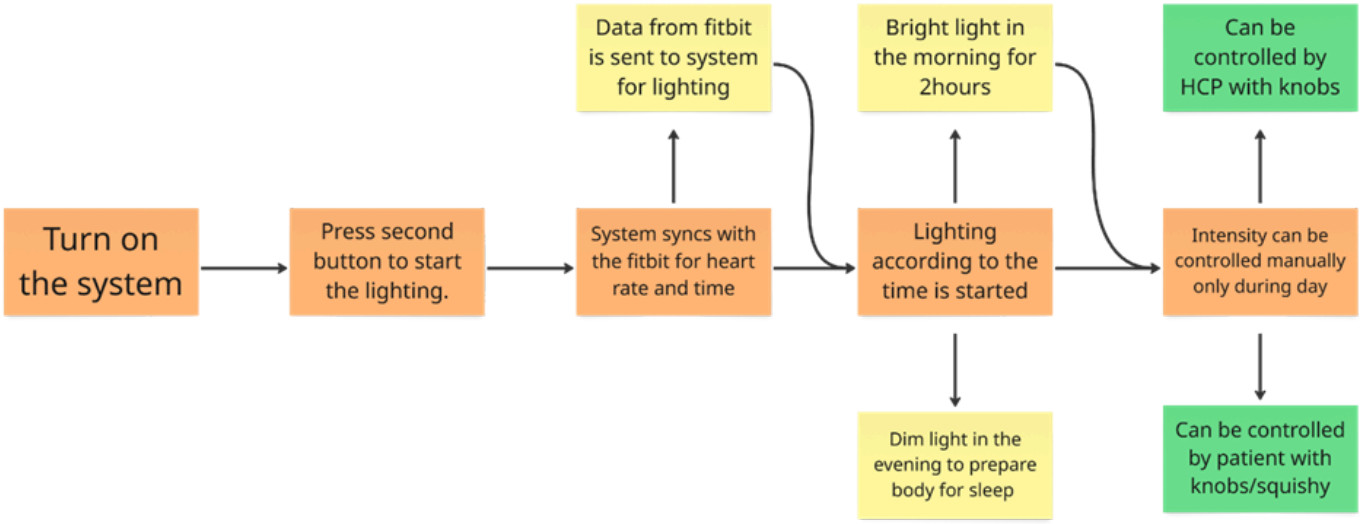


Fig 35: Workflow of the potential intervention system

4.5 RESULTS OF THE CO-CREATION SESSION

With the selection process guided by our 2x2 matrix, focusing on ideas that demonstrated both high impact and feasibility, we proceeded to the next stage of refinement. Drawing on the rich insights from our co-creative session, we began to synthesize and integrate these concepts, aiming to harness the most promising attributes of each. Through this integration, two particularly innovative ideas emerged as standout solutions:

- *Collapsible Light Module*
- *Smart Goggles*

These ideas were developed by combining elements from multiple initial concepts, enhancing their potential to effectively address the identified needs within the ICU environment. This section will explore these refined ideas, detailing how they were inspired and shaped.

4.5.1 COLLAPSIBLE LIGHT MODULE

During our brainstorming session, participants discussed the concept of a collapsible hood or arch designed to provide ambient lighting or project relaxing visual stimuli for patients. While incorporating an additional stimulus was beyond the scope of my project, I adapted this idea to focus solely on delivering ambient lighting. Inspired by the collapsibility of IKEA wardrobe accessories, which are made of cloth for easy folding and storage, I envisioned a similar mechanism for the light module see Figure 36. This module incorporates multiple light components embedded in series within the foldable cloth, allowing it to be easily collapsed and set aside when not in use.

Fig 36: Foldable Wardrobe Accessory from IKEA

To efficiently utilize space, the module is designed to be positioned behind the patient's bed where there is ample empty space. It attaches to the bed's railing with a base that can be easily detached, allowing the module to be removed and stored aside when not needed. This setup ensures minimal interference with medical staff and other equipment.

For control, the module includes two buttons at one end: one to activate the system and another to initiate the lighting, which can be synchronized with a Fitbit device as previously discussed. Additionally, knobs allow healthcare providers (HCP) to adjust the light intensity, a feature validated through interviews and surveys see Figure 37. Recognizing that patients often have limited mobility, I incorporated an innovative feature from the brainstorming session: squishy toys placed where patients rest their hands. Patients can squeeze these toys to adjust the light intensity without needing to reach the module directly.

For the lifting mechanism of the module, various options were considered, and a scissor mechanism was selected for its simplicity and ease of use, ensuring it could be operated without causing any obstruction see Figure 40. To secure the module at a specific height without risk of it descending unexpectedly, I explored several locking mechanisms. The most effective proved to be one similar to those used in baggage handles, simple in design yet highly efficient at maintaining the module's position, see Figure 38.

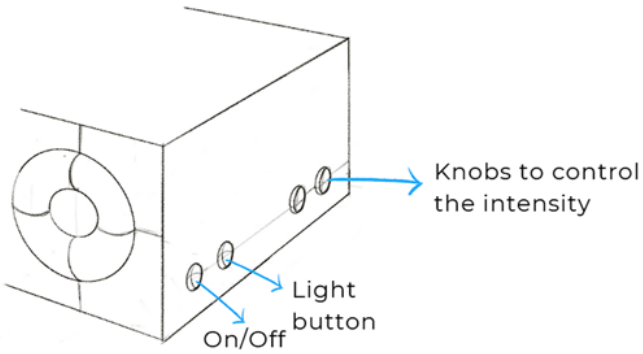


Fig 37: Knobs and Buttons on the device

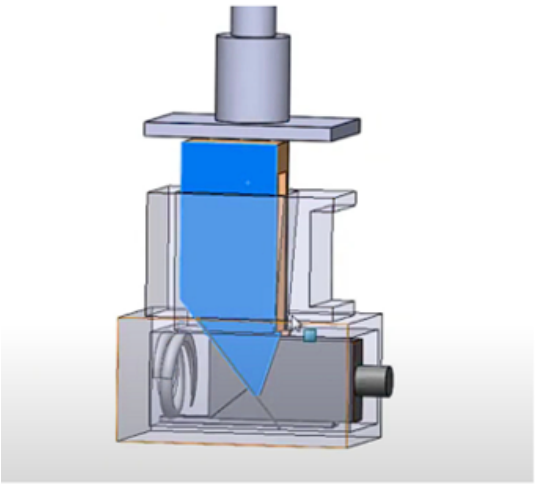


Fig 38: Baggage handle locking mechanism

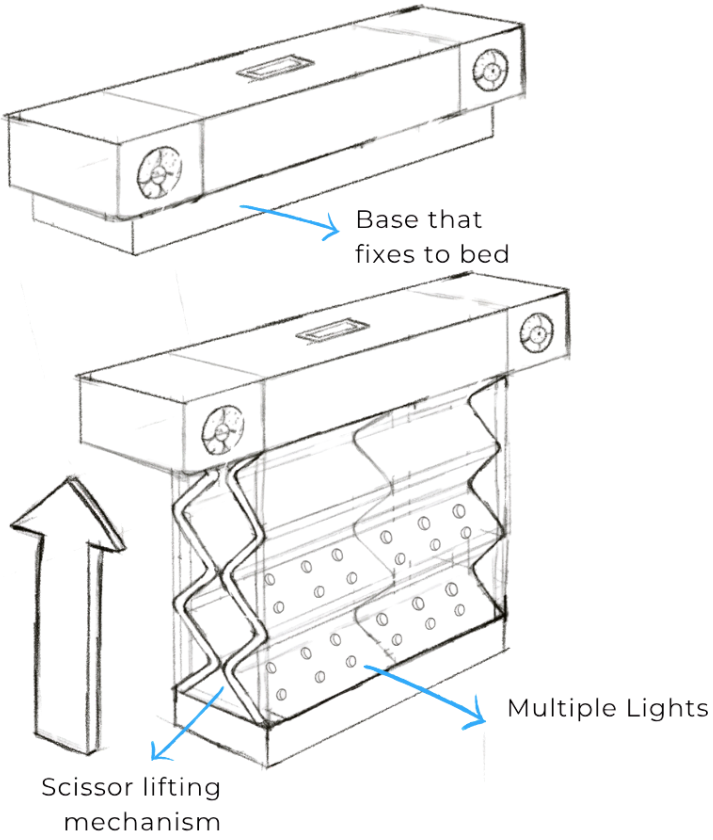


Fig 39: Collapsible light module

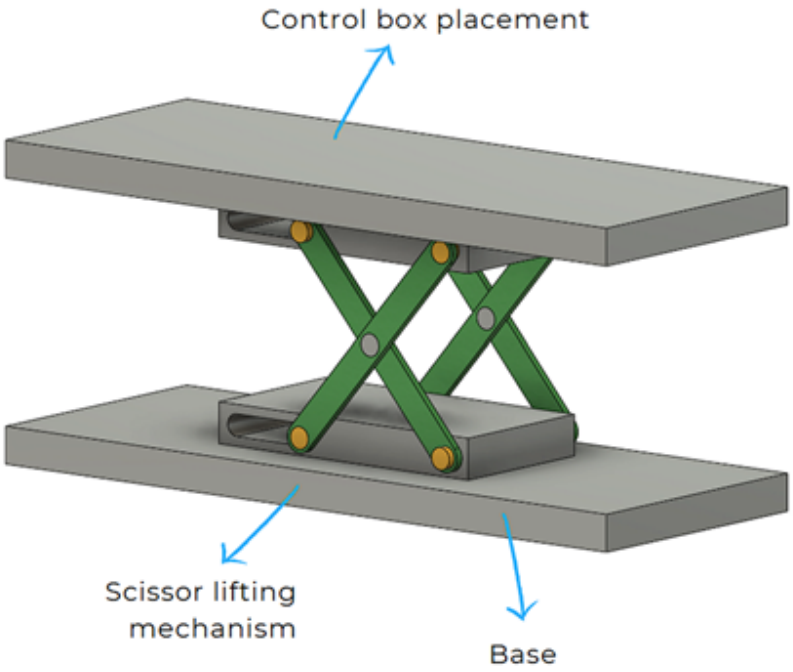


Fig 40: Scissor lifting mechanism

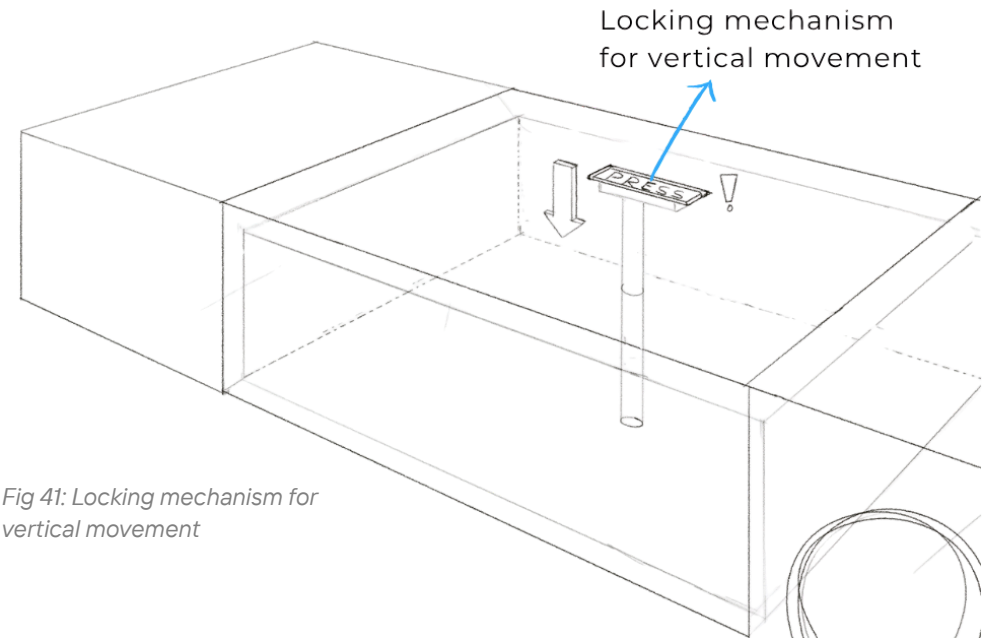


Fig 41: Locking mechanism for vertical movement

4.5.2 SMART GOGGLES

During the creative session, five responses suggested the idea of goggles that would provide visual stimuli, similar to the Apple Vision Pro, to aid in improving the patient's experience. However, upon evaluating the feasibility of this concept, it became clear that it was quite ambitious and challenging to implement in the ICU setting. As a result, I turned to an alternative idea that involved incorporating ambient lighting around the circumference of the goggles. This design concept was inspired by existing products designed to realign sleep cycles, particularly those intended for individuals suffering from jet lag. Many of these products emit blue light, which, while effective for jet lag, was not suitable for our context due to its potential to disrupt circadian rhythms rather than aid in their regulation see Figure 42.

Fig 42: Existing products in the market

Taking inspiration from this, I decided to develop a new design for the goggles, using the frame of snow goggles as the base structure, see Figure 43. This choice was made to ensure durability and comfort while maintaining a functional design. To ensure the goggles would align with the needs of ICU patients, I modified the lens to be translucent rather than opaque, allowing the patient to retain some visibility while still receiving the benefits of the light therapy.

The goggles will feature two adjustable knobs, each with an on/off button, allowing the patient to control the intensity of the ambient lighting. The LED strip will be placed along the top frame of the goggles, with the light directed perpendicular to the wearer's vision, preventing any direct exposure to the eyes and ensuring the light does not cause discomfort or disruption see Figure 44.

Fig 43: Inspiration from Snow Goggle Design

The lighting behaviour of the goggles follows the circadian rhythm adjustment workflow previously outlined, delivering bright light in the morning (>1000 lux, CCT 6000–7000K) and gradually dimming throughout the day, reaching <50 lux with a CCT of 2700–3000K in the evening to support the body's natural sleep–wake cycle. Specifically, the bright light will be activated for two hours each morning at a standard set time, helping to align the patient's circadian rhythm with the natural day-night cycle. To support the goal of re-aligning sleep cycles, the lighting may remain active for up to 9 hours, between 9 a.m. and 6 p.m., even if the patient chooses to rest during the day. This approach aims to gradually adjust the circadian rhythm while allowing flexibility based on individual needs. After 6 p.m., the light will automatically begin to dim, eventually turning off based on the data received from the patient's Fitbit. This approach allows for continuous monitoring and adaptation of the light environment, ultimately aiming to improve the patient's sleep quality and overall well-being during their time in the ICU.

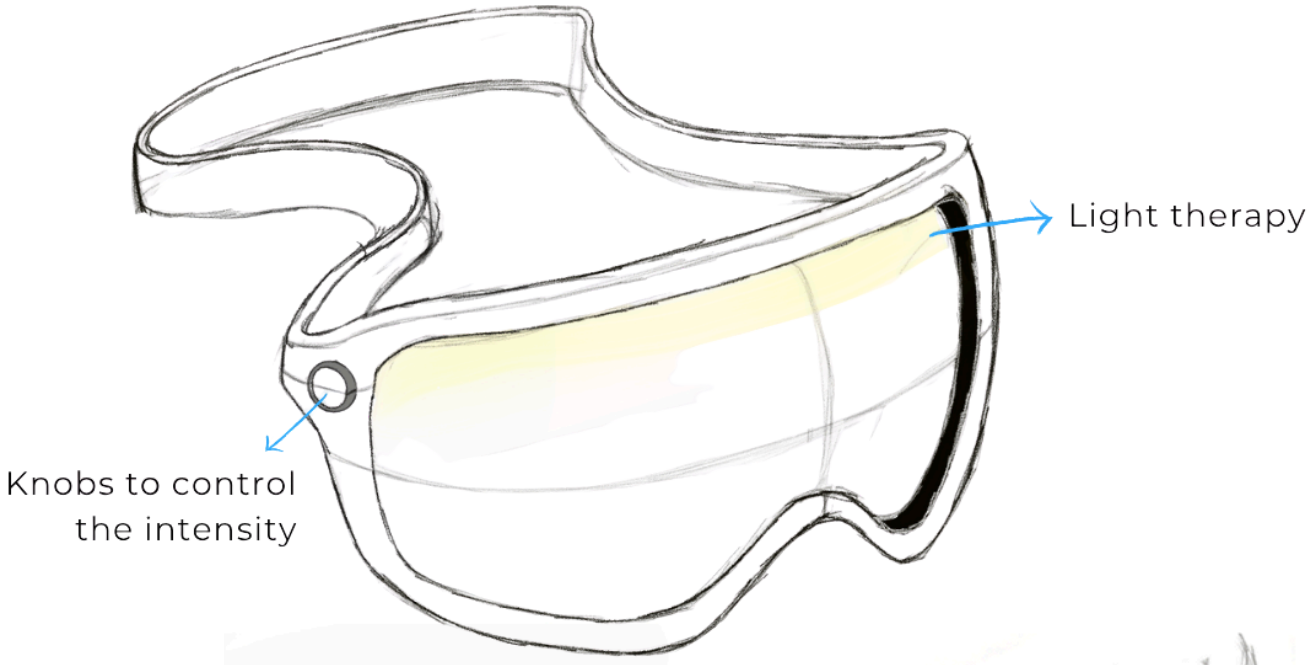


Fig 44: Smart Goggles with knobs

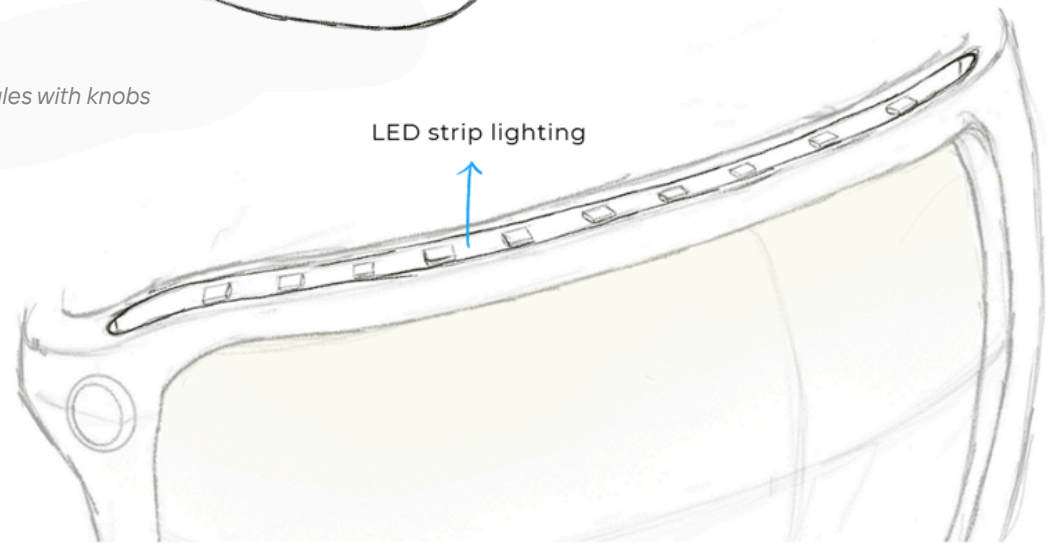


Fig 45: Placement of LED Strip on the Goggles

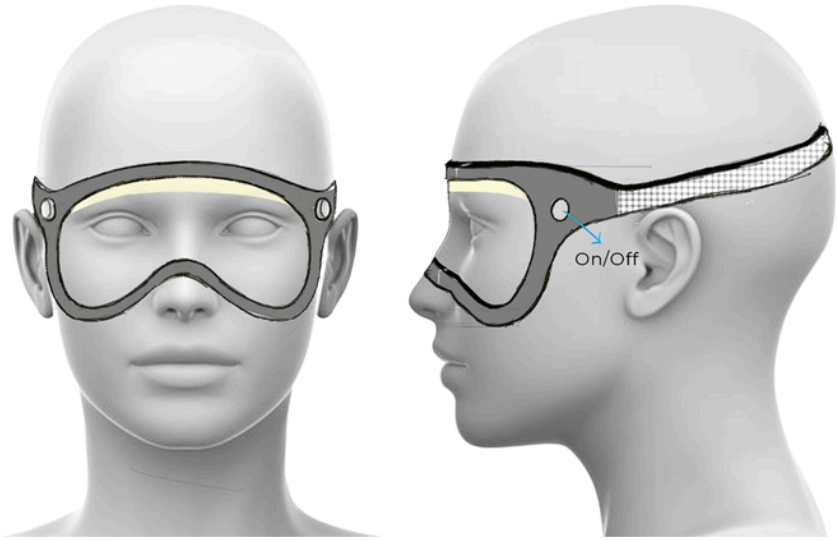


Fig 46: Illustration of Goggle Fit on the Human Face

4.6 CONCLUSION

From this chapter, insights gathered from real patient experiences were effectively translated into actionable design directions. Guided by well-defined criteria, the ideation phase struck a thoughtful balance between imaginative exploration and practical feasibility. The co-creation session proved instrumental in expanding the breadth of ideas and affirming their relevance through input from peers with diverse perspectives.

Among the developed concepts, the Smart Goggles emerged as a particularly promising solution, offering a gentle and non-intrusive approach to light therapy while supporting patient comfort and autonomy. With strong support from the LUMC client, this concept has been selected for further development and prototyping. From this foundation, the next phase of the project will focus on detailing the functionality, integration, and evaluation of the proposed solution within the ICU environment.

5.

DESIGN AND DEVELOPMENT OF INTERVENTION

This chapter outlines the complete development and evaluation of the LumoGlaze system, a wearable circadian lighting intervention designed to support emotional well-being and sleep regulation for patients in critical care environments. The development process integrates technical design, user-centered hardware iterations, and physiological feedback mechanisms through real-time data.

Beginning with the prototyping of core electronics and transitioning into the design of a mobile interface (LumoSync), the system aims to synchronize lighting conditions with individual physiological states using heart rate and sleep data obtained via the Fitbit Web API.

Furthermore, the lighting behavior was tailored using evidence-based RGBW values, grounded in circadian biology and validated through user testing. The physical design of the wearable (LumoGlaze) underwent several ergonomic refinements to ensure comfort and fit.

The chapter concludes with the results of a user study evaluating the system's impact on alertness, relaxation, and comfort, establishing its viability as a personalized lighting intervention for clinical settings.

5.1 SYSTEM ARCHITECTURE AND ELECTRONICS

The initial prototype was built using discrete, low-power components selected for their accessibility, compatibility with wearables, and ease of integration. The design aimed to maintain a balance between simplicity and functional flexibility, enabling both manual operation and automatic operation. The key components used are mentioned below

ESP32 Microcontroller

At the heart of the system is the ESP32, a dual-core microcontroller chosen for its:

- Built-in Bluetooth Low Energy (BLE) capability for wireless communication.
- Sufficient I/O pins for peripheral connections.
- Compatibility with Arduino-based development environments for rapid prototyping.

The ESP32 is responsible for:

- Receiving and processing BLE commands
- Controlling LED brightness through PWM (Pulse Width Modulation).
- Managing user inputs.
- Interfacing with external sensors (e.g., heart rate monitors).

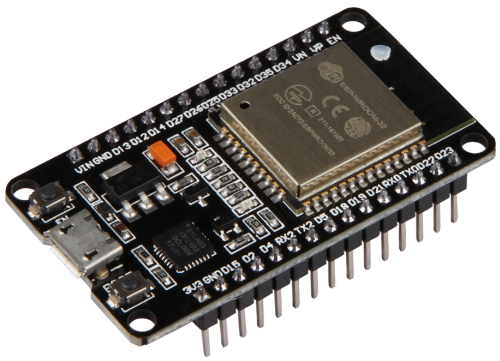


Fig 47: ESP32 micro-controller

MOSFET Driver Circuit

To efficiently control the LED's power, a logic-level N-channel MOSFET was implemented. Key roles include:

- Switching high-current loads based on low-power PWM signals from the ESP32.
- Enabling smooth dimming transitions.
- Maintaining thermal stability during higher brightness operations.

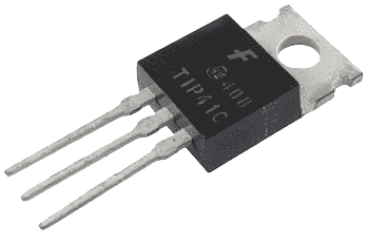


Fig 48: MOSFET Driver

Warm White LED Module

A 5V warm white LED served as the primary light source. It was selected for its:

- Appropriateness for circadian-supportive lighting.
- Visual comfort during extended exposure.
- Simplicity for evaluating baseline light responses in user testing.

Fig 49: Warm white LED

Rotary Encoder (with Push-Button)

For manual brightness control, an incremental rotary encoder was included. Features:

- Allows fine-tuned brightness adjustments.
- Provides tactile feedback.
- Includes an integrated push-button used for power toggling and mode switching.

Fig 50: Rotary Encoder

Slide Switch for Mode Selection

A 3-pin slide switch was added to toggle between:

- Manual Mode: User adjusts brightness using the rotary encoder.
- Automatic Mode: Light intensity is controlled based on predefined rules involving time and physiological signals (e.g., heart rate, sleep phase detection).

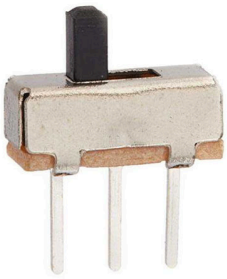


Fig 51: Three pin Slide switch.

5.1.1 FIRST HARDWARE PROTOTYPE AND BREADBOARD ASSEMBLY

The initial hardware prototype was assembled on a standard breadboard, chosen for its flexibility and suitability for rapid prototyping. This setup allowed efficient testing, easy reconfiguration, and straightforward debugging of the lighting intervention system.

Breadboard Layout and Power Distribution

All components were arranged for signal clarity, mechanical stability, and accessible testing points. The breadboard's side power rails were used to distribute 3.3V, 5V, and ground lines sourced from both the ESP32 development board and an external regulated power supply.

- ESP32 Placement: Centrally positioned with accessible I/O pins on both sides.
- Interconnections: Made using male-to-male jumper wires to ensure secure and modular signal routing.

Control Interface Connections

Slide Switch (Manual/Auto Mode Toggle)

- Connected to: GPIO 26
- Configuration:
  - One terminal to ground.
  - One terminal to digital input with internal pull-up resistor enabled via software.
- Function: Switches between manual control (rotary encoder) and automatic mode (time or physiological input).

Rotary Encoder

- CLK and DT Pins: Connected to GPIO 32 and GPIO 33.
- Push-Button: Connected to GPIO 25.
- Edge Detection: Stabilized using pull-up resistors for clean signal transitions.
- Functionality: Adjusts brightness manually and toggles system states when pressed.

LED and MOSFET Driver Circuit

- MOSFET Gate: Connected to GPIO 18 and GPIO 17 of the ESP32 to receive PWM signals for brightness control.
- Source: Tied to ground.
- Drain: Connected to the negative terminal of the LED.

The positive terminal of the warm white LED was powered directly from a regulated 5V DC external supply. To ensure a common electrical reference, the ground of the ESP32 and the external power supply were tied together on the breadboard's ground rail.

A detailed wiring schematic of this configuration is presented in Figure 52, illustrating the complete connections and signal pathways.

While the first prototype successfully demonstrated basic functionality, several limitations were identified during testing that highlighted the need for further refinement in both hardware design and control flexibility. This led to the development of a second iteration, incorporating a more compact and advanced architecture.

5.1.2 SECOND HARDWARE ITERATION

Following the functional validation of the first prototype, a second hardware iteration was developed to address its physical and technical limitations. This new version incorporated the TinyPICO microcontroller and SK6812 GRBW addressable LEDs, replacing the earlier ESP32 and discrete white LED setup. The revised system aimed to deliver a more compact, visually dynamic, and integrated lighting solution, better suited for wearable and therapeutic applications.

Motivation for the Transition

Several limitations emerged during initial testing that justified this hardware redesign:

Limited Color Range

The original prototype used static warm white LEDs controlled via MOSFETs, offering minimal control over color temperature and spectrum range. It lacked the ability to simulate sunrise/sunset transitions or dynamic color changes.

Wiring Complexity

The reliance on external power control components (MOSFETs, voltage dividers) resulted in bulky wiring, increasing the risk of disconnections and reducing the system's portability.

Form Factor Constraints

The ESP32 development board and discrete components occupied considerable space, making it impractical for wearable applications or compact bedside use.

Lack of Addressability

The previous LED setup offered only global control over brightness and no pixel-level modulation, limiting the ability to create engaging, dynamic, or gradual visual transitions.

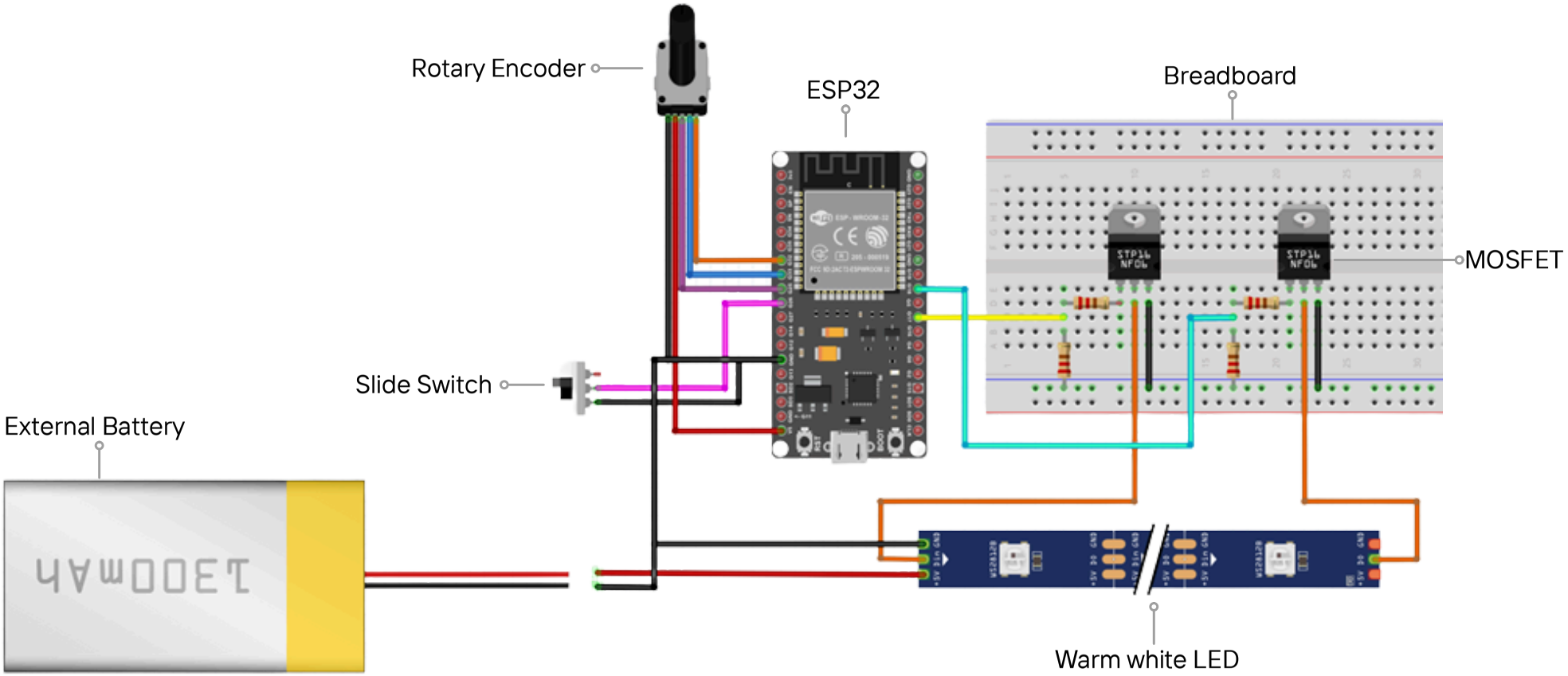


Fig 52: Wiring Schematic of the connections.

Advantages of the New System

To overcome the aforementioned challenges, the second prototype utilized:

- TinyPICO microcontroller (ESP32-based, ultra-compact).
- SK6812 GRBW LED strips (addressable RGB + white).

Compact and Integrated Design

TinyPICO offers the full capabilities of the ESP32 in a significantly smaller form factor, with built-in LiPo battery management, eliminating the need for additional charging circuitry.

Advanced Lighting Control

The SK6812 GRBW LEDs provide individual control over red, green, blue, and white channels per pixel, allowing precise tuning of:

- Color temperature (CCT).
- Brightness.
- Wavelength composition for light therapy simulation.

Simplified Circuitry

The transition removed the need for MOSFETs and analog modulation circuits. All control was shifted to digital protocols using libraries such as FastLED or Adafruit NeoPixel, significantly reducing circuit complexity.

Enhanced Visual Output

Addressable LEDs enabled:

- Smooth gradients.
- Animated transitions.
- Color effects.

These features are essential for simulating natural lighting patterns (e.g., sunrise, sunset) and improving the user experience.

Software and Integration Continuity

Despite the hardware overhaul, the core software architecture remained consistent. Only minimal adjustments were required to support the new lighting system.

Firmware changes included:

- Adopting functions such as setPixelColor() and setBrightness() for digital LED control.
- Handling GRBW color formats appropriately.
- Maintaining Bluetooth Low Energy (BLE) compatibility with the Flutter-based mobile app.

The updated wiring configuration for the TinyPICO and SK6812 setup is illustrated in Figure 53, detailing all key signal paths and power distribution.

5.2 INTEGRATION AND CONTROL: THE LUMOSYNC INTERFACE

5.2.1 PHYSIOLOGICAL DATA INTEGRATION VIA FITBIT API

To create a more responsive lighting experience, the second iteration of the system integrated real-time physiological data from wearable devices with a mobile application interface. This approach enabled the system to adapt lighting conditions not only based on time of day but also the user's biometric state, particularly heart rate and sleep phase, thereby supporting circadian-friendly interventions tailored to individual needs.

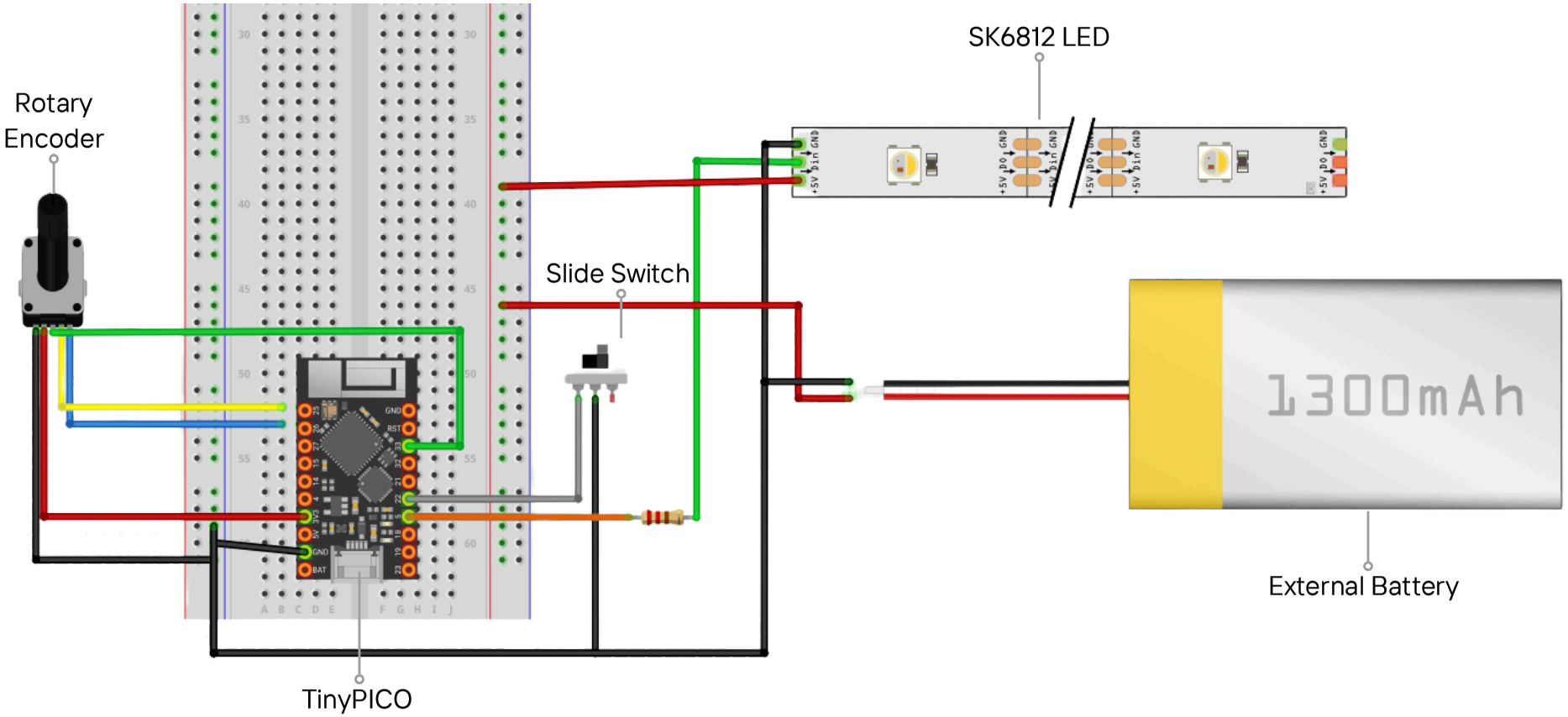


Fig 53: Wiring Schematic of the connections (second iteration).

Why API Integration Was Necessary?

Integrating physiological input was essential to move beyond fixed schedules and enable intelligent, context-aware lighting behavior. Adding dedicated hardware sensors for metrics like heart rate would have complicated the prototype and reduced its wearability. To maintain a compact and user-friendly design, a cloud-based solution was adopted using the Fitbit Web API. This allowed access to high-quality physiological data from commercially available wearables, without introducing additional hardware overhead.

The Fitbit API offered:

- Secure, OAuth 2.0–authenticated access to heart rate, sleep stages, and activity data.
- Reliable endpoints for real-time and historical metrics.
- A way to leverage existing wearable ecosystems for efficient and scalable integration.

This allowed the prototype to remain lightweight while still offering real-time biometric responsiveness.

Fitbit API Integration for Biometric Inputs

The system utilized the Fitbit Web API to access user physiological data and adapt lighting behavior accordingly. Data was polled every 30 seconds, creating a continuous feedback loop. Based on heart rate and sleep phase classification, lighting profiles were adjusted to support either rest or alertness.
Examples of adaptive behavior include:

- Evening response (6:00 PM – 10:00 PM):
  - Dim, warm lighting (<50 lux, CCT 2700–3000K) to reduce blue-light exposure, promote melatonin production, and support natural sleep initiation.
- Morning response (7:00 AM – 9:00 AM):
  - Bright, cool lighting (>1000 lux, CCT 6000–7000K) to stimulate wakefulness, enhance alertness, and help reset the circadian rhythm.

This dynamic adjustment allowed the system to deliver context-sensitive light therapy aligned with the user's circadian and physiological states. Data was also logged for each session to support post-analysis and inform future iterations.

Flutter-Based Mobile App Interface

To provide user control, visualization, and demonstration capability, a mobile app was developed using Flutter, Google's cross-platform UI toolkit. Flutter was selected for its:

- Seamless Bluetooth Low Energy (BLE) support,
- High performance on Android devices,
- Ease of customizing user interfaces.

The app featured a modular structure and fulfilled the following roles:

BLE Communication:

- Scanned for and connected to the ESP32/TinyPICO device.
- Sent commands for brightness adjustment, mode switching, and scene triggering.

Manual Override Interface:

- Enabled users or healthcare professionals to switch between automatic and manual modes.
- Manual mode included sliders for real-time brightness control.

Real-Time Heart Rate Visualization:

- Displayed a live chart of heart rate data for monitoring physiological response during exposure.

Lighting Scene Demos:

- Included buttons for predefined lighting scenes such as "Morning, Daytime, and Evening".

Data Logging and Export:

- Logged biometric and lighting state data in real time.
- Provided CSV export for research and evaluation.

The app was developed using Dart in Visual Studio Code, and its architecture supported bidirectional interaction: while the system could operate autonomously based on Fitbit data, users retained full control and visibility through the app.

5.2.2 USER INTERFACE ARCHITECTURE OF LUMOSYNC APP

While the previous section detailed how physiological inputs and BLE communication were functionally integrated into the system, this section focuses on the visual design and structure of the mobile application developed for user interaction. The app, titled ***LumoSync***, was designed to serve as both a control interface and a visualization platform for dynamic lighting interventions.

The name LumoSync combines two elements central to the system's identity:

- "Lumo", derived from Latin, meaning light, reflects the app's core focus on modulating circadian lighting.
- "Sync" highlights the app's ability to synchronize with physiological data, such as heart rate and sleep stages, using Fitbit's Web API.

Together, the name represents a system that adapts lighting environments intelligently based on the user's internal state. LumoSync was built using Flutter and communicates with the hardware using Bluetooth Low Energy (BLE).

The initial version of the LumoSync application was developed as a single-screen prototype to establish core system functionality, verify hardware integration, and validate the Bluetooth Low Energy (BLE) communication pipeline. This early-stage build served as a proof-of-concept, ensuring that reliable data exchange and lighting control could be achieved between the mobile application and the ESP32-based hardware platform. This approach allowed for rapid development, simplified debugging, and continuous testing throughout the integration of both hardware and software components.

Key Functional Components of the Initial Build:

Integrated BLE Scanning and Connection:
The prototype continuously scanned for nearby BLE devices and displayed available devices directly on the main screen. Upon user selection, the app established the BLE connection and directly discovered the necessary services and characteristics.

Real-Time System Monitoring:
The dashboard displayed live physiological data, such as heart rate and sleep phases, fetched via Fitbit Web APIs. Additional system parameters, including power status, lighting mode, and local system time, were updated in real-time.

Direct Lighting Control Logic:
Both manual and automatic lighting control modes were implemented within the single interface. Users could override the lighting state via a brightness slider, while the system could also operate autonomously based on physiological inputs and predefined logic.

Demo Command Interface:
Dedicated lighting demo buttons enabled quick testing of various preset lighting profiles. These transmitted predefined commands directly to the ESP32 controller to activate corresponding lighting scenes.

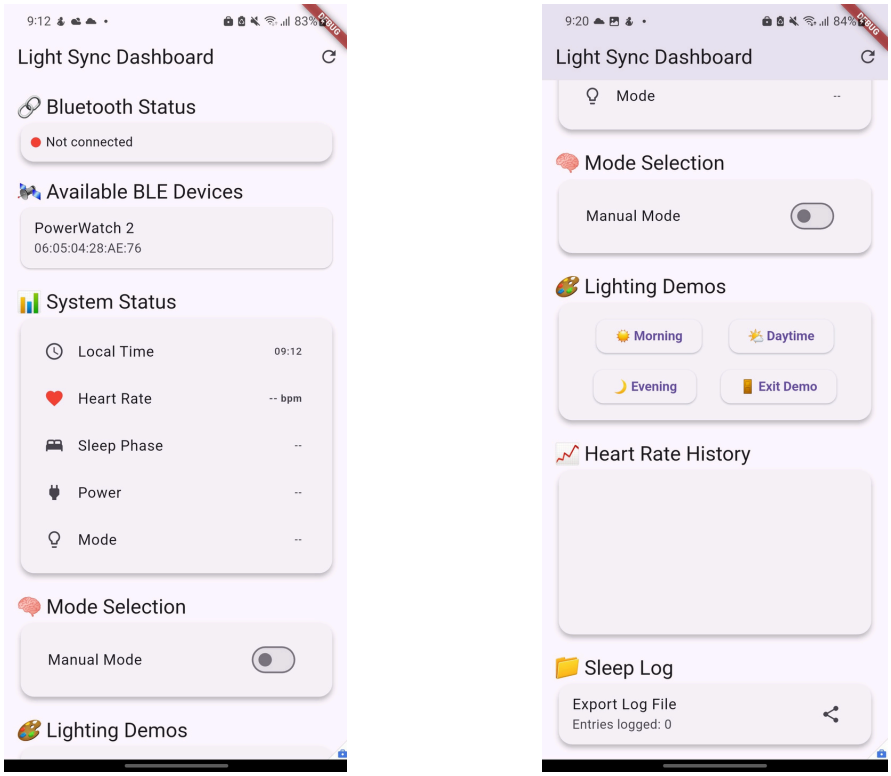


Fig 54: User Interface architecture of LumoSync.

Session Logging and Data Export:
The app supported CSV export of session data, enabling further offline evaluation of lighting behavior in response to physiological states during the development and testing stages.

The initial prototype played a critical role in establishing full end-to-end system functionality before progressing towards a more structured, modular interface design.

5.2.3 SYSTEM WORKING PRINCIPLE

The prototype light intervention system operates through a context-aware control architecture that integrates physiological sensing, user input, and adaptive firmware logic. Its core function is to modulate illumination dynamically based on real-time data, enabling personalized circadian lighting suited for both clinical and home environments. The operation of the system follows the overall logic flow presented in Section 7.2, moving seque

-ntially from data acquisition to output generation. The following subsections describe the system's key operational stages.

Power and Initialization

Upon powering the device, the onboard ESP32 microcontroller initializes all hardware components, including:

- The Bluetooth Low Energy (BLE) module,
- The SK6812 GRBW addressable LED strip,
- The rotary encoder for manual brightness control,
- And the slide switch for mode selection.

Once initialized, the system retrieves the last known power state from memory to maintain continuity across sessions. If the slide switch is set to Auto mode, the system immediately begins polling physiological data via the Fitbit Web API and activates the logic governing adaptive lighting behavior.

Mode Selection: Auto vs. Manual

The system supports two primary modes of operation, toggled using a physical 3-pin slide switch:

Manual Mode
This mode allows the user to bypass automated behavior and directly control the lighting intensity through:

- A rotary encoder, which maps rotational input to brightness levels.
- The LumoSync mobile app provides a real-time brightness slider via BLE communication.

Auto Mode

In Auto mode, manual inputs are disabled, and the system dynamically adjusts lighting based on:

- Time of day (e.g., morning, daytime, evening).
- Heart rate data trends retrieved from Fitbit.
- Sleep stage classification (e.g., REM, light, deep sleep).

This dual-mode structure offers flexibility for both research protocols, where consistent control is critical, and personalized use, where users benefit from real-time, biologically-aligned lighting.

Real-Time Lighting Control Logic

The lighting output is controlled through a central function that calculates and sends appropriate GRBW values to the addressable LED strip. Brightness levels are mapped using either linear or gamma correction, depending on application needs.

Auto Mode Behavior

When operating in Auto mode, the system:

- Divides the day into predefined time blocks (e.g., 7–9 AM for morning, 9 AM–6 PM for daytime, 6–10 PM for evening).
- Cross-references these time blocks with Fitbit-derived data, such as heart rate variability and sleep phase.
- Updates the color temperature and intensity every 30 seconds based on the user's detected rest or wake status.
    - For example, if the heart rate drops below a threshold during deep sleep, the light is dimmed and shifted to warmer tones.

Manual Mode Behavior

In Manual mode, the system listens for real-time brightness adjustments from:

- The rotary encoder, where physical rotation adjusts brightness (mapped from 0–255 8 bt scale).
- The Flutter app sends BLE commands in the format manual:128 (where 128 is a brightness level with a max level of 255).

All incoming control commands are processed by a central logic function that ensures smooth transitions and consistent light output.

5.3 CIRCADIAN LIGHTING DESIGN

The design of the lighting modes for the LumoSync system was directly guided by the findings established in the earlier stages of the project, particularly the emotional challenges faced by ICU patients and the importance of circadian alignment discussed in earlier chapters. Based on these insights, the lighting modes were developed to support patients' circadian rhythms, promoting emotional stability and improving sleep quality throughout their ICU stay.

To achieve this, the system was designed to simulate natural light transitions throughout the day, offering distinct lighting conditions for the morning, evening, and nighttime phases. Each mode was defined not only by its visual comfort but also by its biological effectiveness, taking into account factors such as melatonin suppression, sleep initiation, and cognitive stimulation.

The goal was to create a dynamic lighting environment that could help reduce disorientation, support natural sleep-wake cycles, and contribute to the overall emotional well-being of ICU patients.

The following section details how the RGBW values for each lighting phase were extracted and translated from existing literature on natural daylight spectra, circadian physiology, and lighting intervention studies to form the technical foundation of the system.

5.3.1 EXTRACTION AND TRANSLATION OF RGBW VALUES

The RGBW values implemented in the LumoSync prototype were derived from published scientific research on natural daylight structure, human circadian biology, and the cognitive and physiological impacts of different lighting conditions. This process combined spectral data extraction, color temperature targets, and biological outcomes to develop lighting modes that are both perceptually realistic and biologically effective.

The primary spectral data source was Cehao Yu et al., whose studies provide detailed spectral power distribution (SPD) plots quantifying the spatial, angular, and spectral structure of daylight (Yu et al., 2023; Yu et al., 2022; Yu & Pont, 2021). These SPD plots were used to determine the relative spectral energy contributions across the visible spectrum for different times of day.

Each lighting phase was characterized by:

- A target correlated color temperature (CCT).
- A dominant spectral region.
- A relative intensity profile.

The SPD plots were manually segmented into red (580–700 nm), green (500–580 nm), and blue (400–500 nm) bands. Visual estimation of the relative energy under each spectral region was performed, and proportional contributions were normalized to RGB values (0–255 scale) suitable for SK6812 RGBW LED hardware.

The white (W) channel was additionally applied to balance overall brightness, blend transitions, and simulate neutral white components where necessary.

The derived RGBW values for each lighting phase are summarized in Table 01.

5.3.2 BIOLOGICAL AND COGNITIVE RATIONALE

Beyond spectral simulation, these RGBW targets were informed by additional clinical and behavioral studies addressing the biological effects of light on human health. Several studies demonstrate how specific combinations of illuminance and color temperature affect sleep quality, cognitive performance, melatonin suppression, and circadian phase regulation.

- Nie et al. (2024) demonstrated that lower CCT combined with higher illuminance during nighttime improves sleep quality, supporting the use of warm, low-CCT light in evening and night modes.

Lighting Mode	Target CCT (K)	RGBW Values
Morning	6000–7000K	R: 150, G: 100, B: 255, W: 200
Evening	2700–3000K	R: 5, G: 10, B: 0, W: 80
Night	0K	R: 0, G: 0, B: 0, W: 0

Table 01: Derived RGBW values

- Vethe et al. (2021) highlighted that hospital evening lighting can be designed with reduced blue light to minimize circadian disruption and improve inpatient sleep, which directly supports the inclusion of warm amber-red light in evening modes.

- Kraneburg et al. (2016) investigated melatonin suppression across different color temperatures, emphasizing that higher CCT lighting increases melatonin suppression, while warm low-CCT light allows normal melatonin production, validating the nighttime red-dominant profile applied here.

By integrating both spectral data and biological research, the system's lighting modes were designed to modulate circadian physiology while respecting comfort and behavioral requirements.

5.4 WEARABLE DESIGN: DEVELOPMENT OF LUMOGLAZE

While the electronic and software components defined the intelligence of the lighting intervention system, the physical form factor played an equally critical role in ensuring user comfort, practicality, and the effective delivery of therapeutic light. This chapter presents the design and development of the wearable goggles, which were engineered to project light perpendicularly toward the user's eyes as part of a context-aware, circadian-supportive system.

The final design of the goggles is named ***LumoGlaze,*** a term derived from two core ideas:

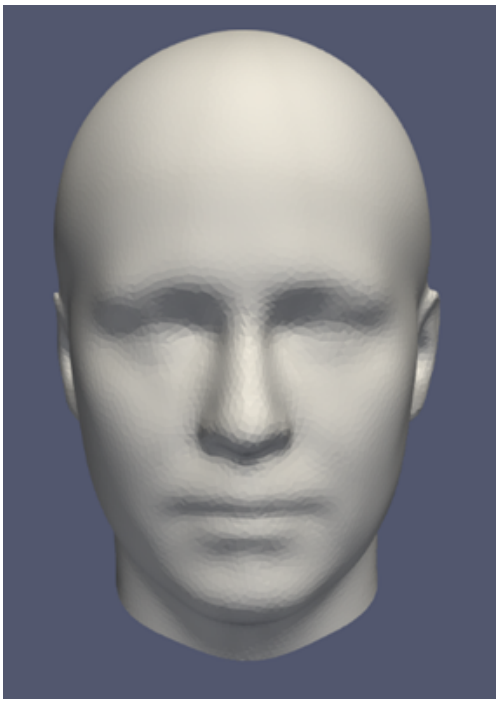
- "Lumo", from Latin, meaning light, consistent with the naming of the broader system (LumoSync), and
- "Glaze" evokes a controlled surface treatment or diffusion of light across the eyes.

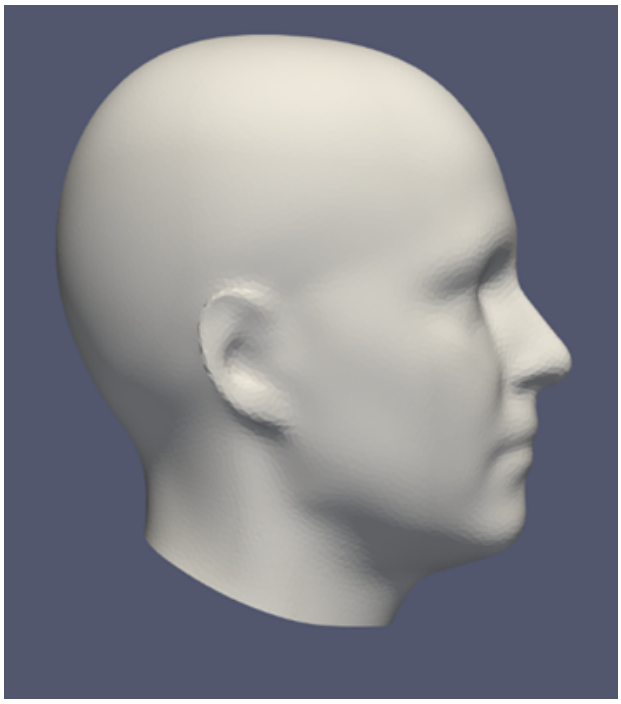
The name LumoGlaze was chosen to reflect the device's role in delivering soft, targeted illumination in a way that is both effective and visually soothing. The term captures the product's dual function as a light therapy delivery mechanism and a wearable interface that seamlessly blends form with function.

5.4.1 ERGONOMIC DESIGN AND DEMOGRAPHIC ADAPTATION

To ensure ergonomic compatibility, the design of the goggles needed to accommodate a wide range of facial structures. This was especially important for the intended clinical context, where patient age and anatomy can vary significantly. In collaboration with MSc F. (Floor) Hiemstra, a representative from the Leiden University Medical Center (LUMC), demographic data was obtained for patients admitted to the ICU between April 1, 2024, and April 1, 2025. The youngest and oldest patients recorded were 15 and 91 years old, respectively.

Using this age range, a 3D anatomical average model was computed in ParaView by blending facial scans representing these two age extremes. This average model served as the primary reference for the design, ensuring the prototype would fit a broad demographic spectrum. (Smulder et al,.2023)





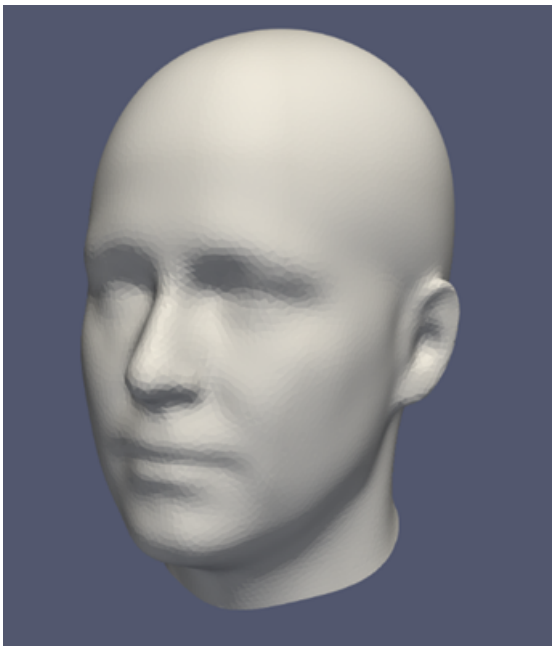


Fig 55: Averaged Mannequin Model Generated Using ParaView

5.4.2 DESIGN ITERATIONS OF LUMOGLAZE

First Iteration – Basic Fit Evaluation

Fig 56: Goggles (Front View)

- Designed to evaluate general form factor, LED positioning, and nose bridge comfort.
- Electronic components were not integrated at this stage.

- Discomfort was observed at the nose bridge due to pressure points and insufficient clearance

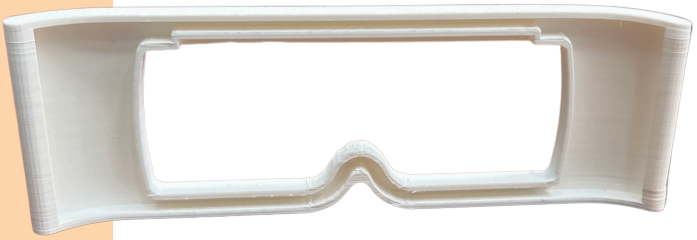


Fig 57: Goggles (Rear View)

Second Iteration – Component Integration

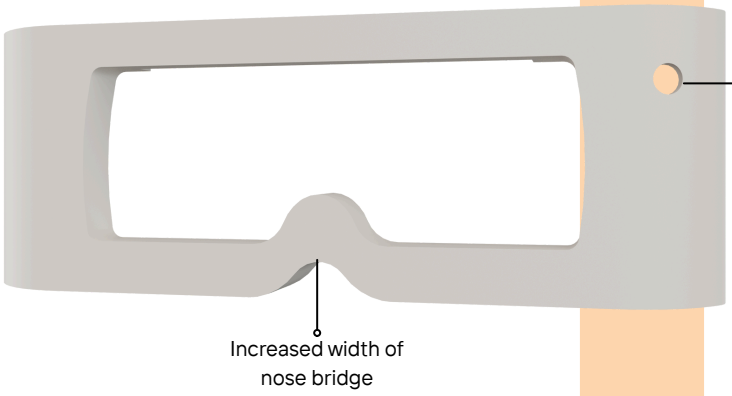


Fig 58: Goggles (Front View) featuring an Increased Nose Bridge

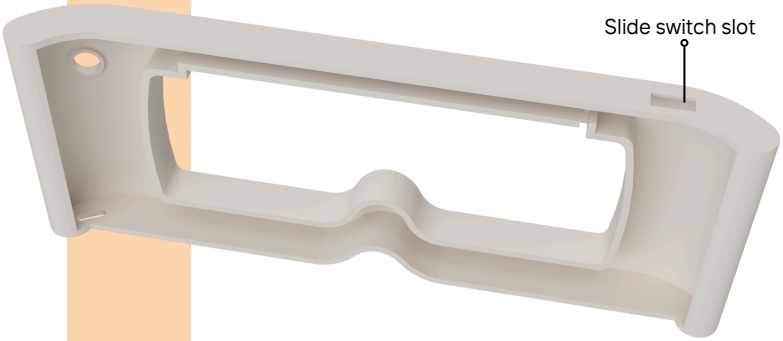


Fig 59: Goggles (Rear View) featuring slots for electronic components

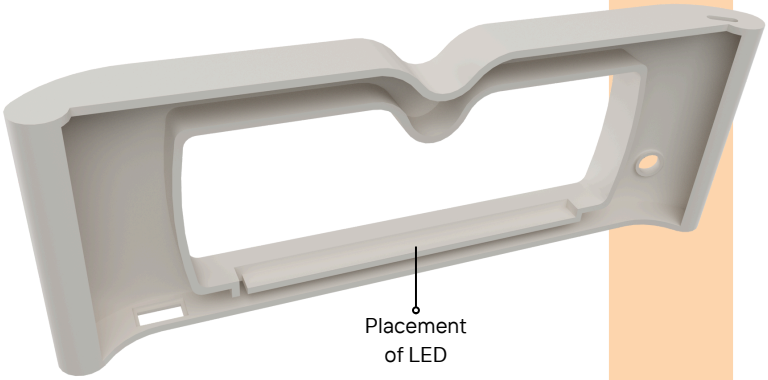


Fig 60: Goggles (Upside down View) featuring LED placement

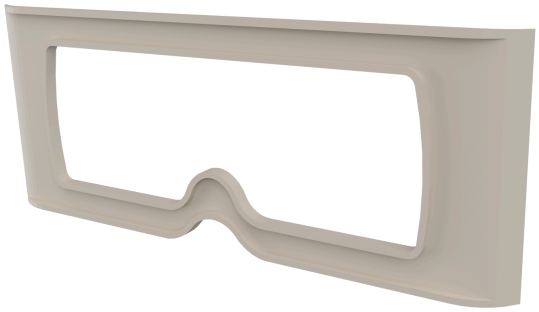


Fig 61: Goggles Back Panel

Third Iteration – Nose Bridge Redesign

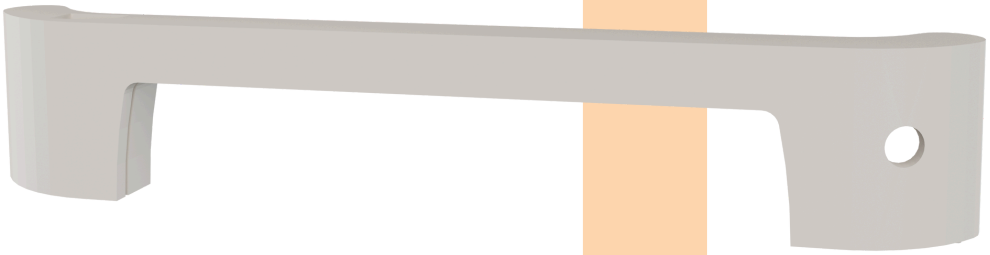


Fig 62: Goggles Top Half (Front View)

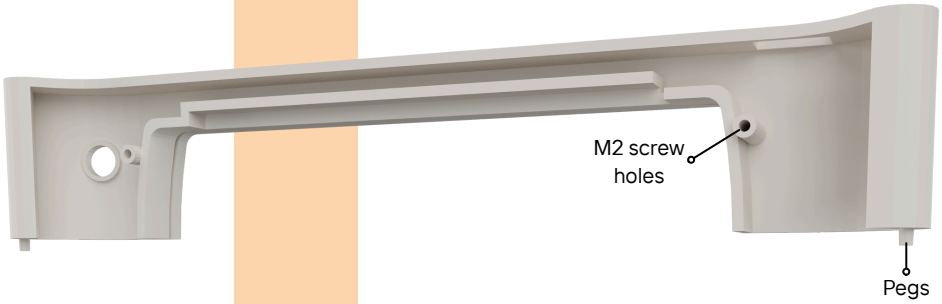


Fig 63: Goggles Top Half (Rear View) featuring peg and screw holes

Fig 64: Goggles Bottom Half (Front View)

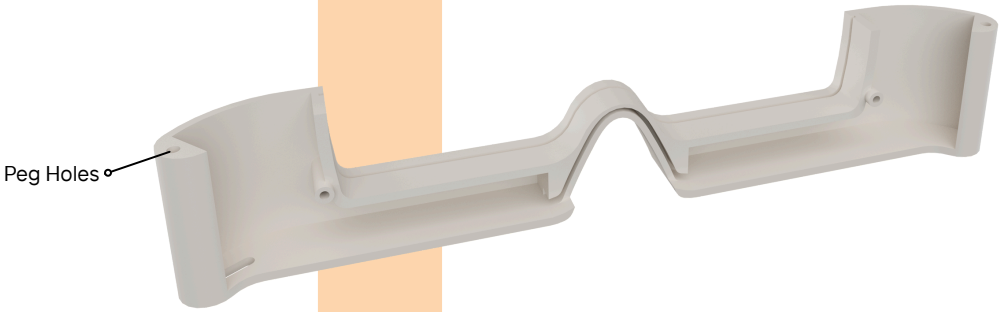


Fig 65: Goggles Bottom Half (Rear View) featuring peg holes

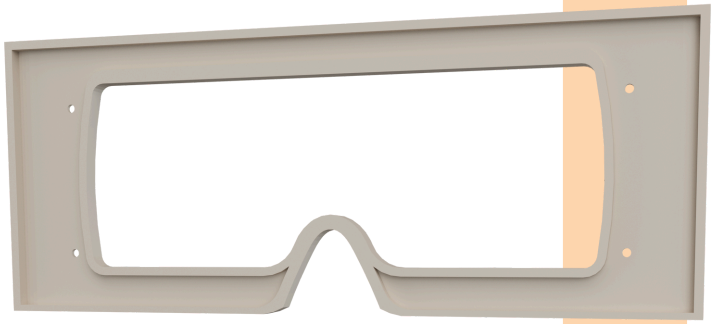


Fig 66: Goggles Back Panel with holes

Fourth Iteration – Structural Enhancements

Fig 67: Goggles Top Half (Rear View) featuring increased peg diameter

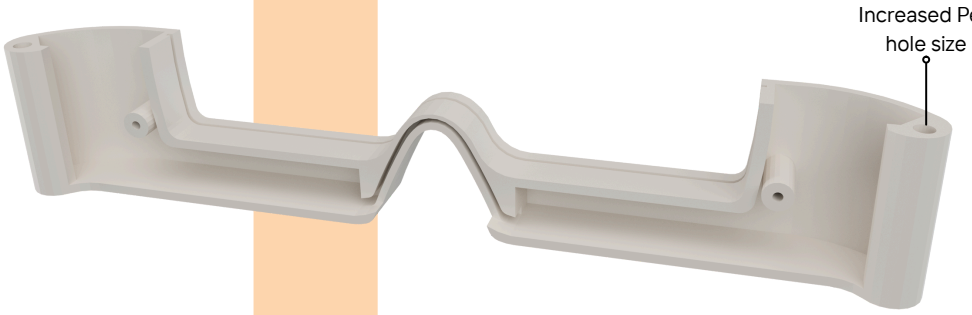


Fig 68: Goggles Bottom Half (Rear View) featuring increased peg hole diameter

Fifth Iteration – Head Strap and Comfort Redesign

Fig 69: Goggles Top Half (Rear View) featuring cut out slot for strap

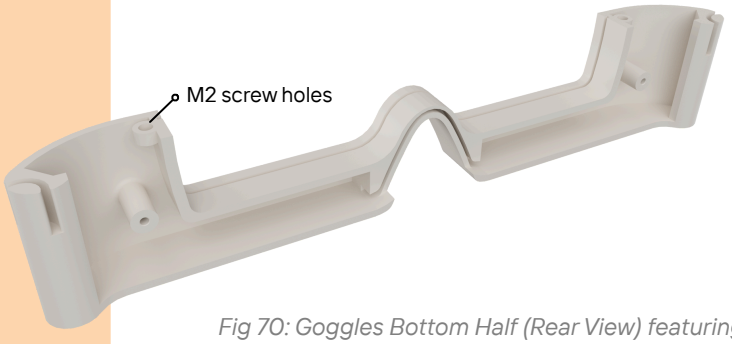


Fig 70: Goggles Bottom Half (Rear View) featuring additional M2 screw holes for clamping

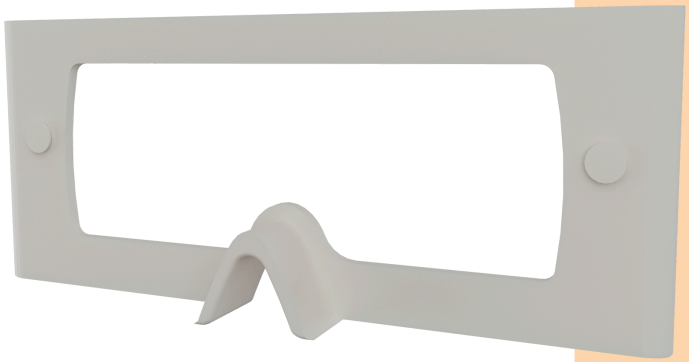


Fig 71: TPU Comfort Add-On

Final Iteration – Compactness and Internal Optimization

Fig 72: Goggles Top Half (Rear View) featuring cut out slot for strap clamp

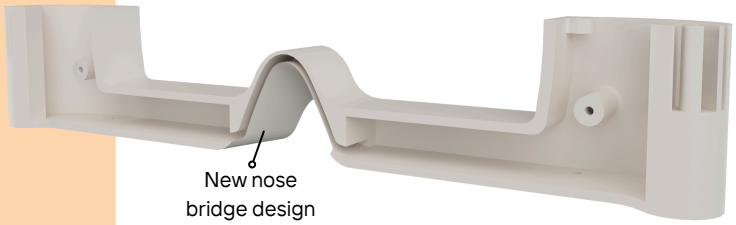


Fig 73: Goggles Bottom Half (Rear View) featuring new nose bridge design

Fig 74: Strap Clamps

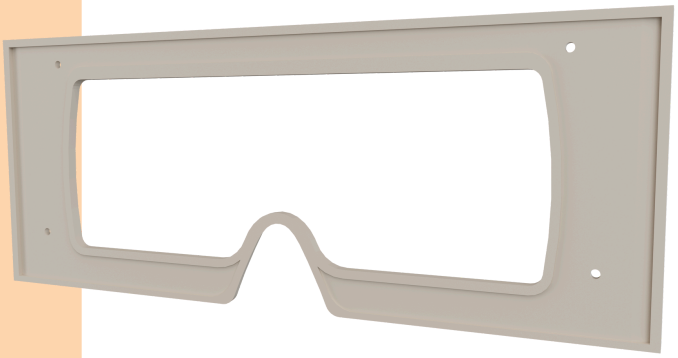


Fig 75: New back panel design

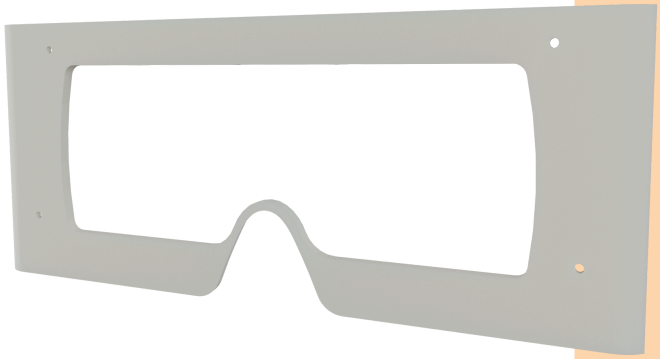


Fig 76: New design for TPU add on

5.4.3 FINAL ASSEMBLY & EXPLODED VIEW OF LUMOGLAZE

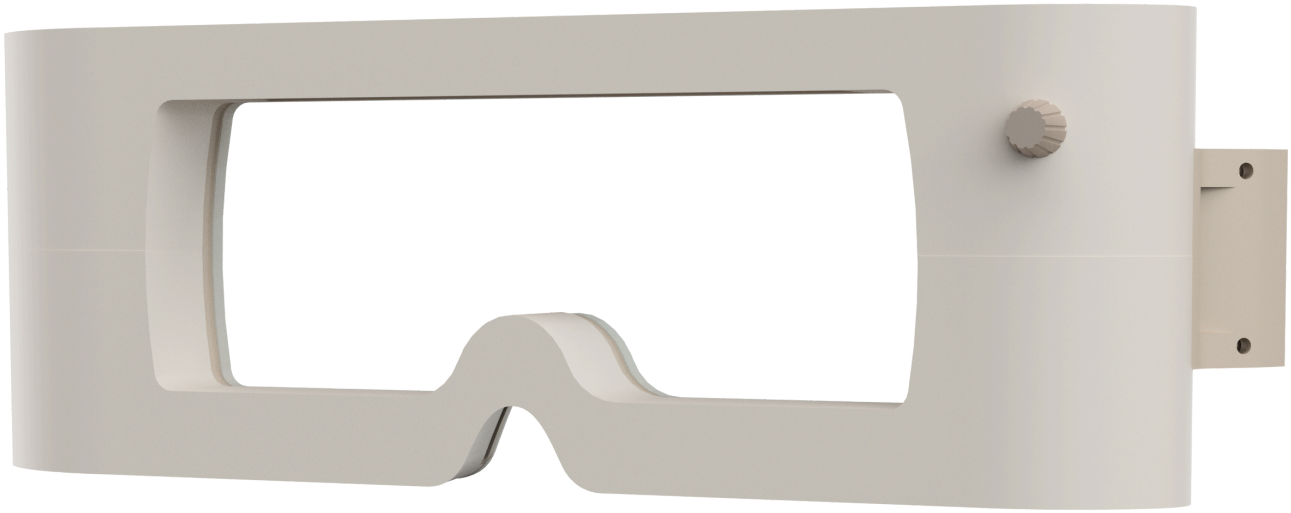


Fig 77: Front View of Fully Assembled Goggles

Fig 78: Rear View of Fully Assembled Goggles

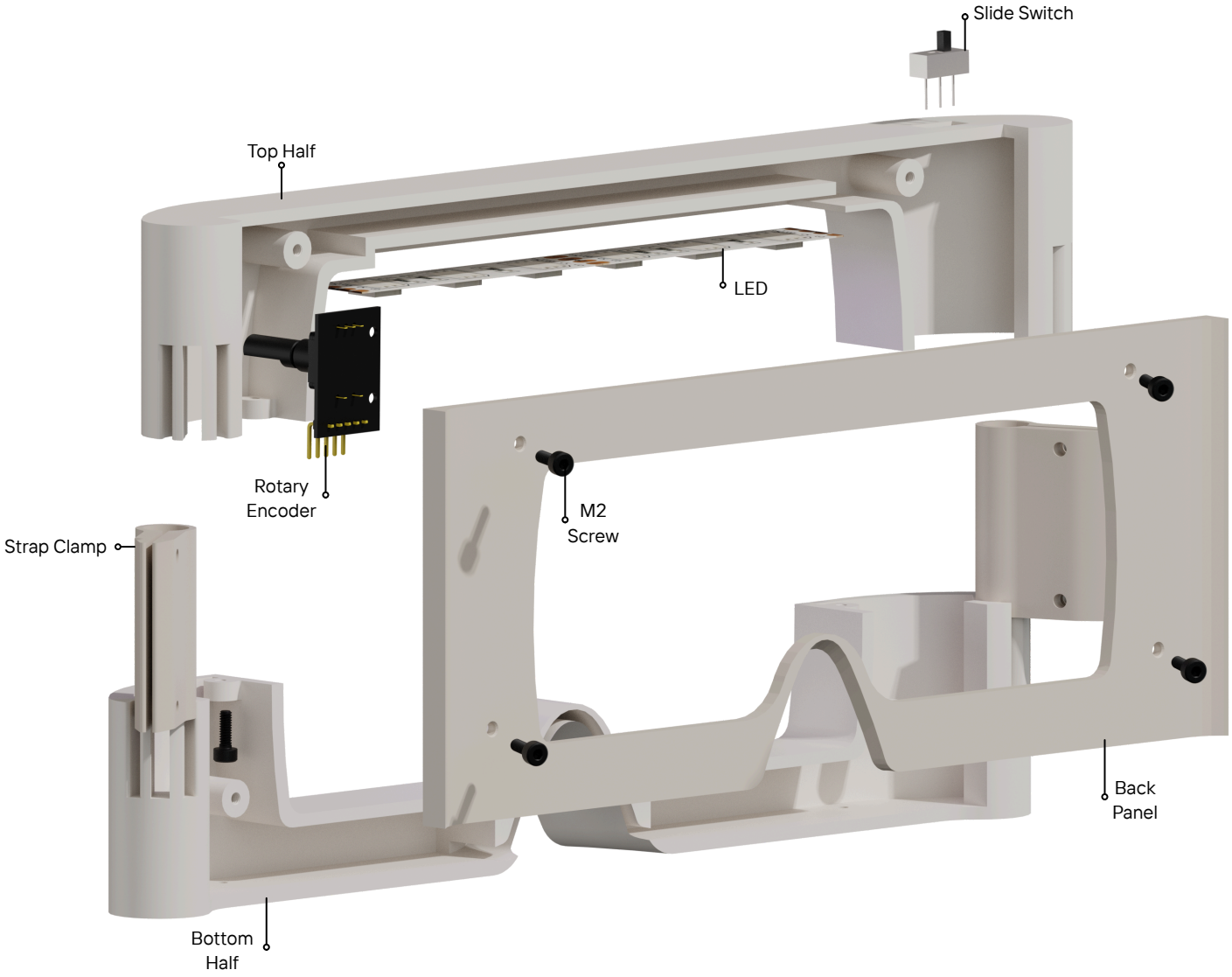


Fig 79: Exploded view of LumoGlaze

5.4.4 LIGHTING MODES

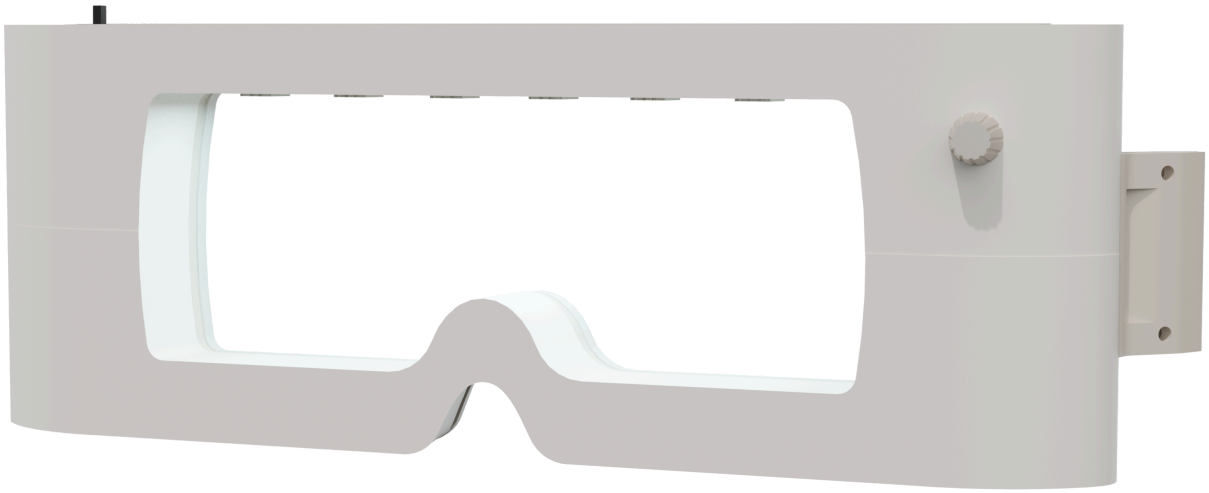


Fig 80: Morning lighting mode

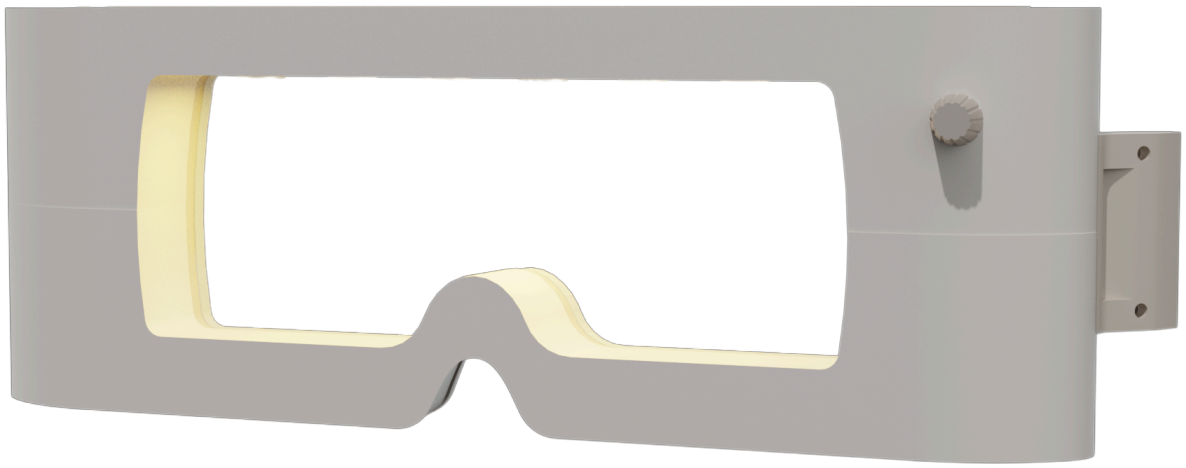


Fig 81: Evening lighting mode

5.4.5 USER TESTING OF LUMOGLAZE

Goal

The primary objective of the user testing phase was to evaluate both the functional and experiential performance of the LumoGlaze smart goggles prototype. The study specifically aimed to:

- Assess the physical comfort and wearability of the device across different lighting conditions.
- Investigate the physiological effects of circadian-supportive lighting interventions, particularly the use of bright morning light to promote alertness and warm evening light to support relaxation.
- Validate real-time physiological monitoring via Fitbit Web API integration, supported by manual heart rate measurements.
- Test the system's Bluetooth Low Energy (BLE) communication robustness and real-world interaction via the LumoSync mobile application.

The user testing was conducted in a semi-controlled environment designed to simulate clinical ICU conditions. The test environment included an ICU bed setup within the IDE building at TU Delft, with minimized natural light interference to ensure consistent lighting conditions during each session.

Participants

A total of 12 healthy adult participants (10 males, 2 females) were recruited. The participants represented a diverse academic background, including five participants from the Industrial Design Engineering (IDE) faculty. All participants were free from visual impairments or sleep disorders that could interfere with the evaluation. Before participation, each individual reviewed study information and provided written informed consent.The study was approved by the TU Delft Ethics Committee under approval number 26.

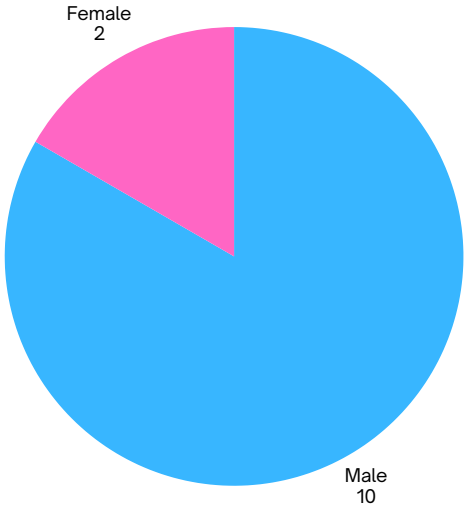


Fig 82: Demographics of participants

Material

The following equipment and instruments were used during testing:

- LumoGlaze Smart Goggles Prototype
- LumoSync Mobile Application
- Fitbit Wearable Tracker
- Pulse Oximeter

Fig 83: Materials Used in User Testing

Set-Up

Testing was conducted in an ICU-simulated environment inside the IDE building at TU Delft. The room included an ICU bed, student table, and controlled ambient lighting to minimize external light interference, see Figure 84. The student table was used to provide information regarding the research and make it easier for participants to write and use the laptop for feedback, and it was also used for discussion. Participants lay in a resting position while wearing the smart goggles and physiological sensors. The LumoSync mobile application was used to control lighting conditions and record system behavior.

Fig 84: ICU simulated room in IDE

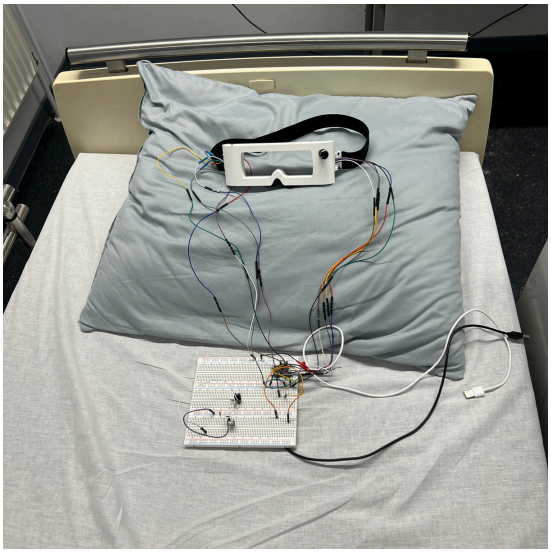


Fig 85: LumoGlaze prototype used for testing

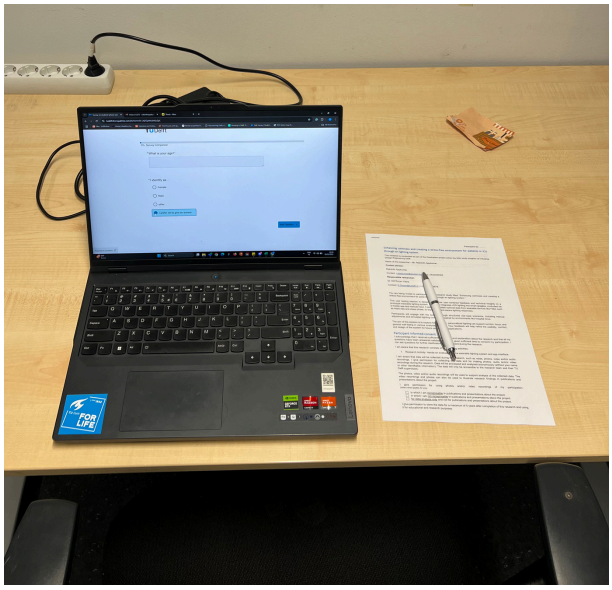


Fig 86: Student table used for briefing the participants

Fig 87: LumoSync app in use

Procedure

This pilot study aimed to evaluate the feasibility and participant experience of the LumoGlaze in a simulated ICU setting.

Upon arrival, participants received a verbal explanation of the study objectives, followed by a short video simulating an ICU environment to provide contextual understanding. After reviewing and signing the informed consent form, they were asked to wear Fitbit tracker and a pulse oximeter to monitor physiological responses throughout the session. Participants were then asked to lie on an ICU bed to replicate a realistic resting posture commonly observed in clinical environments. They were given a few moments to adjust to the smart goggles used for the lighting intervention.

The testing protocol consisted of two lighting conditions, presented in a randomized order to minimise potential order effects:

- Morning Mode: Bright, cool light with a target CCT of 6000–7000 K, designed to promote alertness.
- Evening Mode: Dim, warm light with a target CCT of 2700–3000 K, intended to support relaxation.

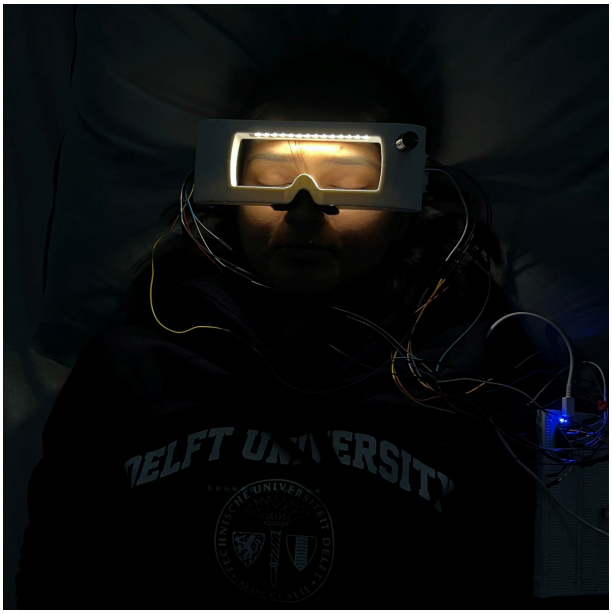


Fig 88: Pilot study with dimmed ambient lighting and observation under evening light. (Pilot study)

Each condition lasted approximately 4–5 minutes, after which participants were given a short break and asked to respond to a set of evaluation questions specific to the lighting experience. Transitions between lighting modes were managed through the LumoSync app using Bluetooth Low Energy (BLE). Verbal cues were provided throughout to guide participants and ensure comfort.

Upon completion of both lighting phases, the smart goggles were gently removed. Participants were then invited to sit at a table to fill in a structured feedback form and engage in a brief follow-up discussion regarding their experience. The total session lasted approximately 20–30 minutes.

Table 02 summarises the full testing schedule.

Phase	Time
1. Briefing & Consent	5 min
2. Baseline (No lighting mode)	2 min
3. Morning Mode	5 min
4. Evening Mode	5 min
5. Manual Mode	3 min
6. Feedback & Exit	5–10 min

Table 02: User testing plan

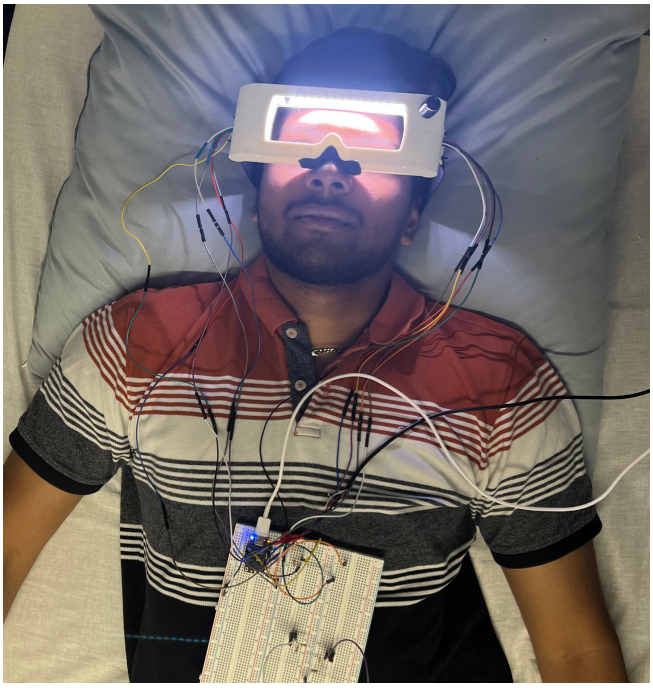


Fig 89: Observation of Participant Under Morning Light Conditions.

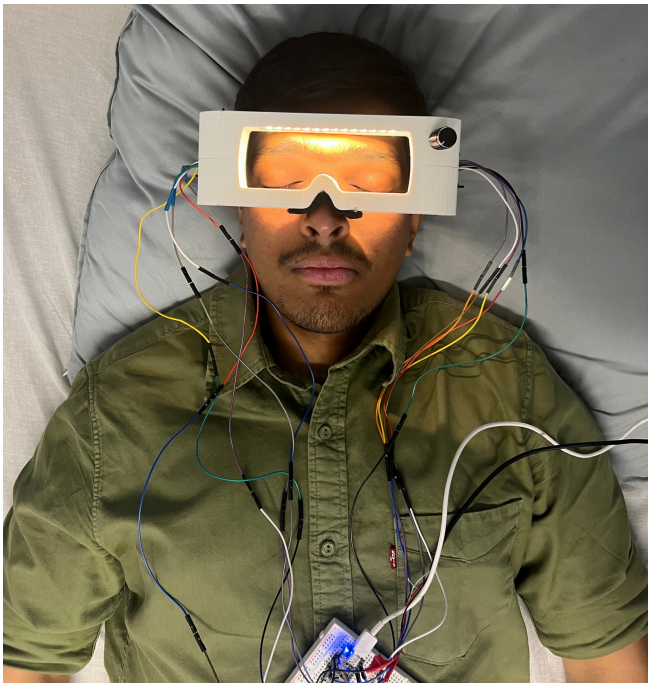


Fig 90: Observation of Participant Under Evening Light Conditions.

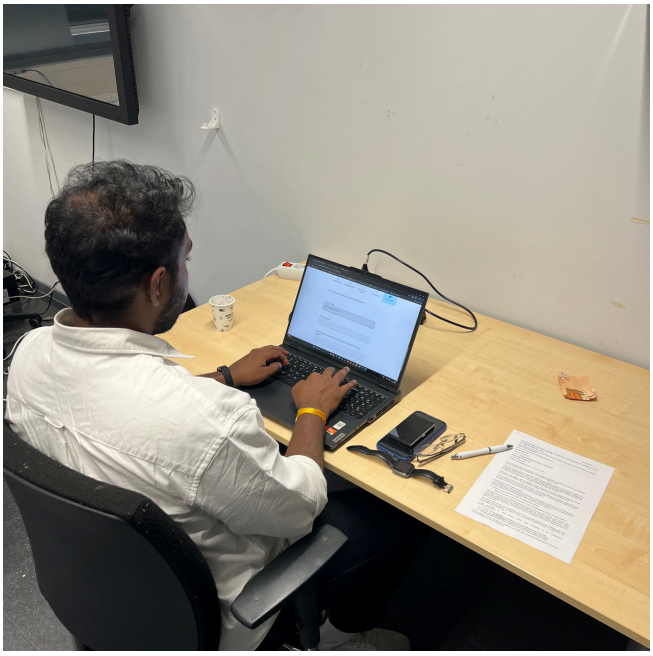


Fig 91: Participant Providing Feedback Following the Test Phase.

Pilot study

Upon arrival, participants received an explanation of the study and watched a short ICU simulation video for context. After informed consent, participants were asked to wear the Fitbit tracker and pulse oximeter. They were positioned lying down on the ICU bed to simulate realistic use. Participants were given a few moments to settle and adjust to the goggles.

Participants were exposed to two lighting conditions in randomized order:

- Morning mode: Bright, cool light to simulate alertness.
- Evening mode: Dim, warm light to simulate relaxation.

After each lighting phase, participants were given a short break, followed by a set of evaluation questions related specifically to that mode. Each condition lasted approximately 4 to 5 minutes. Transitions between conditions were managed through the LumoSync app using BLE. Throughout the test, verbal cues were provided to ensure participant comfort and clear instructions. Upon completion of both phases, the goggles were gently removed, and the participant was invited to sit on the student table to complete a structured feedback form and for further discussion. The session concluded after the participant submitted their responses.

Results

This section presents the results gathered during the first phase of user testing with the LumoSync system and LumoGlaze wearable prototype. The evaluation aimed to capture both subjective user feedback and objective physiological responses to the system's lighting interventions. Participants were exposed to distinct morning and evening light modes, and their experiences were assessed through a combination of Likert-scale surveys, open-ended reflections, and real-time heart rate monitoring. The findings below are organized to reflect user perceptions of brightness and comfort, physiological impact on alertness and relaxation, and general impressions of the device's design and usability. These insights offer critical feedback for refining the lighting behavior, physical ergonomics, and user interaction model of the system in future iterations.

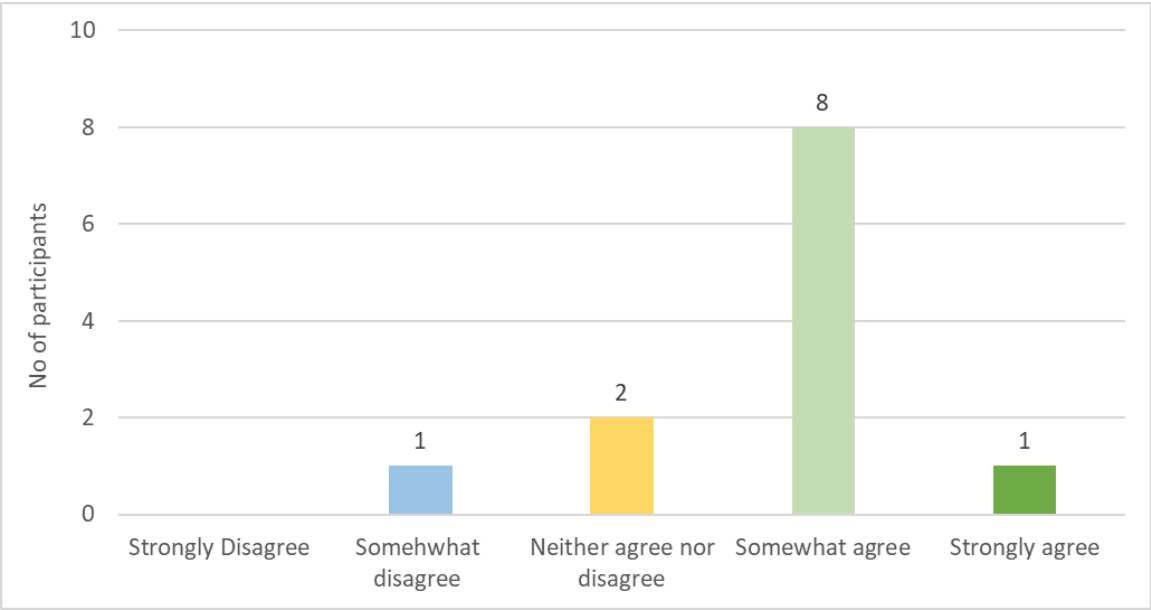
Subjective User Feedback on Lumoglaze

Perception of Morning Light

Participants were asked to rate the comfort and appropriateness of the brightness level of the morning light. Out of the 12 participants, 8 rated it as Somewhat agree, 2 selected Neither agree nor disagree, 1 selected Somewhat disagree, and 1 selected Strongly agree, while no participant selected Strongly disagree. The results of the user responses are illustrated in Figure 92.

The descriptive statistics of the responses were as follows:
Mean = 3.75, Median = 4, and Standard Deviation (SD) = 0.72.

These findings suggest that the majority of participants perceived the morning brightness level as appropriate and comfortable, with the responses generally skewed towards the positive end of the scale.



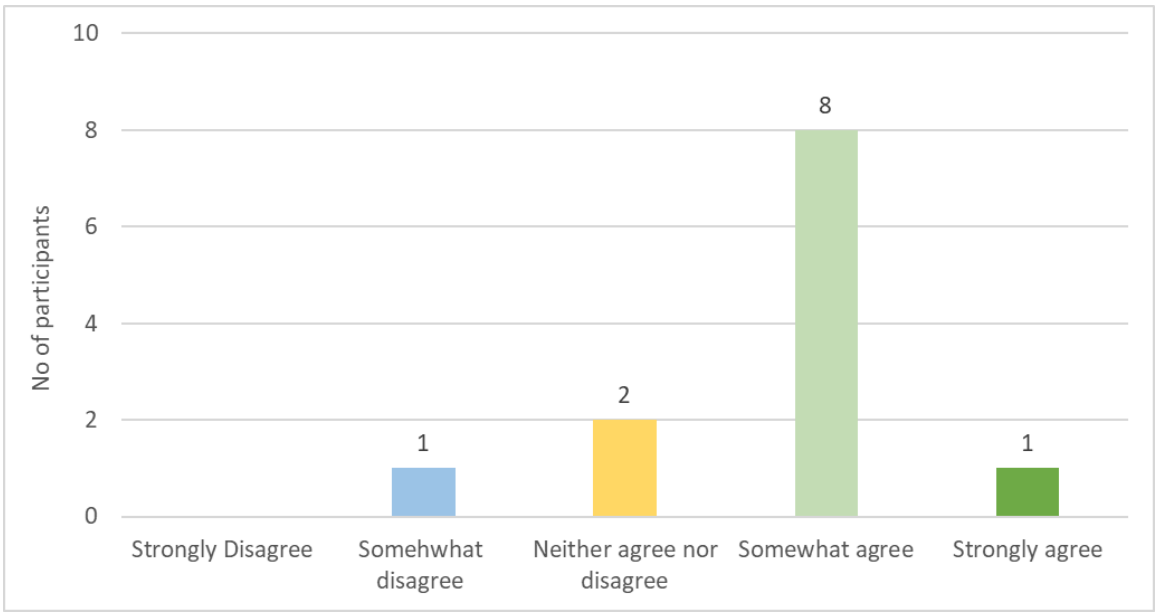
Question: Did you find the brightness level of the morning light comfortable and appropriate?

Fig 92: Participant Ratings on Comfort and Brightness Appropriateness of Morning Light

Participants were asked whether the lighting intervention made them feel more alert or energized. Out of 12 participants, 8 selected Somewhat agree, 2 selected Neither agree nor disagree, 1 selected Somewhat disagree, and 1 selected Strongly agree, while no participant selected Strongly disagree. The results of the user responses are illustrated in Figure 93.

The descriptive statistics of the responses were as follows: Mean = 3.75, Median = 4, and Standard Deviation (SD) = 0.72.

These results indicate that the majority of participants felt that the light contributed positively to feelings of alertness and energy.



Question: Did the light make you feel more alert or energized?

Fig 93: Participant Ratings on Whether the Light Increased Alertness or Energized.

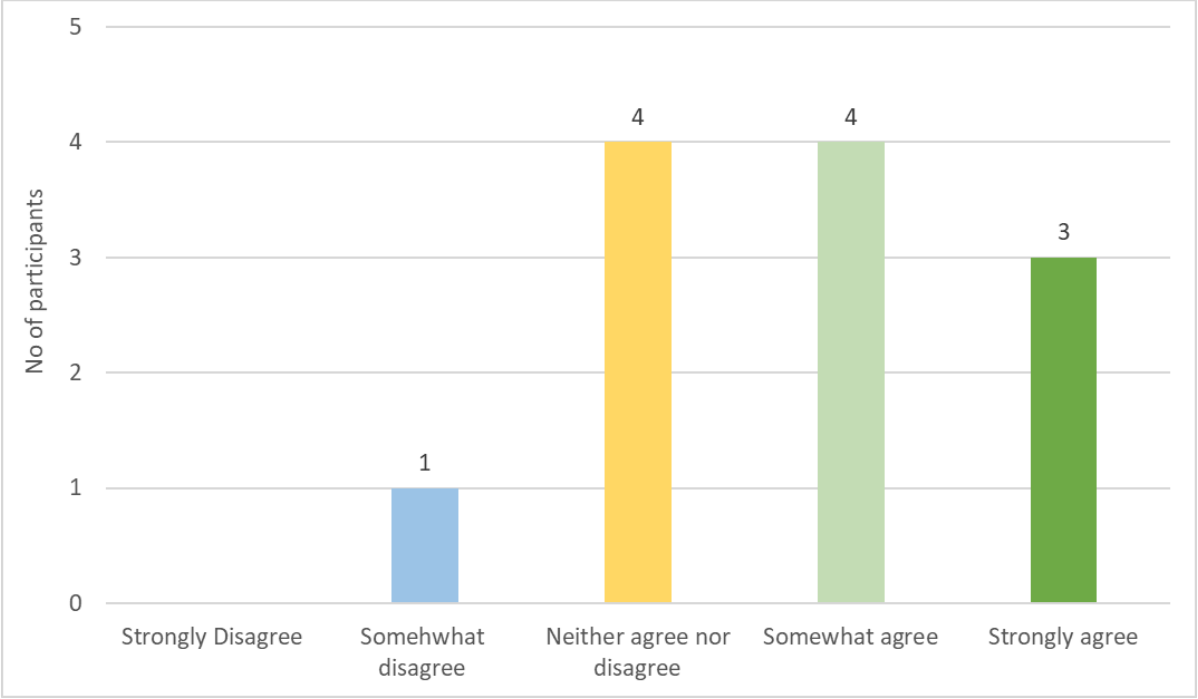
During the testing of the morning mode lighting, participants expressed a diverse range of responses. Several found the light energizing and comparable to natural daylight, noting that it felt like morning sunlight and had a calming effect without the need to shield their eyes. Many reported feelings more alert and awake, with some stating they felt "energetic" or experienced a "constant urge to open my eyes" due to the stimulating nature of the light. However, a subset of participants mentioned discomfort, primarily related to the brightness or intensity describing it as "slightly uncomfortable" or causing "a slight headache" and feelings of restlessness or anxiety. One participant noted that while the brightness initially hurt their head, they adapted quickly. Overall, while the morning mode lighting successfully enhanced alertness and wakefulness for many users, the feedback also underscored the need to manage light intensity to accommodate individual sensitivity and ensure long-term comfort.

Perception of Evening Light

Participants were asked whether the evening light felt gentle and non-intrusive. Out of 12 participants, 4 selected Neither agree nor disagree, 4 selected Somewhat agree, 3 selected Strongly agree, 1 selected Somewhat disagree, and no participant selected Strongly disagree. The results of the user responses are illustrated in Figure 94.

The descriptive statistics of the responses were as follows: Mean = 3.75, Median = 4, and Standard Deviation (SD) = 0.92.

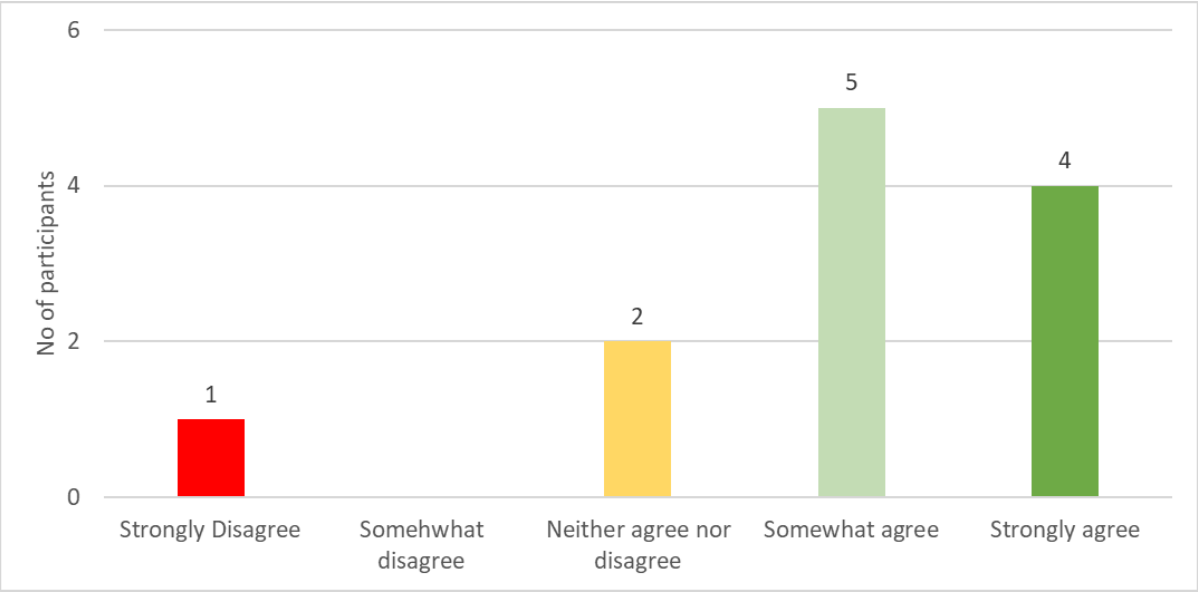
These results suggest that the evening lighting was generally well-received as calming and appropriate for a restful setting



Question: Did the evening light feel gentle and non-intrusive?

Fig 94: Participant Ratings on the Gentleness and Non-Intrusiveness of Evening Light

Participants were asked whether they felt relaxed or sleepy while experiencing the evening light. Out of 12 participants, 5 selected Somewhat agree, 4 selected Strongly agree, 2 selected Neither agree nor disagree, 1 selected Strongly disagree, and no participant selected Somewhat disagree. The results of the user responses are illustrated in Figure 95.



Question: Did you feel relaxed or sleepy while experiencing this light?

Fig 95: Participant Ratings on Feelings of Relaxation or Sleepiness During Evening Light Exposure.

The descriptive statistics of the responses were as follows: Mean = 3.92, Median = 4, and Standard Deviation (SD) = - 1.12.

Overall, the responses suggest that the evening lighting configuration effectively supported feelings of relaxation or sleepiness for most users. Participants generally found the evening mode lighting to be comfortable and conducive to relaxation. Many described the experience as calming, soothing, and even sleep-inducing, with several noting a gradual increase in drowsiness over time. The dimming nature of the light appeared to support a restful state, with one participant commenting that they felt as though they could "sleep through" the session toward the end. Others associated the lighting with familiar ambient environments, stating it reminded them of the lights they use at home to unwind. While most responses highlighted comfort and a sense of relaxation, a few participants initially found the light too intense or overly "white," although this sensation often diminished as the session progressed. One user suggested the mode would feel more complete if it ended with the lights turning off entirely. Overall, the evening lighting was effective in promoting a calm, restful atmosphere, though a small number of users remained alert or found it difficult to fully transition into a sleep-ready state.

Overall Impressions and Emotional Response

Overall impressions of the lighting effects were generally positive, with several participants describing them as calming, soothing, and effective. The evening mode was consistently noted for its relaxing qualities, with some users stating it helped induce sleep even within the short 4-minute testing window. Participants appreciated how the lighting mimicked natural or ambient light, with comments such as "gave me a sense of time" and "felt good" reflecting a positive response to its realism and emotional effect. However, the morning mode was perceived by

some as overly bright or intense, especially at peak intensity, which caused mild discomfort even with eyes closed. While one participant reported no particular impression, most found the lighting transitions noticeable and the effects to be distinguishable and well-controlled. Collectively, the feedback suggests that the lighting modes were successful in achieving their intended psychological and physiological effects, though fine-tuning of brightness, particularly in the morning mode, may enhance overall comfort.

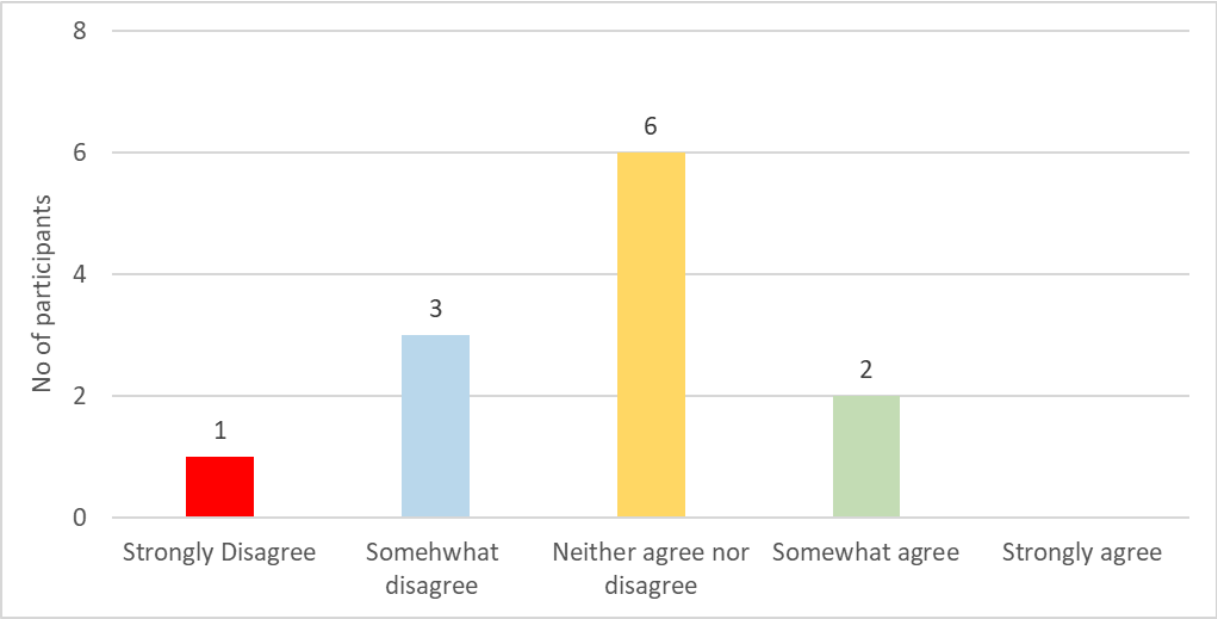
Goggle Comfort and Ergonomic Feedback

Participants were asked about the comfort of wearing the goggles during the session.

Out of 12 participants, 6 selected Neither agree nor disagree, 3 selected Somewhat disagree, 2 selected Somewhat agree, 1 selected Strongly disagree, and no participant selected Strongly agree.

The descriptive statistics of the responses were as follows: Mean = 2.75, Median = 3, and Standard Deviation (SD) = 0.83.

These results point to an opportunity for ergonomic refinement in the design of the goggles. The results of the user responses are illustrated in Figure 96.



Question: The goggles felt comfortable to wear during the session.

Fig 96: Participant Ratings on the Comfort of Wearing the Goggles During the Session.

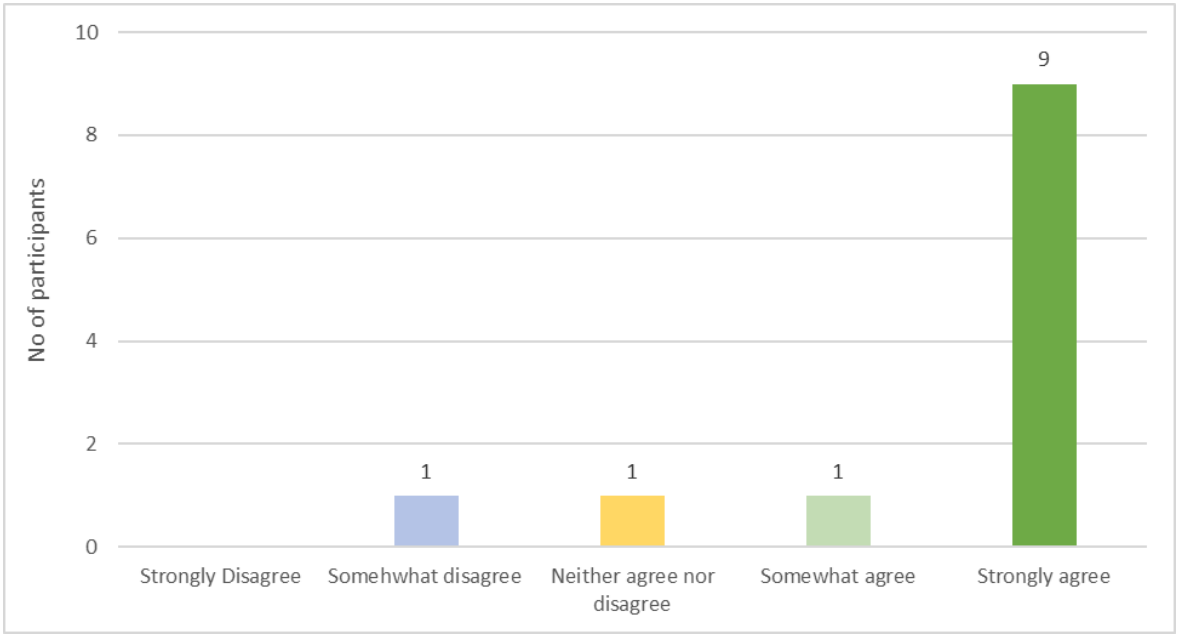
Feedback from participants indicated that the most common area of physical discomfort was around the nose bridge. Multiple users specifically cited the nose area as being uncomfortable or in need of additional padding to improve the fit and reduce pressure. Phrases such as "not comfortable on the nose," "nose bridge," and "near the nose bridge" were frequently mentioned, highlighting this region as a key area for ergonomic improvement. In a few cases, mild discomfort was also reported on the forehead and behind the ears, suggesting that pressure distribution across the contact surfaces may need to be optimized further. These responses underscore the importance of refining the nose bridge design and potentially integrating softer or more adaptive materials in future iterations to enhance user comfort during extended use.

Recognition of Light Mode Transitions

Participants were asked whether they could clearly perceive the difference between the morning and evening light. Out of 12 participants, 9 selected Strongly agree, 1 selected Somewhat agree, 1 selected Neither agree nor disagree, 1 selected Somewhat disagree, and no participant selected Strongly disagree. The results of the user responses are illustrated in Figure 97.

The descriptive statistics of the responses were as follows: Mean = 4.50, Median = 5, and Standard Deviation (SD) = 0.96.

These results suggest that the majority of participants were able to distinguish between the morning and evening lighting conditions.



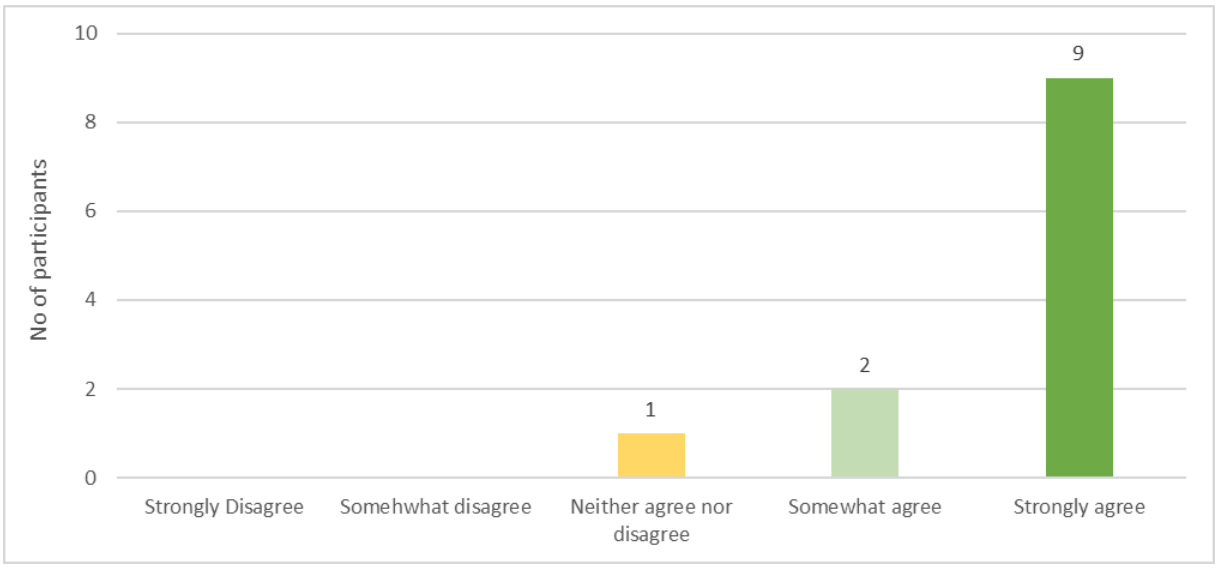
Question: I could clearly perceive the difference between morning and evening light.

Fig 97: Participant Ratings on Perceived Differences Between Morning and Evening Light.

Perceived Internal State Changes

Participants were asked whether they noticed a change in their internal state such as increased alertness or calmness during the lighting session. Out of 12 participants, 9 selected Strongly agree, 2 selected Somewhat agree, 1 selected Neither agree nor disagree, and no participants selected Somewhat disagree or Strongly disagree.

Participants were asked about the likelihood of accepting the lighting system as part of their environment for an extended period. Out of 12 participants, 8 selected Likely, 3 selected Neutral, 1 selected Very likely, while no participants selected Unlikely or Very unlikely. The results of the user responses are illustrated in Figure 98.



Question: I noticed a change in how I felt (alertness or calm) during the test.

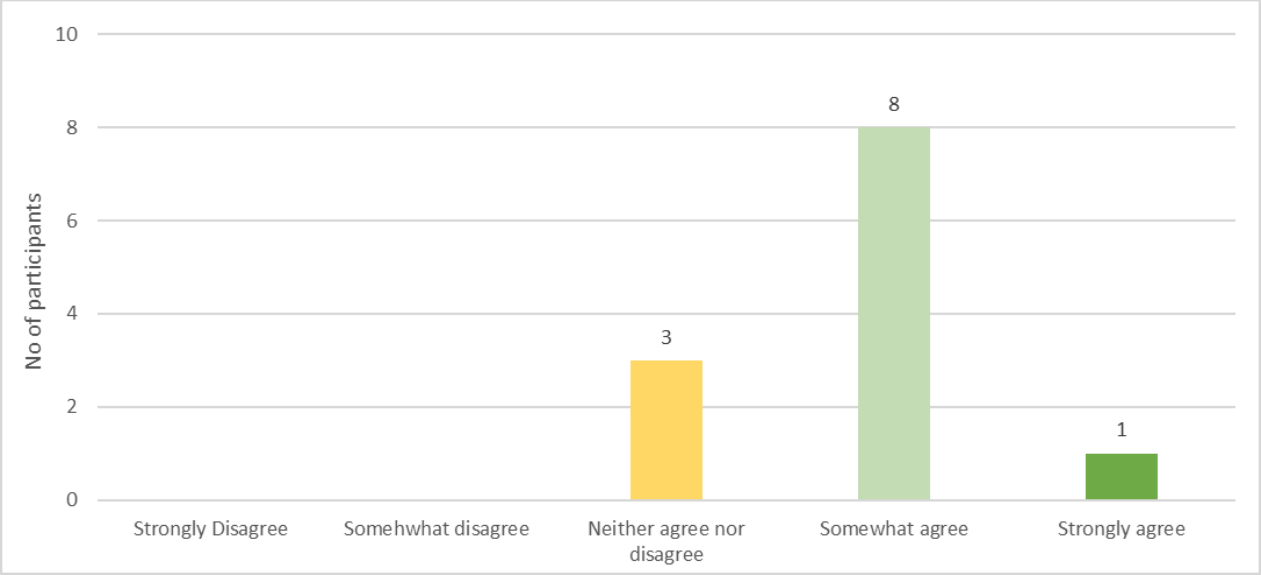
Fig 98: Participant Ratings on Perceived Changes in Internal State

The results of the user responses are illustrated in Figure 99. The descriptive statistics of the responses were as follows: Mean = 4.67, Median = 5, and Standard Deviation (SD) = 0.62.

These results indicate that most participants perceived a noticeable positive change in their internal state during the lighting session.

The descriptive statistics of the responses were as follows: Mean = 3.83, Median = 4, and Standard Deviation (SD) = 0.55.

These results indicate that most participants were positively inclined towards long-term acceptance of the lighting system in their environment.



Question: If you had to use this for an extended period, how likely would you be to accept it as part of your environment?

Fig 99: Participant Ratings on Willingness to Adopt the Lighting System Long-Term

Acceptance and Suggested Improvements

Participants provided several valuable suggestions to enhance the usability and effectiveness of the device in clinical or rest environments. A major recurring theme was the need for improved physical comfort, particularly regarding the fit of the goggles. Suggestions included better padding, material changes, and ergonomic adjustments to reduce pressure points. The rotary switch used to control brightness was also highlighted as an area for potential redesign to enhance ease of use.

From a lighting perspective, several participants recommended adjusting the color temperature, particularly by shifting from white light to warmer tones. It was noted that the morning light should strike a better balance between stimulation and comfort serving as a gentle wake-up cue rather than causing discomfort. Additionally, a greater range of color and brightness options was suggested to account for individual sensitivities and preferences.

Other feedback addressed environmental considerations. Some participants emphasized the importance of hygiene, especially for use with ICU patients, while others suggested enhancing the realism of the testing environment by incorporating subtle background sounds. One participant also noted that the time of day when the test is conducted could influence results and recommended that the user remain unaware of the actual time to preserve the authenticity of the experience.

Finally, for evening use, there were calls for the lighting to dim to total darkness to support sleep readiness more effectively. These insights collectively point toward a more personalized, comfortable, and context-aware product design for future clinical implementation.

Physiological Response to Lighting Modes

Morning Light Mode – Heart Rate Trends

The heart rate data is taken from fitbit and its averaged among participants and collected over 4-minute and 30-second testing duration under the morning light mode suggests a modest but notable pattern of physiological arousal. Participants were exposed to a light setting intended to promote alertness and increased energy levels, both of which are typically associated with elevated heart rate. As shown in Figure 100, the average heart rate at the start of the session (00:30) was 71 bpm. A brief initial decline was observed, reaching a minimum of 69 bpm at 01:00. However, following this dip, the heart rate showed a consistent upward trend, peaking at 72 bpm at 02:30. This peak may indicate the point of maximum physiological responsiveness to the morning light stimulus.

After reaching the maximum average value, heart rate slightly fluctuated but remained relatively elevated compared to the initial trough. From 03:00 onwards, it alternated between 70 and 71 bpm, ending at 71 bpm at the 04:30 mark—the same value recorded at the session's onset but higher than the early-trough values.

These preliminary observations suggest a potential trend toward increased alertness under the morning light mode. While a gradual rise in heart rate was observed during this condition, the effect was modest and could also be attributed to inter-participant variability. Therefore, further investigation with a larger sample size is needed to confirm this relationship. This aligns well with the objective of morning light settings—to promote a smooth transition into a more alert and activated state.

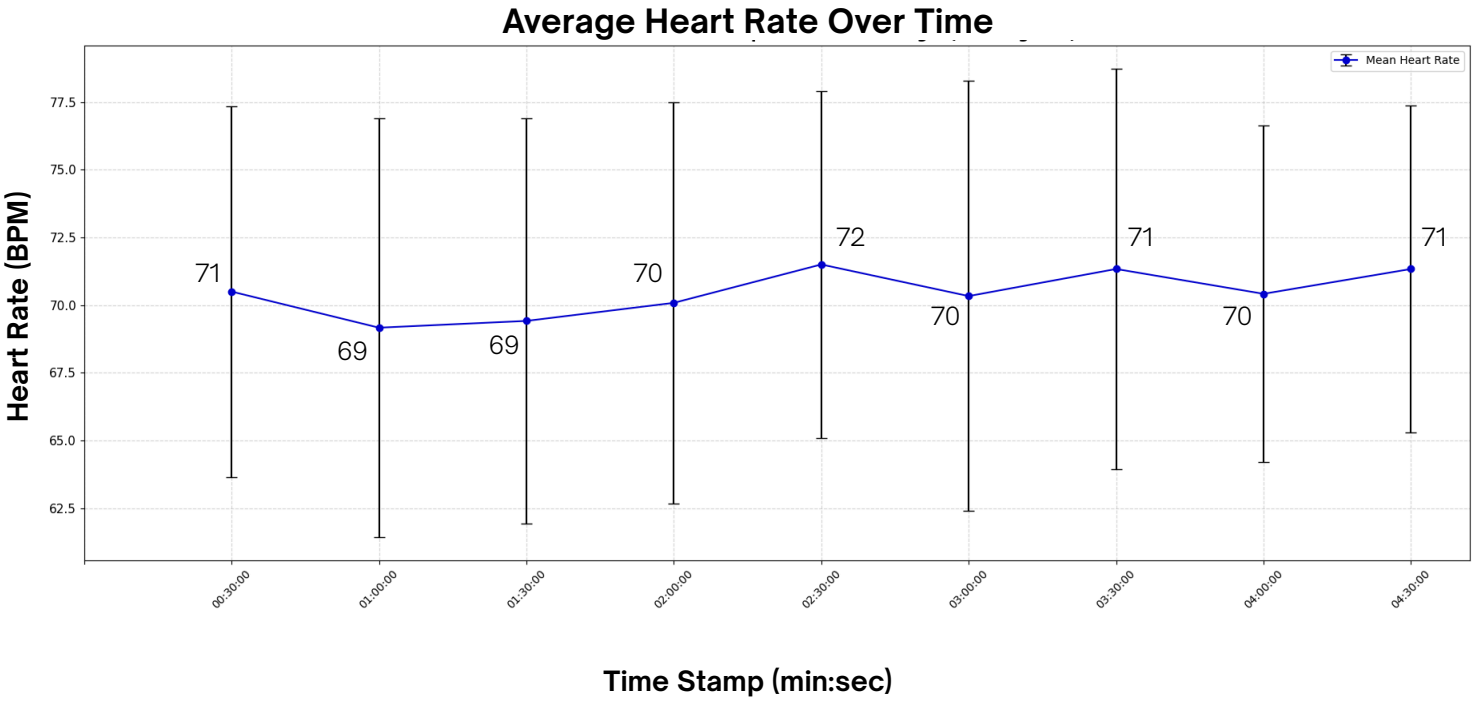


Fig 100: Averaged Heart Rate Readings at Each Timestamp in Morning Mode.

Evening Light Mode – Heart Rate Trends

The heart rate response recorded during the 4-minute and 30-second exposure to the evening light mode reflects a gradual downregulation of physiological arousal, aligning well with the intended calming and relaxing effect of this lighting condition.

As seen in Figure 101, the averaged heart rate among participants taken from fitbit began with an heart rate of 70 bpm at 00:30. A slight early dip to 67 bpm occurred at 01:00, followed by a brief increase to a peak of 71 bpm at 02:00. This momentary rise may represent a transitional adjustment as participants shifted from baseline to the influence of the ambient light.

Following this initial adjustment, heart rate steadily declined over time from 69 bpm at 02:30 to 66 bpm by the session's end at 04:30. This consistent downward trend indicates a progressive reduction in physiological arousal, suggesting the evening light mode successfully promoted a calming effect. The decreasing heart rate pattern aligns with expectations for evening settings designed to help prepare the body for rest or a lower-activity state.

Overall, the data suggest that the evening light mode effectively facilitated a state of relaxation. The gradual and sustained decrease in heart rate reflects a soothing physiological response, supporting the goal of creating a restful and tranquil lighting environment during evening hours.

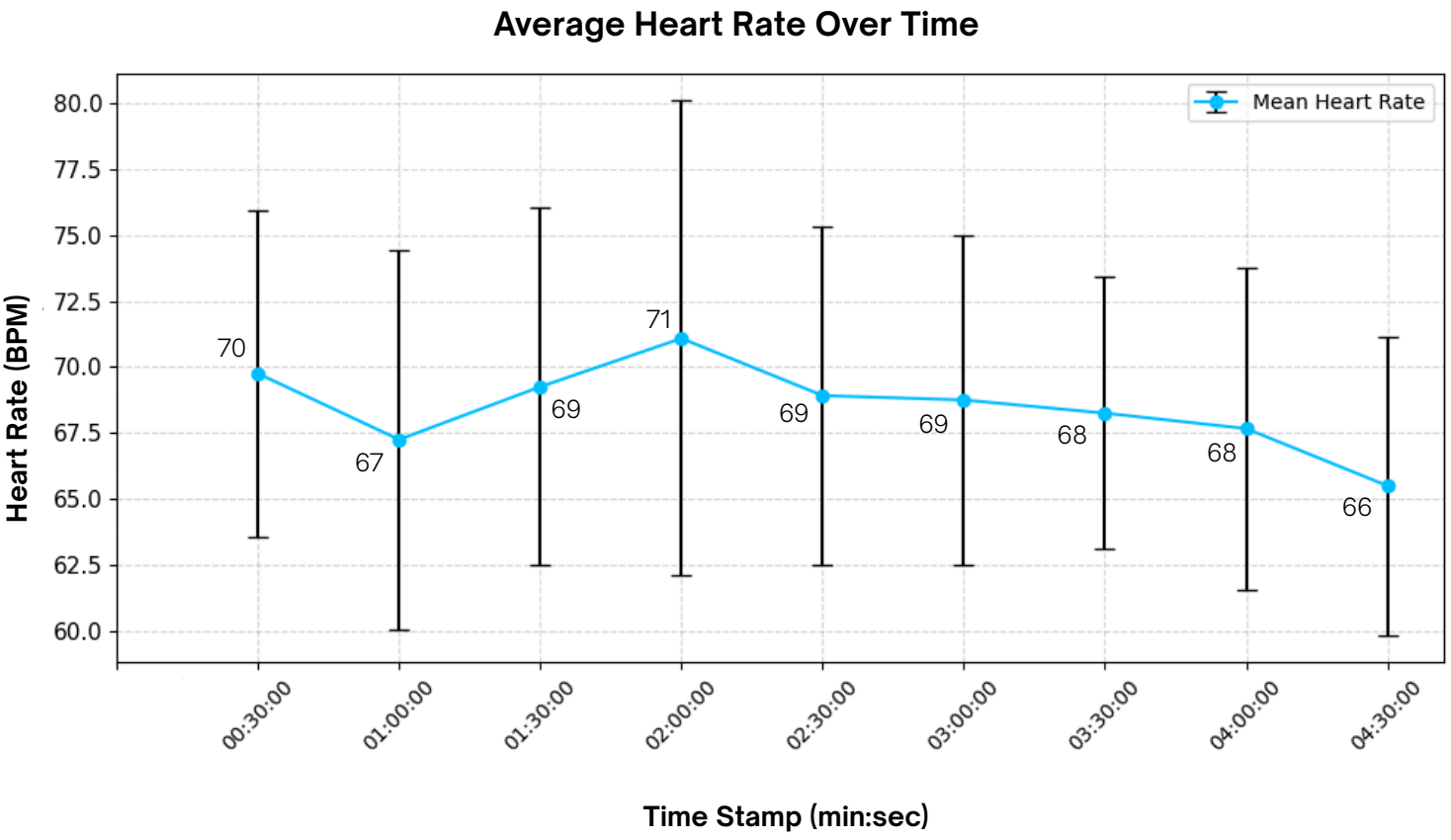


Fig 101: Averaged Heart Rate Readings at Each Timestamp in Evening Mode.

Comparative Analysis of Morning vs. Evening Modes

A comparison of the heart rate responses under morning and evening light modes (Figure 102) highlights the contrasting physiological effects each setting is designed to achieve. The morning light mode elicited a gradual increase and stabilization of heart rate, peaking at 72 bpm around 02:30 and maintaining elevated levels (70–71 bpm) through the remainder of the session. This pattern indicates a successful activation of physiological arousal, consistent with the goal of promoting alertness and energy during morning hours. In contrast, the evening light mode showed a progressive decline in heart rate following a brief peak at 02:00 (71 bpm). From that point onward, heart rate steadily decreased to 66 bpm by the session's end, reflecting a calming and relaxing effect.

Interestingly, from the overall heart rate trend, it can be observed that during the initial 2 to 2.5 minutes of exposure, the body appears to undergo an adjustment phase as it adapts to the new lighting condition, see Figure 103. Following this adaptation period, the heart rate response begins to align more consistently with the specific physiological effect of the light mode, either increasing under the morning light or decreasing under the evening light. This transitional adjustment period may reflect the body's circadian and autonomic regulation processes responding to environmental light cues. A similar adaptation phase could potentially occur in ICU patients when exposed to tailored lighting interventions, suggesting that both the timing and duration of light exposure may be critical factors in optimizing therapeutic outcomes in clinical settings.

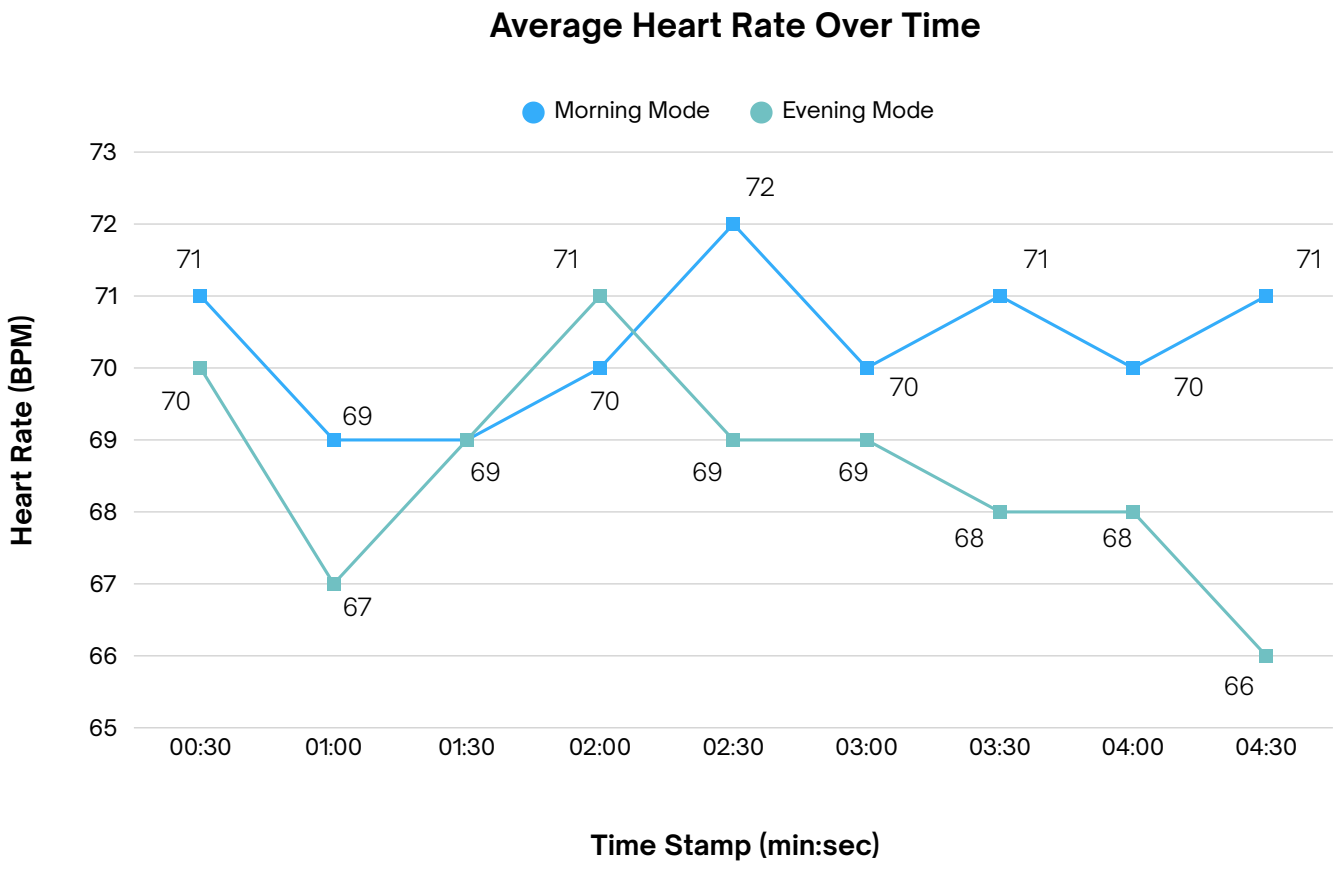


Fig 102: Comparison Between Morning and Evening Lighting Modes

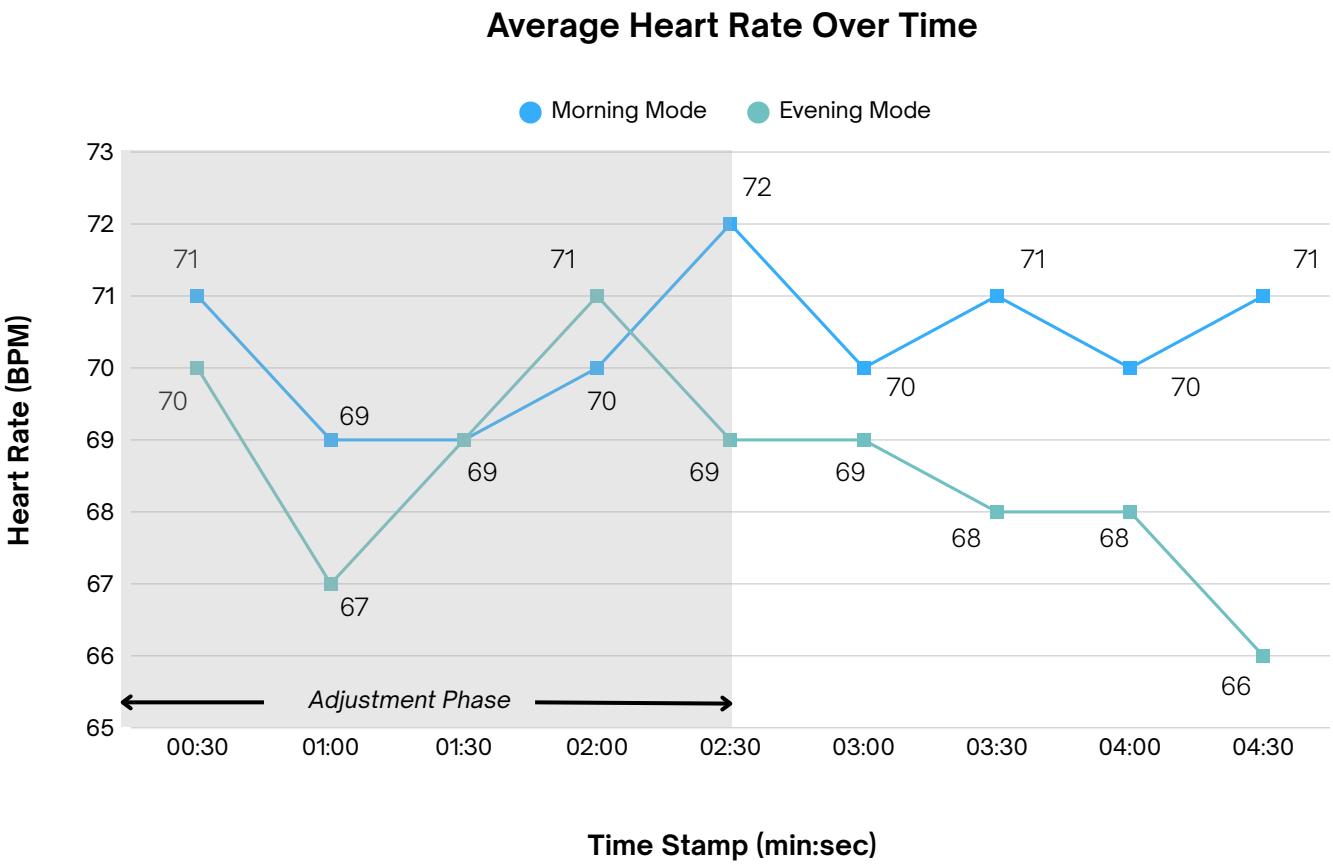


Fig 103: Representation of Adjustment phase on graph.

Limitations of the first evaluation

While the user testing provided valuable insights into the physiological effects of different lighting modes, several limitations should be acknowledged. Firstly, an exact replication of the Intensive Care Unit (ICU) environment was not possible. In a typical ICU setting, lighting panels are positioned behind the patient's head, whereas in the testing room, light was emitted from two ceiling-mounted panels. This difference in spatial lighting orientation may have influenced the distribution and intensity of light exposure, potentially affecting heart rate responses. Additionally, the overall duration of the test was approximately 30 minutes, with each lighting mode applied for only 4 minutes and 30 seconds. Analysis of the collected data suggests that this exposure time may have been too short to capture the full physiological impact of the lighting conditions. Extending the exposure duration in future tests may provide more robust and conclusive data. Another limitation was the prototype used during the session; it was not fully optimized for comfort, making it difficult for participants to remain relaxed or sleep uninterrupted for the full 20-minute resting periods. This discomfort could have influenced physiological readings, including heart rate variability. Addressing these limitations in future iterations will be essential for enhancing the accuracy and ecological validity of the findings.

5.5 CONCLUSION

This chapter presented a comprehensive walkthrough of the LumoGlaze system from circuit-level design and software integration to ergonomic prototyping and user testing. By incorporating adaptive lighting strategies responsive to physiological states, the system demonstrates a novel approach to supporting circadian health in high-stress environments such as the ICU.

The evaluation revealed encouraging results, indicating that users perceived meaningful differences between light modes and experienced changes in internal states aligned with the intervention's objectives. While areas for refinement remain particularly in comfort and light intensity modulation, the findings validate the design intent and lay a strong foundation for future clinical application and longitudinal testing.

These findings will directly inform the next iteration of LumoGlaze. The forthcoming design phase will focus on improving the physical comfort of the wearable, optimizing lighting parameters for both stimulation and relaxation, and refining the testing environment to better replicate real-world ICU conditions. Extended testing durations will also be incorporated to validate and strengthen the system's therapeutic potential.

Together, the outcomes underscore the system's potential to redefine how light can be used therapeutically in healthcare settings, blending technical sophistication with human-centered design.

6.

REFINING THE INTERVENTION SYSTEM

This section describes the refinement phase of the LumoGlaze and LumoSync system, focusing on addre-ssing key issues identified during the first round of user testing. The primary goal was to enhance physical comfort, improve the ergonomic fit of the wearable, and advance the functionality of the system through technical and interface-level improvements. These refinements included a fully integrated power supply, simplified internal wiring, a more compact form factor, and an updated app interface with enhanced usability features.

A second user evaluation was conducted in a semi-controlled ICU-simulated environment to assess the system's comfort, usability, and physiological impact. Participants engaged with both morning and evening light modes while wearing the updated prototype, and their feedback provided valuable insights into the revised system's performance. The section concludes with a comparative analysis of heart rate responses across lighting conditions and highlights opportunities for future improvements in long-term usability and therapeutic potential.

6.1 ERGONOMIC REDESIGN OF LUMOGLAZE

In the first version, the goggles followed a simple, flat profile similar to standard spectacles, lacking sufficient curvature to follow the natural contour of the user's head. This straight design contributed to localized pressure points, particularly at the nose bridge. In response, the second version introduced a fully curved form factor inspired by the head geometry extracted earlier from the mannequin model (Section 5.4.1). The integration of curvature allowed the frame to naturally wrap around the head, distributing pressure more evenly and eliminating the need for additional cushioning materials in this prototype phase. Due to time constraints, further exploration of comfort padding was postponed to subsequent iterations.

In addition to the structural redesign, several functional modifications were implemented:

- The placement of components was adjusted for better usability. The rotary encoder, originally positioned on the left side in V1, was shifted to the right-hand side in V2. Similarly, the slide switch was relocated to the left-hand side for improved balance and accessibility during use.

- The product assembly was simplified from a three-part structure in V1 to a two-part structure (front and back) in V2. This reduction decreased both overall weight and the number of fastening points, improving handling while retaining previously validated screw dimensions from V1.

- The attachment mechanism for the head strap was redesigned to eliminate additional clamping components. Instead, dedicated cut-outs were integrated directly into the housing to secure the strap using screws, avoiding additional pressure on the ear area.

- An angled cut-out was added to facilitate smoother cable routing towards the external microcontroller, improving the ease of assembly and wire management.

Collectively, these design refinements reflect a balance between addressing comfort concerns raised during user testing and preserving the functional requirements necessary for the lighting system, electronics integration, and overall durability of the device.

6.2 UPDATED LUMOSYNC USER INTERFACE

In parallel with the hardware improvements of the LumoGlaze wearable, the accompanying LumoSync mobile application was also refined to enhance user interaction, system control, and data monitoring capabilities. While the core functionality of BLE-based device pairing, mode selection, and biometric monitoring remained consistent with the earlier version, several interface elements were redesigned to improve usability, visual clarity, and workflow consistency. The updated app structure maintains a minimal cognitive load while providing researchers and users with intuitive access to real-time system status, manual controls, and session data exports. The app interface is structured across multiple purpose-driven screens, as outlined below.

Fig 104: New LumoGlaze Front Panel (Front View)

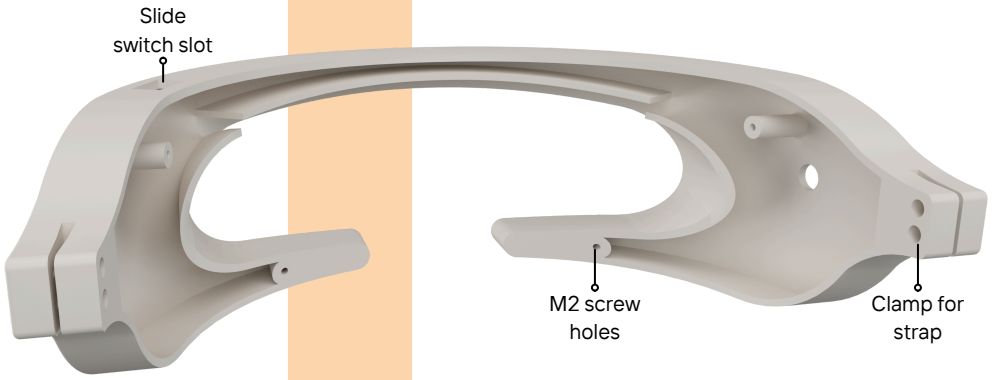


Fig 105: New LumoGlaze Front Panel (Rear View)

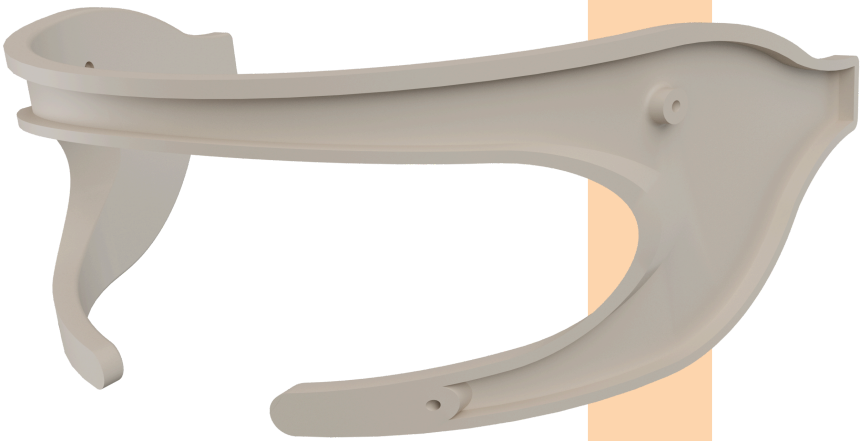


Fig 106: New LumoGlaze Back Panel

Welcome Screen (LumoSync Intro)

The Welcome Screen introduces users to the system in a visually minimal yet informative manner. It features institutional logos, a glowing lightbulb icon, the app name “LumoSync” and the tagline “Smart Lighting for Sleep Wellness.” A fade-in animation creates a smooth onboarding experience, while a simple “tap anywhere to continue” interaction reduces cognitive load.

This screen also disables the back button to maintain a linear flow, leading directly to the device connection interface.

BLE Device Connection Screen (ConnectSync)

The ConnectSync screen initiates BLE scanning and displays a list of nearby devices with identifiable names and IDs. Users can tap to connect to a device, trigger a rescan, or skip the pairing process for offline testing or demonstration.

A dynamic feedback interface shows scanning progress or “no devices found” messaging, maintaining user awareness. The screen also includes styled navigation elements and ensures seamless transition back to the Welcome screen if needed.

Dashboard Screen (LumoDash)

LumoDash acts as the central control panel and monitoring interface. It includes modular, card-style sections for:

- Bluetooth Status: Indicates real-time device connection.
- System Status: Displays current time, heart rate, sleep phase, power, and light mode.
- Mode Selection: Allows toggling between automatic and manual modes, with slider-based brightness control in manual mode.
- Heart Rate History: A real-time line chart visualizes biometric trends.
- Sleep Log Export: Enables session data export in CSV format for research analysis.

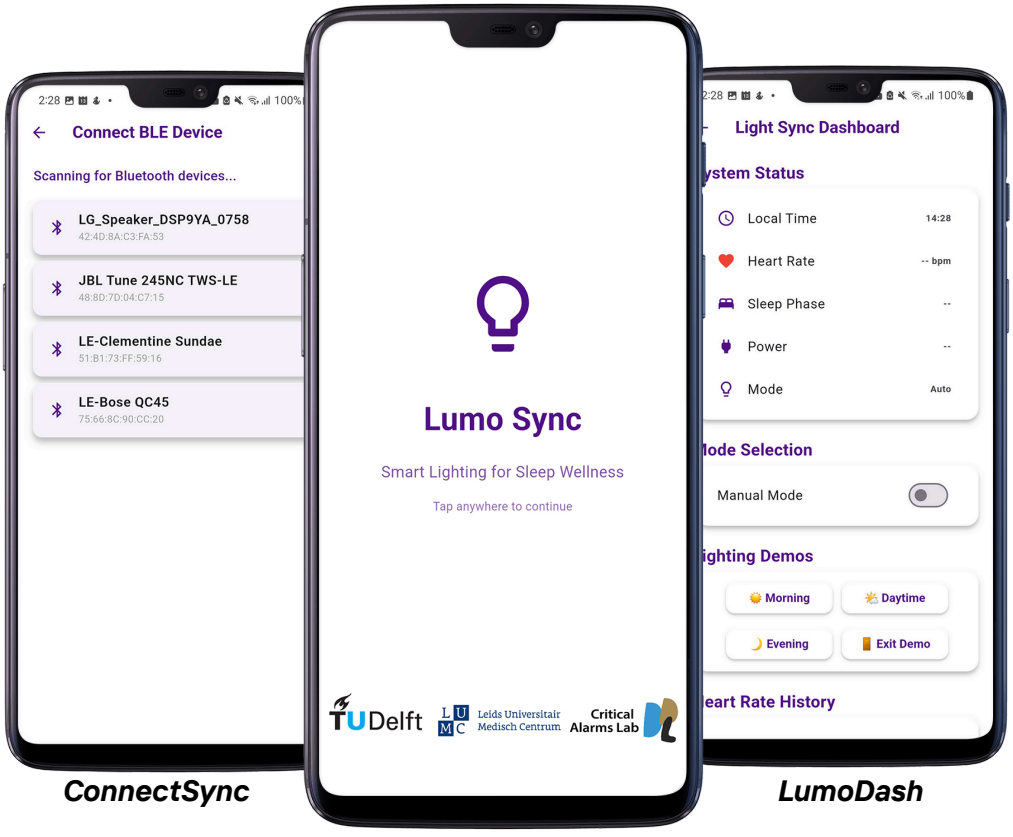


Fig 107: New LumoSync User Interface

6.3 FINAL ASSEMBLY & EXPLODED VIEW OF NEW LUMOGLAZE

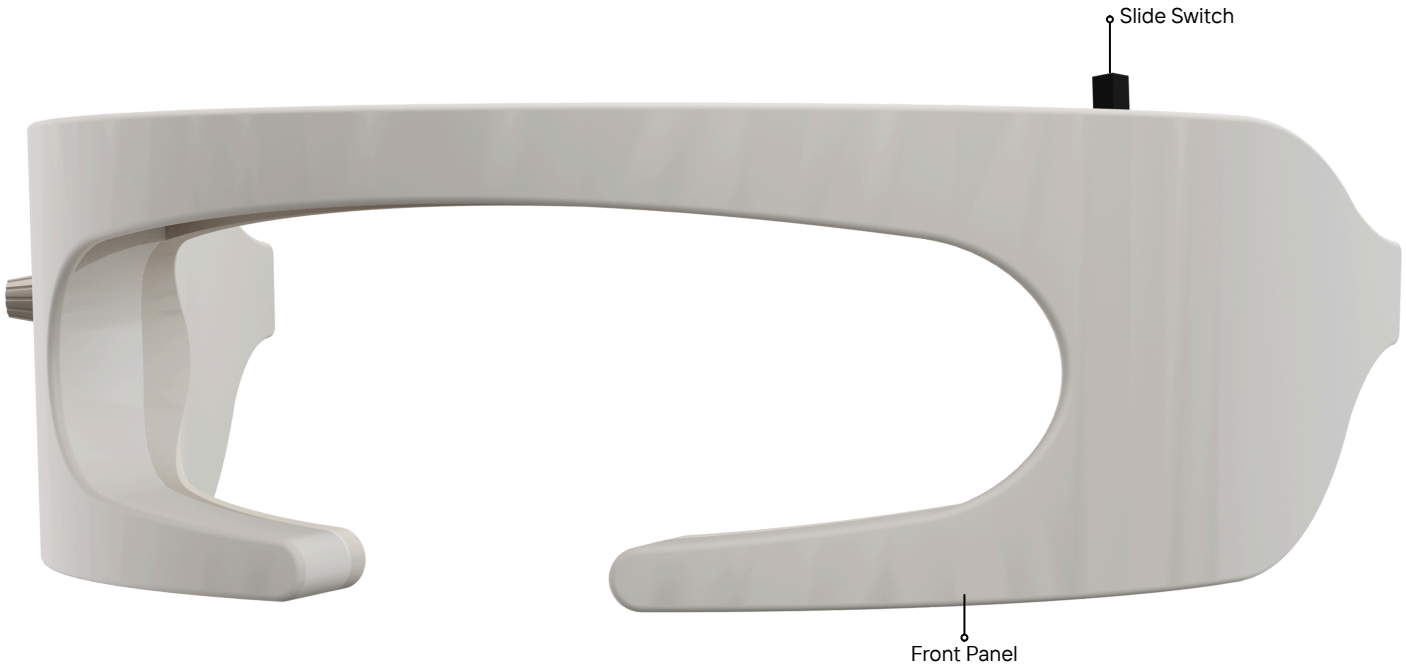


Fig 108: New LumoGlaze front view

Fig 109: New LumoGlaze Back Panel

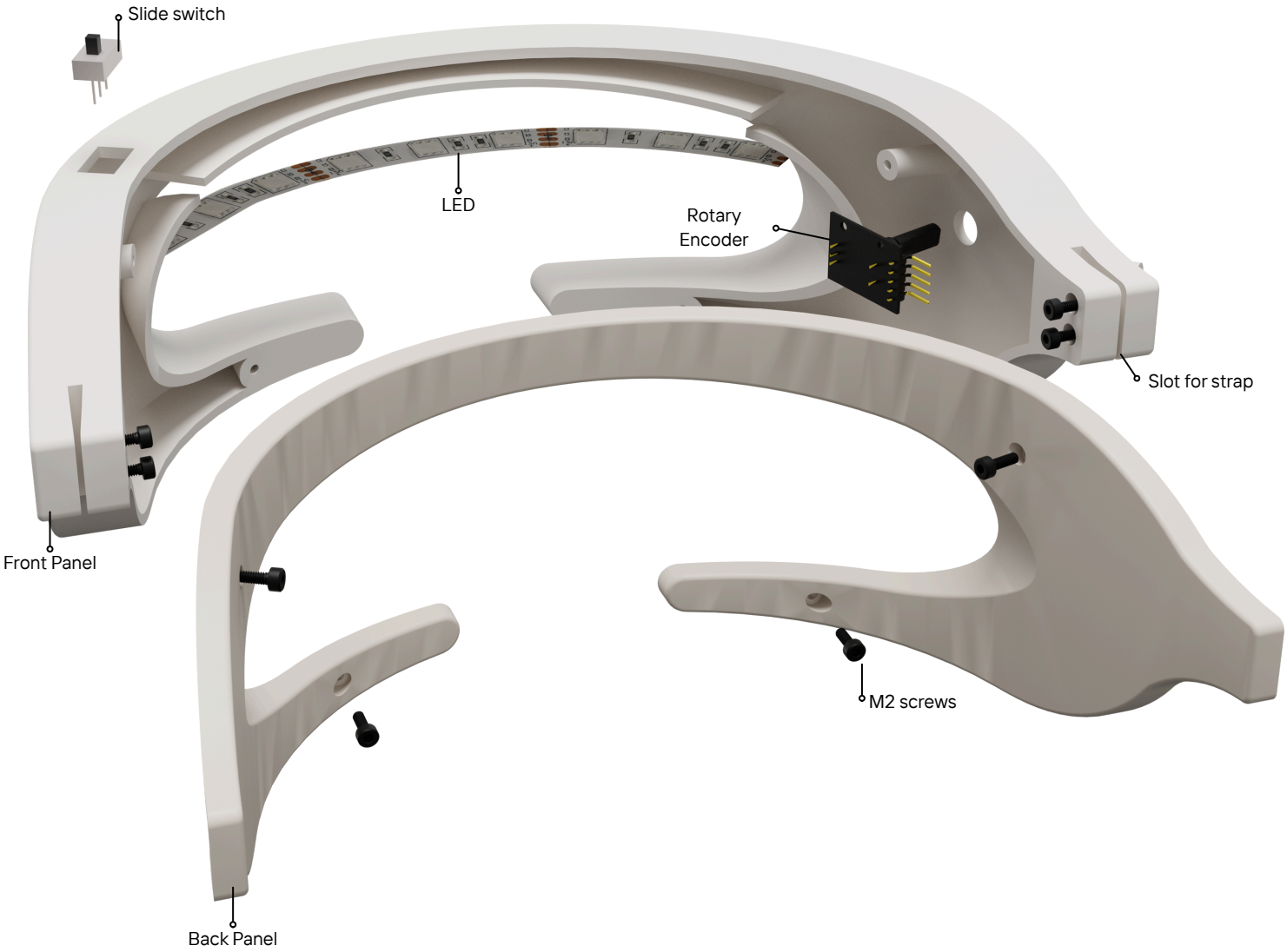


Fig 110: Exploded view of new LumoGlaze

6.4 LIGHTING MODES

Fig 111: Morning lighting mode

Fig 112: Evening lighting mode

6.5 POWER SUPPLY INTEGRATION AND WIRING ARCHITECTURE

A key objective of the final prototype was to achieve complete standalone operation without reliance on external power sources. The initial version of the system was dependent on an external 5V power supply, which limited portability and required constant connection to either a power outlet or an external battery pack. This configuration was not suitable for the intended wearable application, where compactness, autonomy, and ease of use are critical.

To address these limitations, the power system was redesigned to integrate directly into the goggles, enabling full mobility and eliminating the need for external cables. After evaluating multiple options, Li-Po batteries were selected for their favorable balance between size, weight, and capacity. A 250 mAh Li-Po cell was chosen, providing sufficient operating time while fitting within the available space alongside other components, see Figure 113 .

Fig 113: 250 mAh Li-Po Battery

However, these batteries deliver a nominal voltage of ~3.7V (ranging from 3.0V to 4.2V during discharge cycles), which is insufficient to power the 5V LED strips and the microcontroller directly. To resolve this, a boost converter module was introduced to step up the battery voltage to a constant 5V output see Figure 114, ensuring stable operation of both the TinyPico microcontroller and the LED system, independent of the battery's charge state.

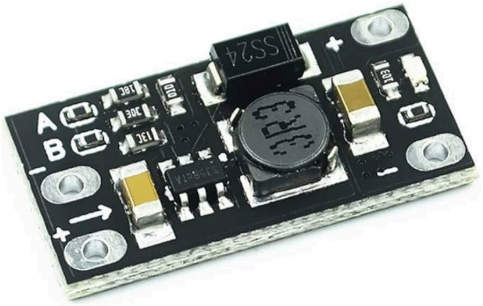


Fig 114: Boost Module

An additional improvement was made by utilizing the TinyPico's integrated charging circuit via USB-C, which allowed safe and efficient battery charging without the need for a separate external charging module. This reduced overall system complexity and contributed to further weight and space savings — critical for a wearable system.

Connection Architecture

The finalized wiring configuration includes:

- The 250 mAh Li-Po battery is connected to the boost converter through a slide switch.
- The boost converter outputs a regulated 5V that powers:
  - The TinyPico microcontroller.
  - The LED strips are powered through a direct 5V rail.
- A common ground is maintained across all components to ensure stable electrical operation.
- The TinyPico manages battery charging directly via its onboard USB-C port.

Slide Switch Integration and Functional Benefits

To provide additional control and protection, a slide switch was integrated between the battery and the boost module. This addition offers several key advantages:

- Standalone Power Control: Allows the system to be turned ON or OFF without disconnecting any physical wiring, supporting the fully self-contained design.
- Battery Protection: Prevents unnecessary power consumption when the system is not in use, helping to preserve battery charge during periods of inactivity.
- Safe Charging Isolation: Enables the battery to charge safely while keeping the rest of the system fully powered down, minimizing risks during charging cycles.

These design modifications have collectively transformed the prototype from a test setup into a fully functional, compact, and user-friendly wearable system optimized for real-world application and testing.

The complete wiring diagram illustrating this integrated power architecture is provided in Figure 115.

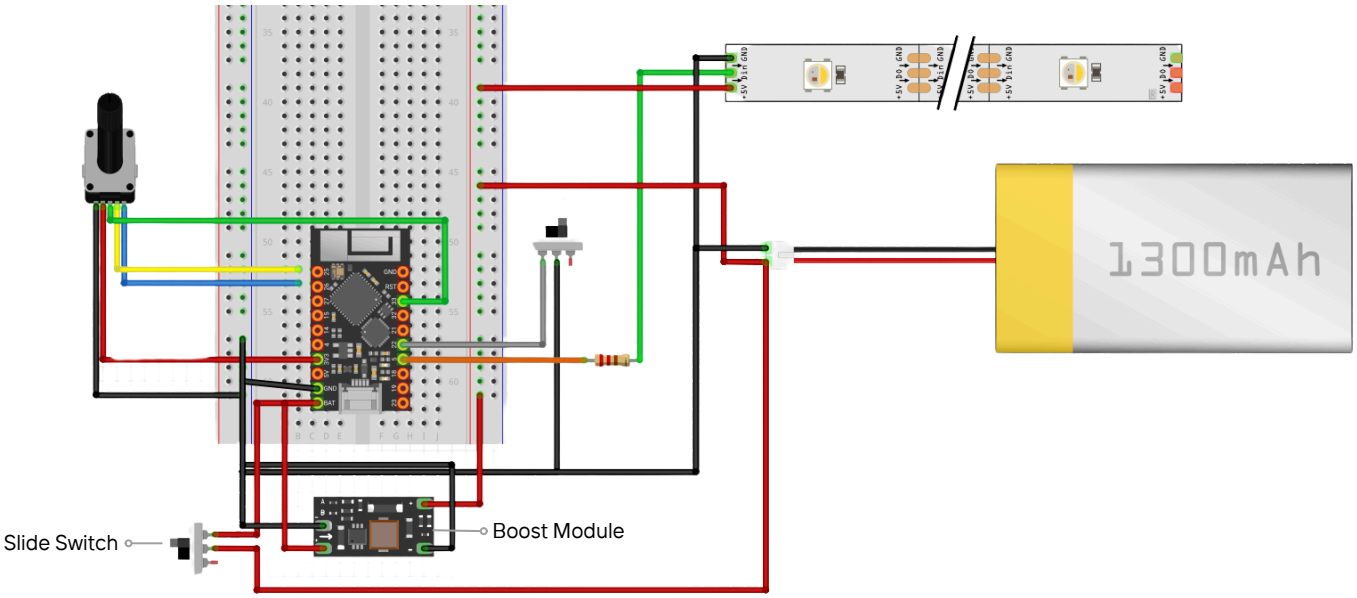


Fig 115: Wiring Schematic of the connections.

6.6 USER TESTING PHASE II

Goal

The primary objective of this second user testing phase was to evaluate the new LumoGlaze smart goggles and the LumoSync mobile application with a focus on both usability and comfort.

Specifically, the study aimed to:

- Assess the physical comfort and fit of the improved LumoGlaze prototype during a 15-minute usage period.
- Evaluate the usability and intuitiveness of the LumoSync app, particularly its core functions such as lighting control, manual/automatic mode selection, and live system status monitoring.
- Gather first-time user impressions regarding interaction flow and visual communication within the app interface.

The 15-minute session length was chosen to balance in-depth interaction with the system and meaningful physiological data collection, providing a comprehensive snapshot of both user experience and performance impact.

Participants

A total of 8 healthy adult participants took part in this evaluation. All participants were male, with an average age of 25 years. The group consisted of students with varied academic backgrounds, providing relevant feedback on both the physical design and interaction elements of the system. All participants reported no known visual impairments or sleep-related disorders that could influence the results. Before participation, each individual was informed about the study procedure and provided written consent, following ethical guidelines for user testing. The study was approved by the TU Delft Ethics Committee under approval number 26.

Material

The following equipment and instruments were used during testing:

- LumoGlaze Smart Goggles Prototype
- LumoSync Mobile Application
- Fitbit Wearable Tracker
- Pulse Oximeter

Fig 116: Materials Used in User Testing.

Set-Up

Testing took place in a semi-controlled, ICU-simulated environment inside the IDE building at TU Delft. The test space included:

- An ICU bed, inclined to simulate typical resting posture and improve light exposure.
- A student table, used for briefing, feedback collection, and informal discussion.
- Controlled ambient lighting, with minimal natural light interference, ensuring consistent exposure across all participants.

Participants lay in a resting position wearing the goggles and physiological monitors, while the LumoSync app was used to operate the light modes and log session details.

Procedure

Upon arrival, participants were welcomed and given a verbal explanation of the study objectives. Participants then reviewed and signed an informed consent form prior to the evaluation.

Each participant was fitted with a Fitbit tracker and pulse oximeter to monitor physiological parameters. They were guided into a reclined resting position on an inclined ICU bed to simulate clinical resting posture. The New LumoGlaze smart goggles were carefully positioned, and participants were given a few moments to acclimate to the device before testing began.

The sequence of lighting exposures was randomized for each participant, to minimize the order effect.. Although the overall session lasted between 45 to 50 minutes, each lighting condition morning and evening mode was presented for 15 minutes, allowing sufficient time for physiological responses such as heart rate variation to be observed. The order of the two lighting modes was randomized for each participant to minimize order bias and adaptation effects.

Throughout the session, the LumoSync mobile application was used to control light transitions and manage manual/automatic settings. After both lighting modes were experienced, participants were asked to provide structured feedback via verbal Likert scale responses and informal discussion.

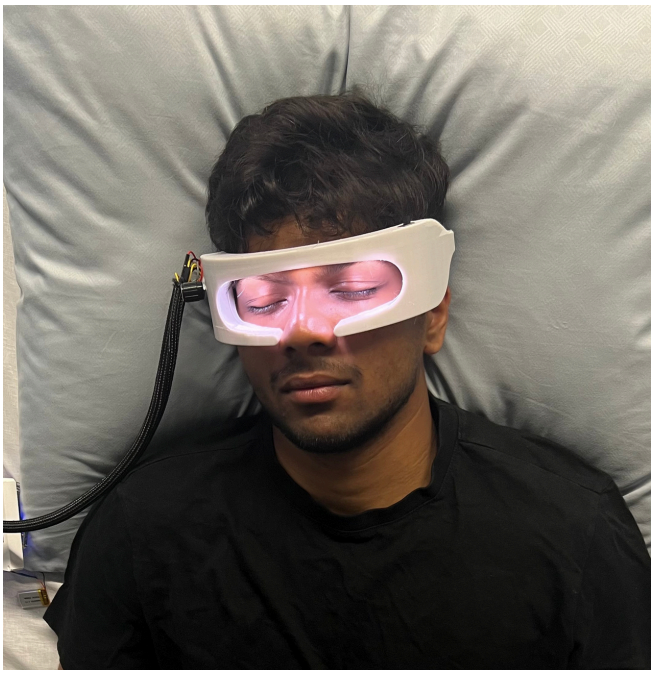


Fig 117: Observation of Participant Under Morning Light Conditions.

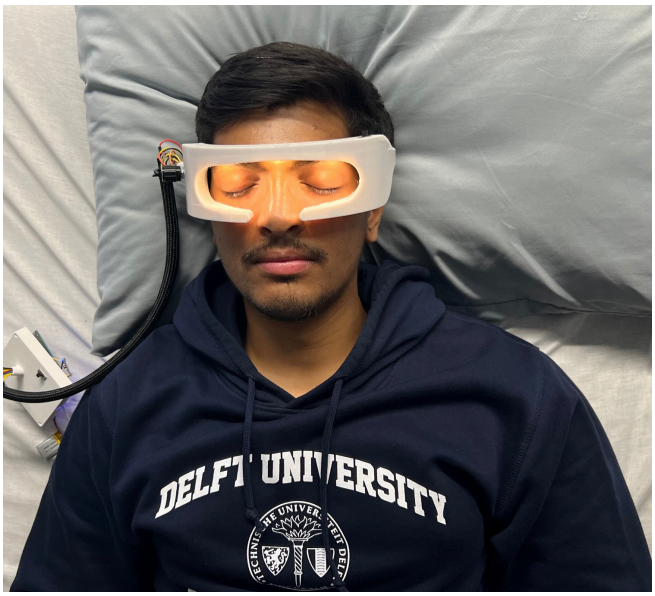


Fig 118: Observation of Participant Under Evening Light Conditions.

Results

This section presents the findings from the second user testing session, which focused on evaluating the updated LumoGlaze smart goggles prototype and the newly introduced LumoSync mobile application. Unlike the first session, which placed equal emphasis on physiological responses, lighting behaviour, and physical comfort, this round of testing prioritized physical comfort, wearability, and interface usability, with more data points of physiological parameters (Heart rate) as the lighting modes had already been validated in the earlier evaluation.

As the number of LEDs was reduced in this prototype iteration, no specific questions were posed regarding the perceptual experience of different lighting modes, apart from the perceived brightness level, which was assessed informally to ensure it was comfortable for participants. The main aim was to understand if the design modifications improved user comfort and to identify any areas that still caused discomfort during prolonged use.

Additionally, since the LumoSync app was introduced for the first time in this session, participants were asked to provide feedback on the clarity, intuitiveness, and responsiveness of the user interface. Questions focused on whether the app flow was easy to understand, whether commands provided visible or meaningful feedback, and whether the manual and automatic controls were accessible and logically structured.

Both verbal Likert-scale responses and open-ended comments were used to capture the participants' subjective feedback. The following sections summarize these findings across key themes, including physical comfort, app usability, and overall impressions.

Subjective User Feedback on Lumoglaze and LumoSync

Goggle Comfort and Ergonomic Feedback

Participants were asked to rate the comfort level of wearing the LumoGlaze smart goggles during the session. Out of 8 participants, 6 selected "*Strongly agree"*, and 2 selected *"Somewhat agree"*, while no participant chose neutral or negative responses. The results are illustrated in Figure 119.

The descriptive statistics of the responses were as follows:
Mean = 4.75, Median = 5, and Standard Deviation (SD) = 0.46.

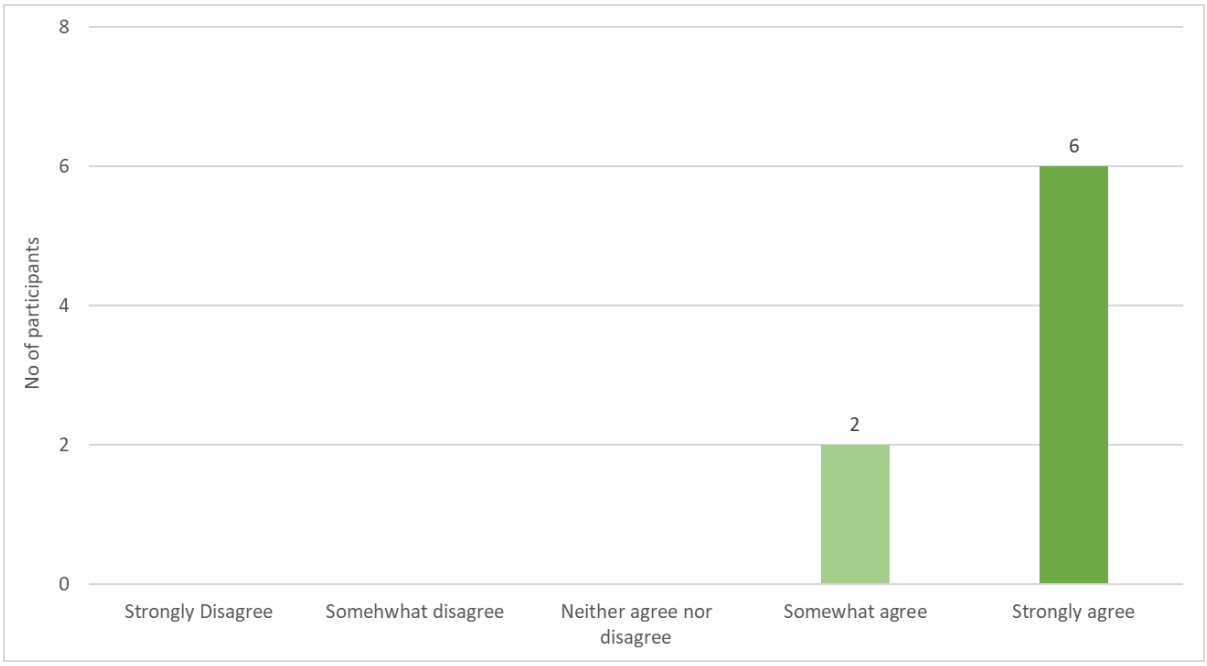
These results suggest that participants found the updated goggle design highly comfortable, with all responses skewed towards the positive end of the scale, indicating strong acceptance of the device's physical wearability for extended use.

Perception of Overall Brightness

Participants were asked to rate the overall brightness level of the lighting during the session. Out of 8 participants, 5 selected *"Somewhat agree"* and 3 selected *"Strongly agree"*, indicating that none of the participants expressed neutrality or dissatisfaction. The results are illustrated in Figure 120.

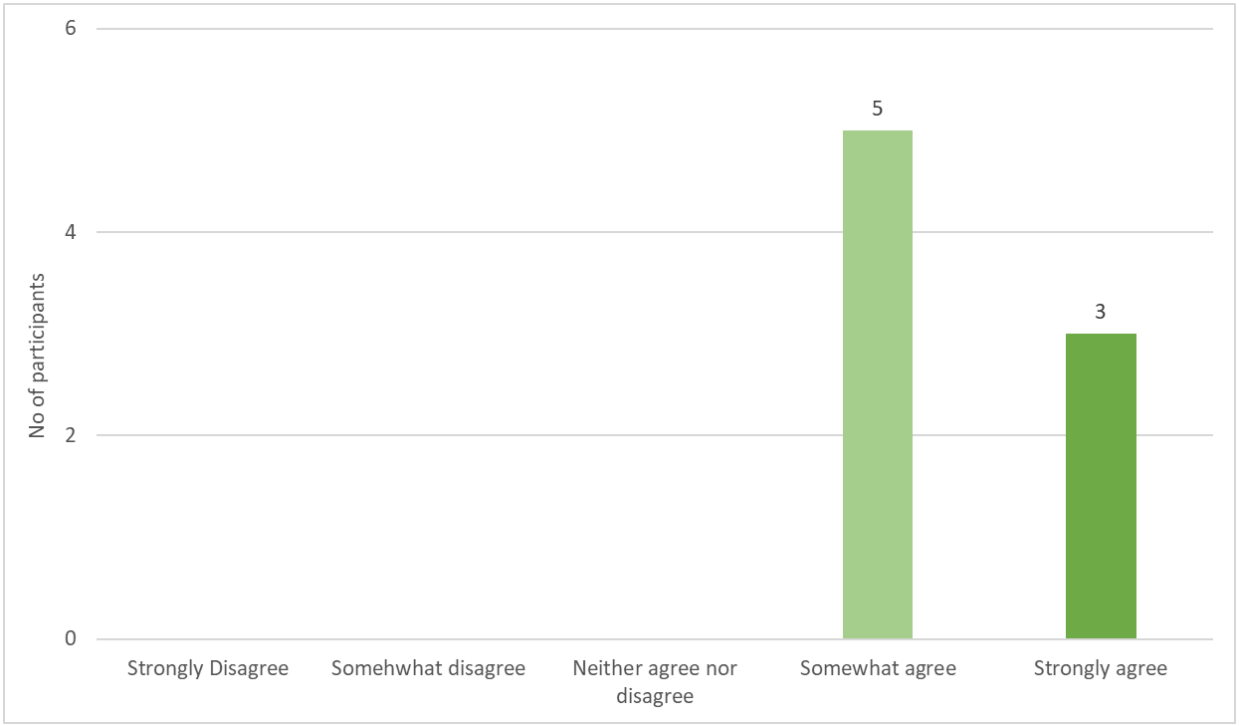
The descriptive statistics of the responses were as follows:
Mean = 4.38, Median = 4, and Standard Deviation (SD) = 0.52.

These results indicate that the brightness level was perceived as generally appropriate and well-balanced. The consistency in positive ratings suggests that the reduced number of LEDs still delivered a satisfactory lighting experience.



Question: Did the goggles felt comfortable to wear during the session?

Fig 119: Participant Ratings on the Comfort of Wearing the Goggles During the Session.



Question: How would you rate the overall brightness level of the light?

Fig 120: Participant Ratings on the overall brightness level of the light.

App Interface and Usability

Participants were asked to evaluate the clarity of the feedback provided by the LumoSync app during their interaction, for example, whether button presses or lighting changes were clearly communicated. As shown in Figure 121, responses were positive: 5 participants *"Strongly Agreed"*, and 3 *"Somewhat Agreed"* that the app gave clear and immediate feedback. No participants expressed disagreement.

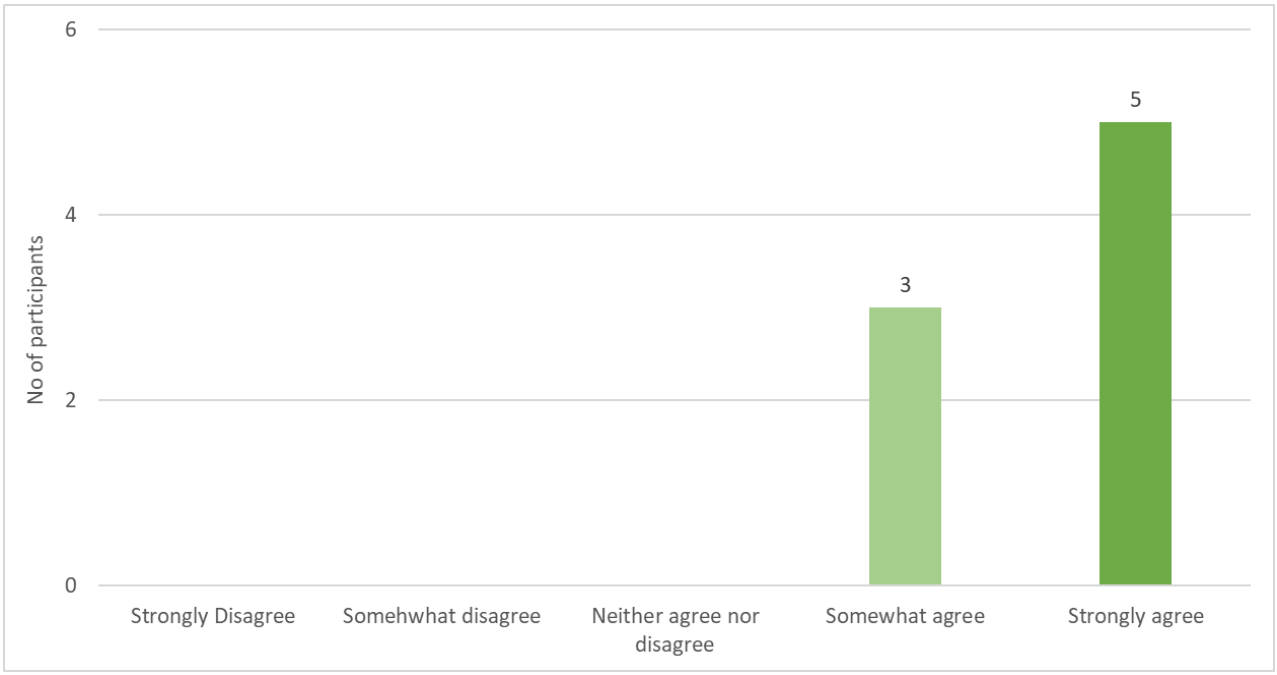
The descriptive statistics of the responses were as follows:
Mean = 4.6, Median = 5, Standard Deviation = 0.52

These results indicate that the app's interaction logic was perceived as intuitive and responsive.

In addition to the quantitative data, participants were asked to share open-ended feedback on the interface design. Their responses reinforced the positive ratings from the Likert scale:

- "Simple, and it's good to have all under one page."
- "Looks good, quite simple."
- "Keep different subsections in the dashboard screen."

While most comments praised the app's simplicity and clarity, one participant suggested adding clearer structural divisions within the dashboard to enhance usability. This feedback highlights an opportunity for refinement in future iterations while affirming the app's overall usability and user-friendliness.



Question: Did the app give clear feedback when you interacted with it?

Fig 121: Participant Ratings on weather the app gave clear feedback when interacted.

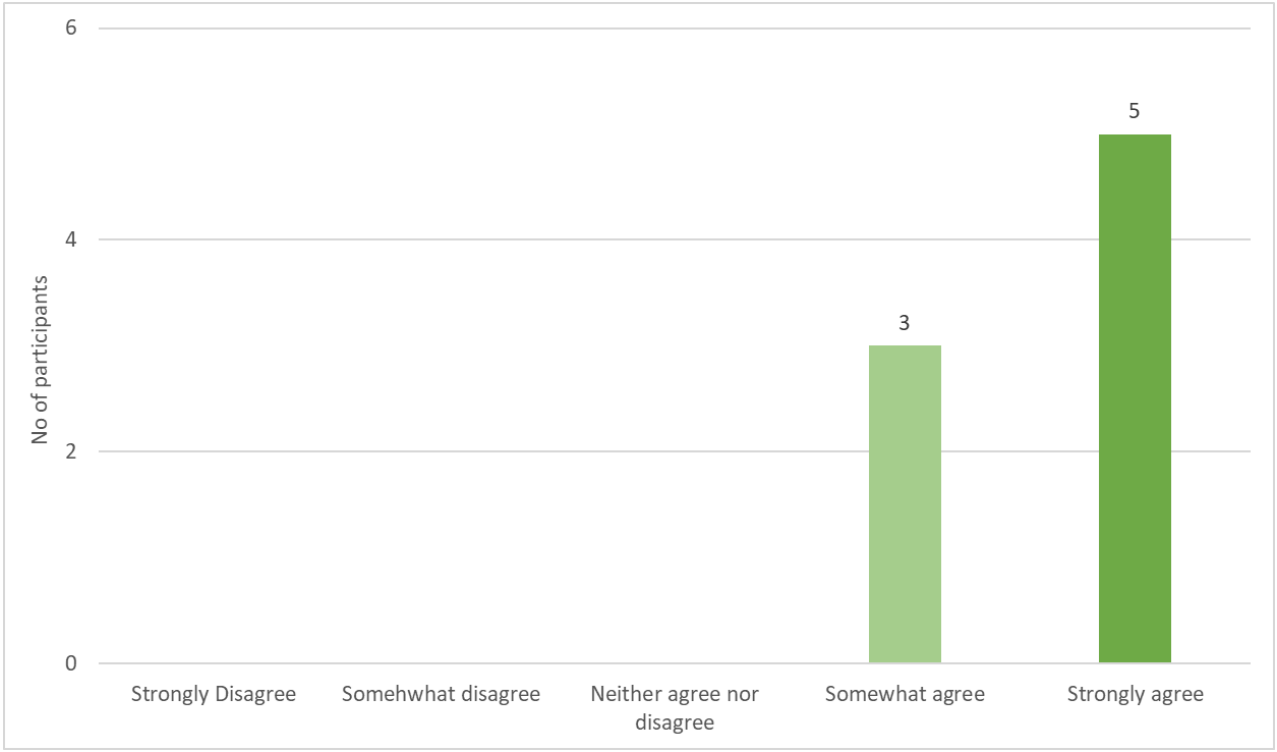
Ease of App Navigation

Participants were asked to rate how easy or difficult it was to navigate the LumoSync mobile application. As shown in Figure 122, responses were largely positive, with 5 participants selecting *"Strongly agree"* and 3 selecting *"Somewhat agree"* regarding the app's ease of use. No participants expressed neutrality or disagreement.

The descriptive statistics of the responses were as follows:
Mean = 4.6, Median = 5, Standard Deviation = 0.52

The descriptive statistics of the responses were as follows:
Mean = 4.6, Median = 5, Standard Deviation = 0.52

These results indicate that the LumoSync app was generally perceived as highly intuitive and easy to navigate. The consistently positive ratings reflect successful UI design choices that allowed participants to interact with the system fluidly and confidently.



Question: How easy or difficult was it for you to navigate the app?

Fig 122: Participant Ratings on how easy or difficult was it for you to navigate the app.

Physiological Response to Lighting Modes

To assess whether different lighting conditions influenced physiological responses, heart rate data was collected during 15-minute exposures to both the morning and evening light modes using the LumoGlaze system. The primary objective was not to prove causality but to explore whether light-based interventions could elicit measurable changes in heart rate trends, as an indirect indicator of arousal or relaxation

Morning Light Mode – Heart Rate Trends

During the morning light exposure, participants' heart rates remained relatively stable, with values ranging between 71 and 75 BPM. The calculated mean heart rate was approximately 73.3 BPM, with a median of 73.5 BPM. No significant upward or downward trend was observed over the 15-minute period, and the heart rate remained within a narrow band for most participants (Figure 123).

While a few minor fluctuations were noted, there were no consistent changes across participants that would suggest a clear activation or alertness effect. The lack of variability may indicate that the light intensity used was neither physiologically stimulating nor disruptive, suggesting a neutral and non-invasive response. However, due to the resting posture and limited physical movement during the session, such stable readings may also reflect baseline physiological states rather than a lighting-induced change.

Evening Light Mode – Heart Rate Trends

Heart rate patterns during the evening light condition were similarly stable, with values ranging from 64 to 69 BPM. The mean heart rate was approximately 66.6 BPM, with a median of 66 BPM. No significant decrease or downward trend was detected across participants (Figure 124). Although a lower average heart rate compared to the morning session was observed, this difference is not sufficient to conclude a lighting effect, especially given the absence of a control group and inter-individual variability.

A minor dip in heart rate was recorded during the later phase of the session for some participants, but this pattern was not consistent or statistically significant. As with the morning session, the controlled posture and environment likely contributed to the overall stability in physiological readings.

Comparative Analysis of Morning vs. Evening Modes

When comparing both lighting conditions, the data reveals minor differences in average heart rate; morning mode showed slightly higher BPM values than evening mode (Figure 125). However, the absence of consistent directional trends across participants suggests that these differences may reflect natural variability rather than a direct physiological response to the lighting modes. Importantly, no adverse reactions or abrupt changes in heart rate were observed, indicating that both light settings were physiologically tolerable and non-disruptive.

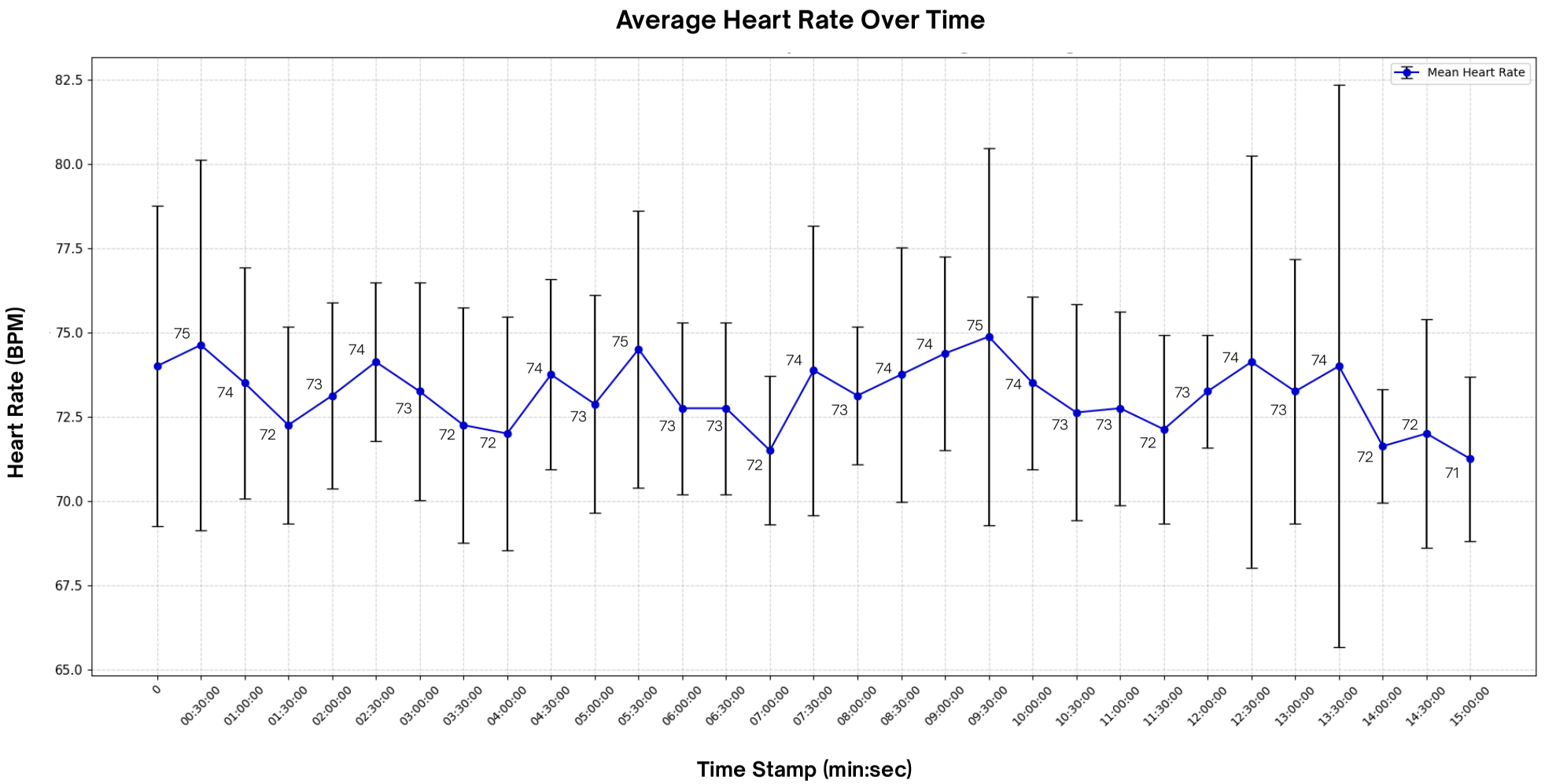


Fig 123: Averaged Heart Rate Readings at Each Timestamp in Morning Mode.

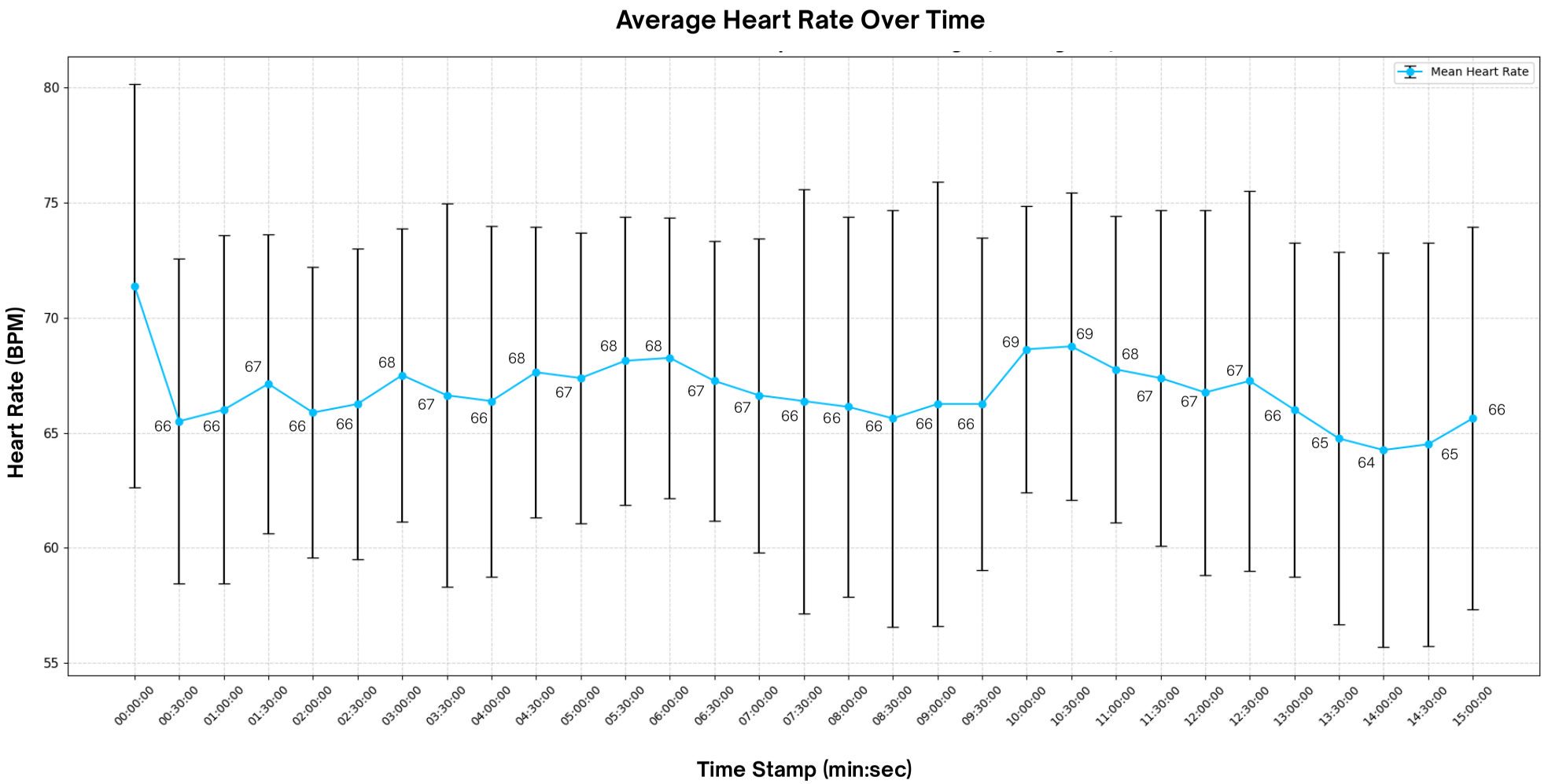


Fig 124: Averaged Heart Rate Readings at Each Timestamp in Morning Mode.

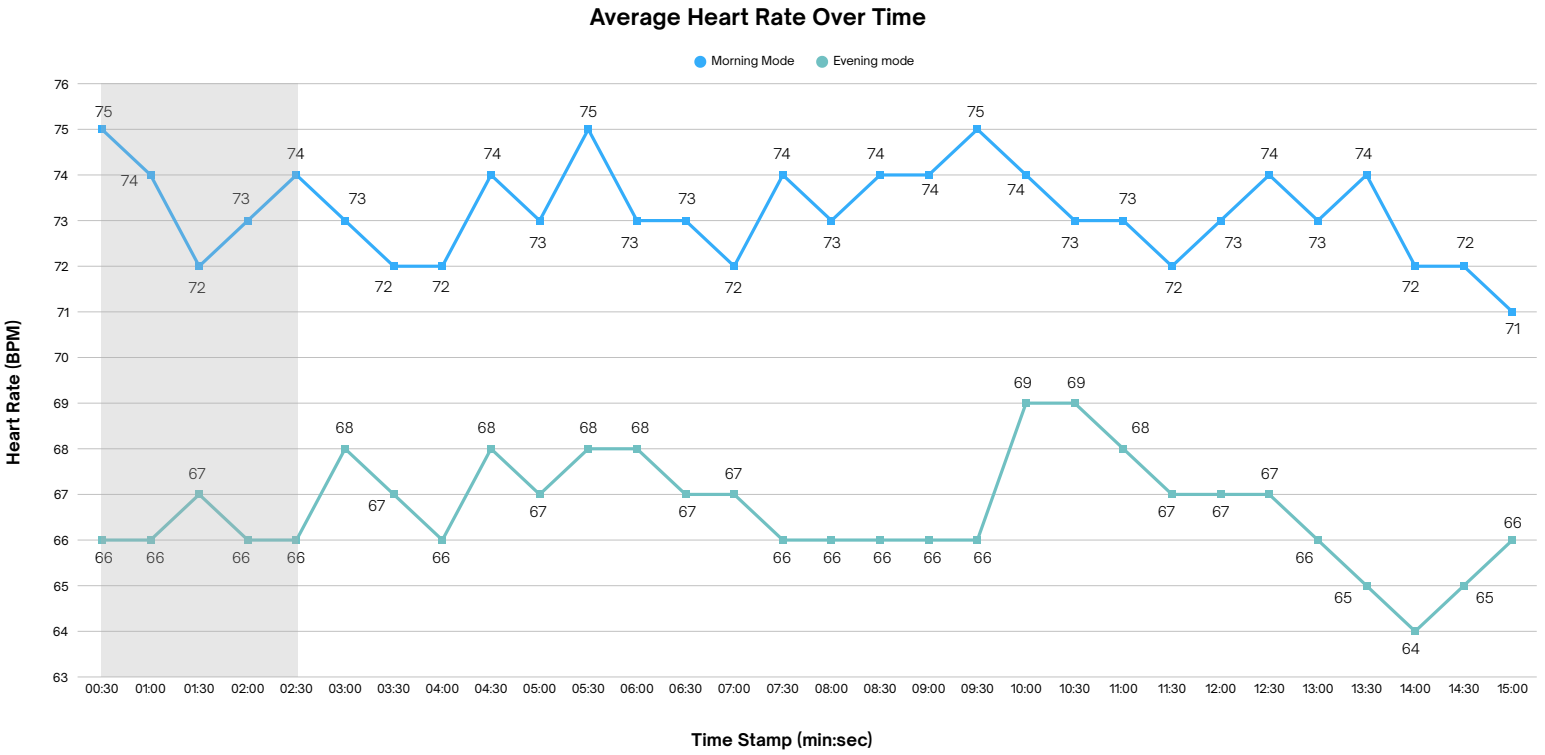


Fig 125: Comparison Between Morning and Evening Lighting Modes

6.7 CONCLUSION

This section documents the second development iteration of the LumoGlaze system, reflecting meaningful progress in both design and usability. The ergonomic redesign improved overall comfort during wear, while the internal battery and interface refinements enhanced system autonomy and user experience. Participants in the second user testing reported positive impressions of both the wearable and the LumoSync app, indicating improved usability and comfort.

Physiological data collected during morning and evening sessions showed stable heart rate trends across participants, with no strong directional shifts. While these findings do not confirm significant physiological effects, they do support the safety, tolerability, and feasibility of the intervention in a controlled environment. The outcomes of this refinement phase affirm the system's design direction and highlight the need for further testing with extended use and diverse patient populations to explore its full clinical potential.

7.

PRODUCT EVALUATION

The product evaluation aimed to assess the LumoGlaze system from practical, clinical, and technical perspectives. ICU nurses provided feedback on usability and workflow integration, highlighting both the potential and challenges of implementing the system in real patient-care settings. In parallel, expert reviewers offered insights into circadian lighting design, material considerations, and technical feasibility. Additionally, spectrometer-based measurements were conducted to validate the system's light output against its intended design specifications.

7.1 EVALUATION WITH HCP

Purpose of Evaluation

The objective of this product evaluation was to assess the practical usability of the smart lighting goggles when used by healthcare professionals (HCPs) within a typical ICU setting. The focus was on evaluating the integration of the prototype into routine caregiving tasks, checking for any interference with existing ICU equipment, and understanding the general acceptance and perceptions of the HCPs regarding the product.

Participants

A total of 13 ICU nurses from LUMC participated in the evaluation. All participants had direct experience in critical care settings and were familiar with the challenges surrounding patient monitoring, sedation, and circadian rhythm disruptions in ICU patients. Their insights offered highly relevant and practical feedback regarding the integration of such a product into ICU workflows.

Methodology

The evaluation followed a structured yet informal procedure:

- A brief demonstration of the product and its lighting modes was first provided by the researcher.
- Nurses were then invited to interact with the prototype.
- This was followed by a verbal feedback session and Likert-style verbal ratings, focusing on the device's comfort, usability, and potential to interfere with clinical activities.
- Participants were encouraged to think aloud and share spontaneous impressions during interaction.

Fig 126: Nurse testing the LumoGlaze prototype.

Fig 127: Nurse wearing the LumoGlaze during prototype assessment.

7.1.1 RESULTS

Setup and Placement

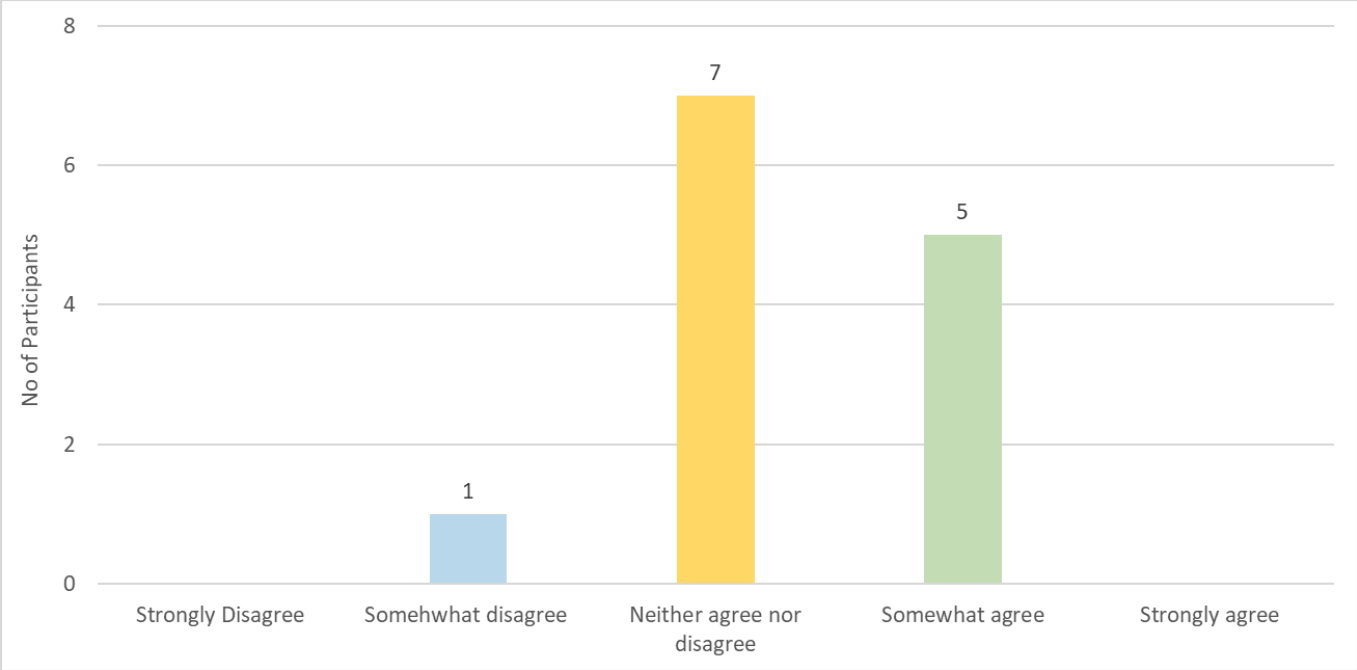
Most participants found the device intuitive to handle and straightforward to set up. As shown in Figure 128 below, a majority either agreed or remained neutral when asked if the placement of the goggles would interfere with existing ICU equipment.

However, multiple nurses raised valid concerns about applying the device to sedated or unconscious patients. Specifically, the side-mounted light modules might obstruct lateral head movement, which could pose challenges during patient repositioning or interfere in scenarios where ventilator tubes are in place.

Integration with Clinical Workflow

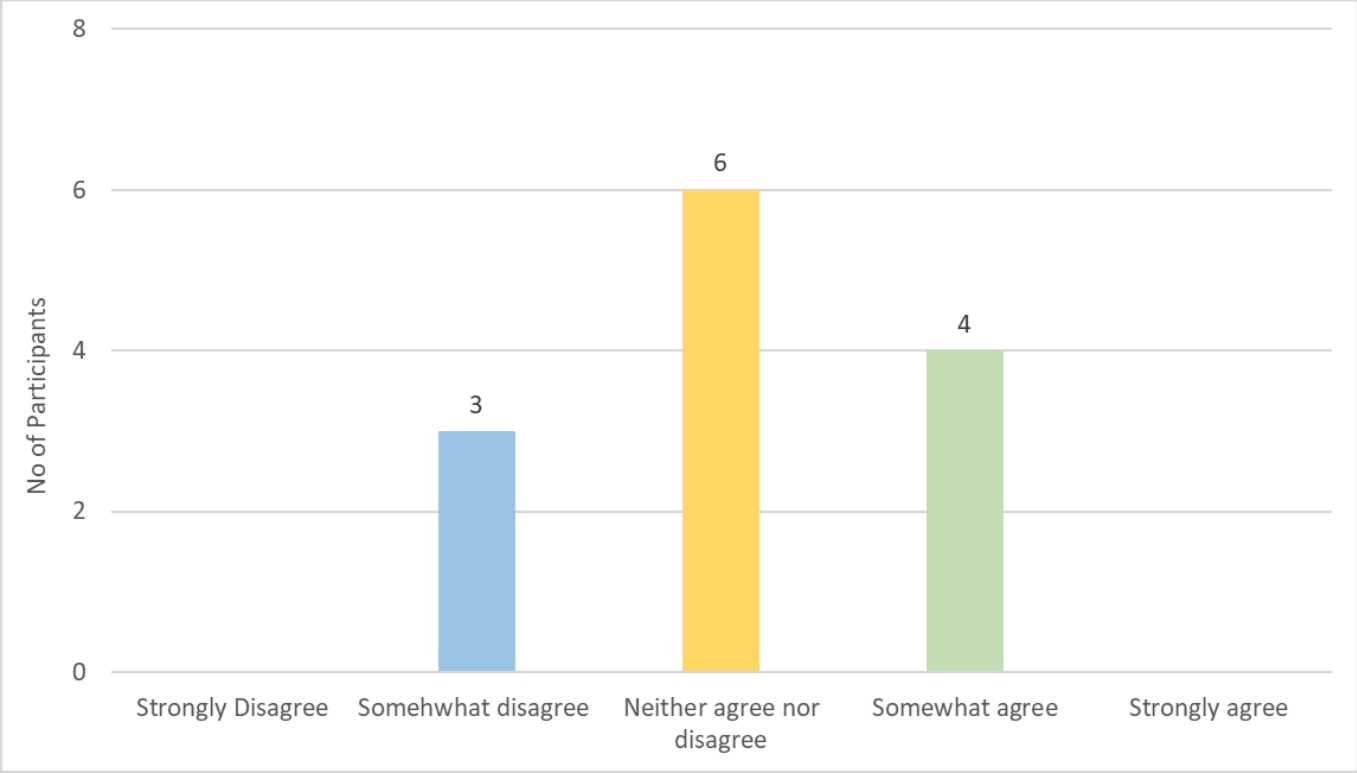
The evaluation revealed that the prototype is unlikely to disrupt routine ICU tasks. Participants generally felt that the device does not hinder essential caregiving activities, such as administering medication, performing hygiene procedures, or repositioning patients. As shown in the Figure 129 below, a majority either agreed or remained neutral

Notably, participants pointed out that the product's usability depends more on patient behaviour, particularly their tolerance and comfort, than on interference with medical staff workflow. If the patient remains undisturbed by the device, caregivers expressed confidence in seamlessly integrating it into standard routines.



Question: The placement of the device wont interfere with existing ICU equipment.

Fig 128: Participant Ratings on weather the the placement of the device wont interfere with existing ICU equipment.



Question: The device wont interrupt routine caregiving tasks.

Fig 129: Participant Ratings on on if the device interrupts the routine caregiving activities.

Lighting Modes and Clinical Relevance

The lighting behavior, particularly the simulation of sunrise and sunset, was met with enthusiastic approval. Nurses recognized circadian rhythm disruption as a real issue in ICU patients and were intrigued by the potential for lighting to serve as a non-invasive therapeutic tool.

"I think this could help patients fall into a better rhythm and reduce their restlessness," one nurse commented.

The idea of using light as a structured intervention to support patient well-being was widely supported, with several participants expressing curiosity about future clinical applications.

Material and Comfort Considerations

Comfort was a recurring theme in verbal feedback. Nurses consistently emphasized the importance of using soft, flexible materials to enhance comfort for long-term wear. They noted that:

- Softer materials could prevent pressure marks and discomfort.
- Comfort improvements would increase patient acceptance, especially for those in delicate or sedated conditions.

7.2 EVALUATION WITH EXPERTS

Purpose of Evaluation

The purpose of the expert evaluation was to gain informed, critical feedback on the LumoGlaze system from professionals with domain expertise in lighting and technical development. While earlier stages of the project focused on user-centered design and functional prototyping, this evaluation aimed to assess the intervention's technical soundness, physiological relevance, and implementation feasibility within real-world healthcare contexts.

Specifically, the evaluation was intended to:

- Validate the effectiveness and appropriateness of the lighting strategy from a circadian biology perspective.
- Assess the design's material, ergonomic, and communication choices against clinical standards and patient safety.
- Identify potential limitations, risks, or unintended effects that may not emerge during user testing.
- Inform future directions for personalization, integration, and clinical validation.

This process ensured that both the scientific rationale and the technical execution of the system aligned with best practices in healthcare innovation.

Experts

Dr. Y. (Wolf) Song

Wolf Song is an Associate Professor at TU Delft's Industrial Design Engineering department and was selected for his expertise in integrating electronics, materials, and communication systems within complex product designs. With a background in mechanical engineering and extensive experience in multidisciplinary mechatronic systems, his research focuses on smart materials, embedded electronics, and system-level design.

His ability to assess functional prototypes from both technical and implementation perspectives made him a valuable expert in evaluating the material choices, communication reliability, interaction design, and scalability of the LumoGlaze prototype.
For the remainder of this section, Dr. Y. (Wolf) Song will be referred to as Expert 1 (E1).

Prof. Dr. Sylvia C. Pont

Sylvia Pont was selected for her extensive expertise in human perception, lighting design, and the perceptual impact of product interactions. As the Head of the Perceptual Intelligence (π-lab) at TU Delft, her research combines insights from vision science, design, and cognitive psychology to explore how lighting and spatial cues affect human behavior and experience. Her work on illumination perception, light-material interactions, and the circadian relevance of lighting made her an ideal expert for assessing the LumoGlaze lighting system. Her evaluation provided valuable input on light angle optimization, user comfort, personalization potential, and the role of lighting in influencing circadian rhythms within sensitive healthcare environments.
For the remainder of this section, Prof. Dr. Sylvia C. Pont will be referred to as Expert 2 (E2).

Methodology

The expert evaluations were conducted in person through semi-structured sessions, allowing for open-ended discussion while focusing on key aspects of the LumoGlaze system. Each expert session was tailored to their domain of expertise and aimed at gathering in-depth feedback on the prototype's performance, design decisions, and future applicability.

For Expert 1 (E1), the session took place at the Applied Labs, TU Delft. The full prototype, including the LumoGlaze goggles and the LumoSync mobile application, was demonstrated in real-time.

The discussion followed a semi-structured format and covered hardware components, system communication protocols (specifically BLE), material choices, interaction model, and production scalability. Real-time notes were taken during the session and later categorized for analysis.

For Expert 2 (E2), the evaluation was conducted in her office at TU Delft. A brief walkthrough of the project and a hands-on demonstration of the prototype were provided to establish context. This was followed by a series of targeted questions around circadian lighting design. During the session, correlated color temperature (CCT) of the prototype's LEDs was also validated using Sekonic C-7000 Spectrometer in the presence of E2, allowing for direct calibration and feedback on the system's lighting effectiveness.

7.2.1 RESULTS

The expert evaluations yielded valuable insights that guided critical refinements to the LumoGlaze system. Each expert provided targeted feedback grounded in their respective fields of technical product development and lighting design, offering a multifaceted perspective on the system's feasibility, performance, and applicability in real-world contexts. The results are organized into thematic categories, highlighting strengths, identifying limitations, and suggesting opportunities for improvement across both the hardware and the lighting strategy.

Optical Performance and Circadian Strategy

E2 emphasized that adding a diffuser could improve dispersion, but individual LED sources remained visible, suggesting inadequate diffusion. E2 identified light directionality and optimal angle as critical for targeting intrinsically photosensitive retinal ganglion cells (iPRGCs). E2 noted that scattering on regions like the nose bridge weakens efficacy and advised exploring literature on optimal exposure angles for wearable light therapy.

E2 acknowledged the use of a day-night automated light protocol as appropriate but stressed the need for personalization of light recipes, as patients may respond differently due to age, medication, or baseline circadian alignment. She proposed future reliance on core body temperature or similar physiological parameters instead of heart rate for assessing impact.

E1 further pointed out that ambient lighting conditions in ICUs (e.g., from screens or windows) may interfere with the device's effects. He recommended evaluating lighting effectiveness under varying environmental contexts and incorporating adaptive lighting logic if needed.

Material and Ergonomic Considerations

Both E1 and E2 emphasized the importance of comfort and soft contact materials for ICU patients. E1 recommended the use of flexible PCBs and skin-compatible soft materials to reduce discomfort and improve long-term wearability. E1 also proposed incorporating shy-tech principles, embedding electronics subtly into the wearable form to avoid drawing attention or causing psychological discomfort.

E2 reinforced the importance of physical ergonomics, suggesting shape and material adjustments to improve fit and diffuse light uniformly without hotspots or shadows.

Communication

E1 focused on BLE (Bluetooth Low Energy) communication and advised verifying frequency compliance with hospital standards to prevent interference with critical medical devices. E1 recommended real-world validation in ICU settings with dense electronic infrastructure to assess signal robustness.

Although power consumption was not flagged as an issue, E1 stressed ensuring reliable BLE operation, particularly in environments with multiple monitoring systems operating simultaneously.

Interaction Design and Patient Control

E1 cautioned against physical switches or controls on the device itself, noting that such features could invite curiosity from semi-conscious patients and disrupt therapeutic intent. E1 advocated for a minimalist and clearly defined app interface, with logic tailored to single-patient or multi-user scenarios, depending on deployment strategy.

E2 suggested that awake patients might benefit from a sense of control, though this should be implemented carefully to avoid over-stimulation or misuse. E2 also raised the possibility of combining manual override with automation, especially in palliative or recovery settings.

Scalability and Validation

E1 was optimistic about mass production feasibility, estimating that unit costs could remain below €6 with proper manufacturing and material choices. E1 suggested formal validation via a randomized controlled trial (RCT) with over 100 participants and a control group to verify the system's clinical impact across different demographics.

E2 supported the idea of expanding the intervention to non-ICU patients, such as those in elderly care or rehabilitation. E2 also proposed exploring multi-sensory extensions, combining light with sound or haptic feedback, to enhance calming or alerting effects based on patient needs.

7.2.2 PHYSICAL VALIDATION OF LIGHTING

Purpose of Validation

While the RGBW values and lighting transitions of the LumoGlaze system were conceptually defined based on circadian lighting principles, it was essential to confirm that the actual light output matched the intended specifications in terms of correlated color temperature (CCT). The purpose of this validation was to measure the spectral quality of the light produced in different modes and ensure it aligns with biologically effective ranges for supporting circadian regulation. This process also served to verify the consistency and accuracy of the prototype's RGBW settings in real-world usage conditions.

Tools

The primary measurement tool used for this validation was the Sekonic C-7000 Spectrometer. This device is designed for industrial and scientific-grade assessment of light sources, offering precise readings of:

- Correlated Color Temperature (CCT)
- Spectral Power Distribution (SPD)
- Color rendering indices (CRI, R9, etc.)

The spectrometer features a cosine-corrected receptor and allows data export for post-processing and visualization. Its reliability in controlled environments makes it ideal for evaluating wearable lighting systems like LumoGlaze.

Fig 130: Sekonic C-7000 equipment

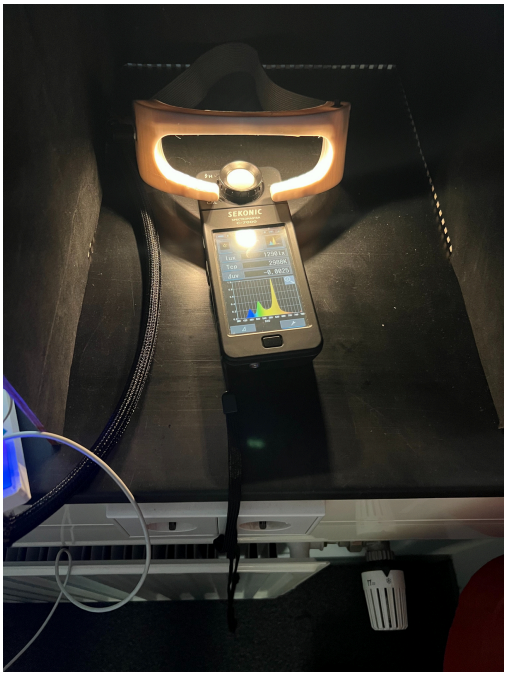


Fig 131: CCT levels of different lighting modes being measured

Methodology

The validation procedure was conducted in a controlled environment to minimize external lighting influence. The LumoGlaze prototype was placed inside a light-isolated dark box, with the LEDs turned on in one of the predefined lighting modes. The sensor head of the Sekonic C-7000 was positioned directly beneath the illuminated portion of the goggles, approximately at the distance from which a patient's eyes would receive the light, to simulate realistic exposure.

Measurements were taken for both the Morning and Evening modes. After recording each sample, the data was exported and visualized as CCT plots and SPD graphs to assess whether the prototype met the designed spectral criteria.

Results

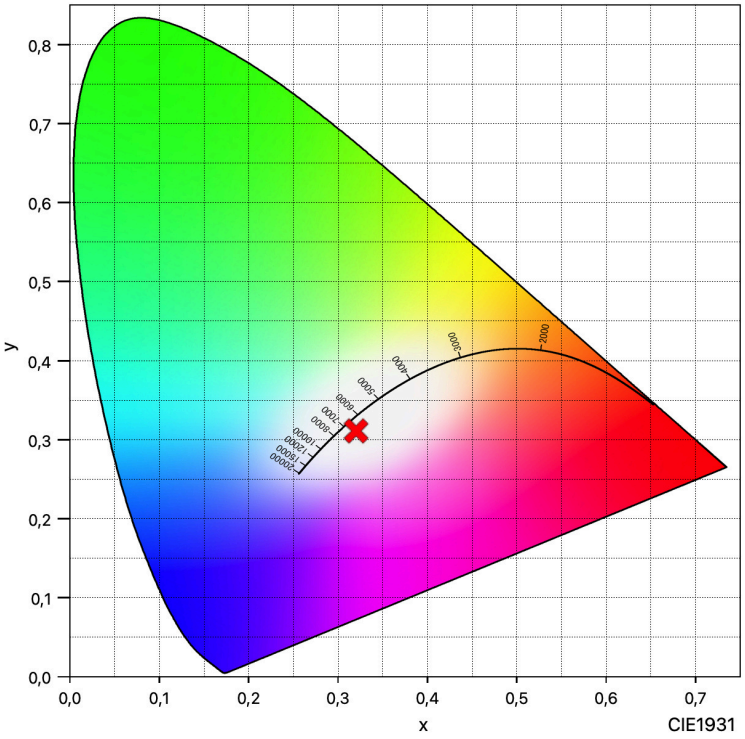
Morning Mode

The physical validation of Morning Mode lighting yielded results confirming strong alignment with the intended design specifications. According to the predefined RGBW settings, the target Correlated Color Temperature (CCT) for Morning Mode was set between 6000–7000K to simulate natural daylight and promote circadian stimulation (see Table 01).

The spectrometer measurement yielded a CCT of 6222K, indicating that the light output from the prototype is well within the targeted morning range. The spectral power distribution (SPD) graph (Figure 133) displays a dominant blue peak at 463 nm, a key wavelength associated with melanopic sensitivity and iPRGC stimulation. This is followed by a balanced spread of green and red components, confirming a coherent and functional white light mix.

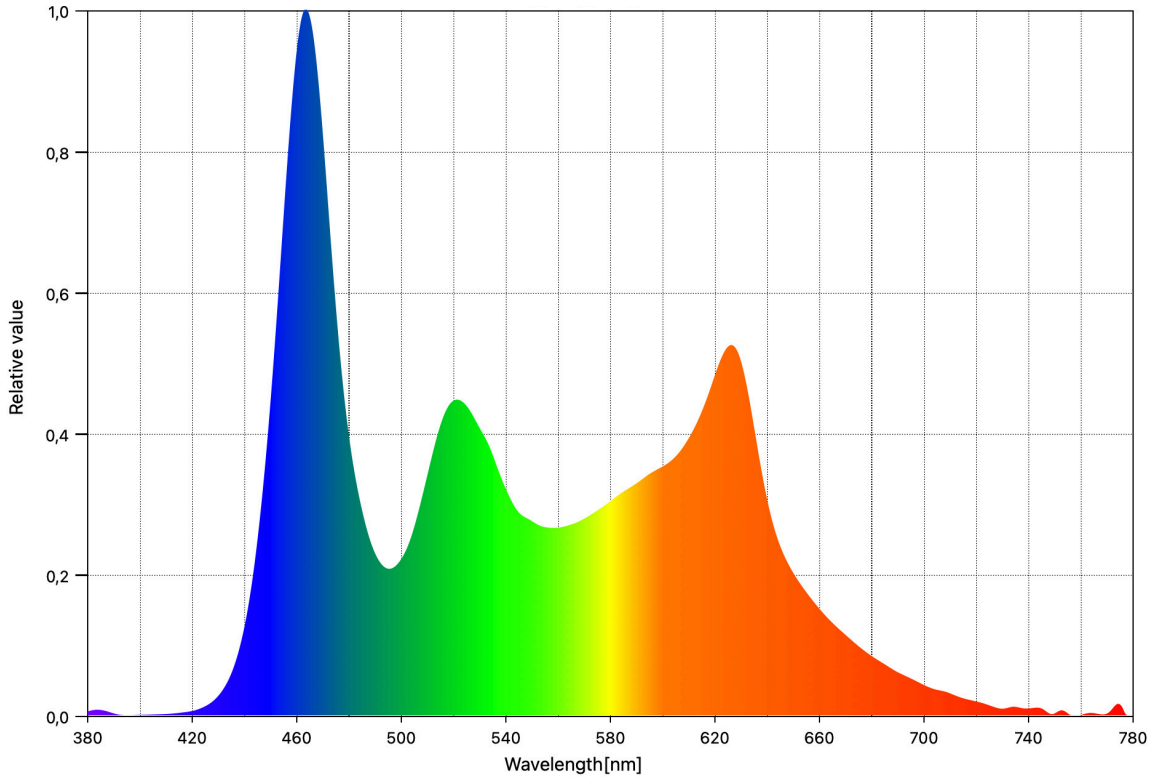
Additionally, the CIE 1931 chromaticity diagram (Figure 132) shows the light coordinates at x = 0.3198 and y = 0.3109, which plot squarely within the daylight region. This further confirms that the prototype achieves a visual white light profile appropriate for morning-phase circadian activation.

Together, these measurements verify that the physical light output of the LumoGlaze system in Morning Mode meets both the perceptual and physiological criteria set forth in the design stage.



Measuring Mode = Ambient	CCT = 6222K
x = 0,3198	y = 0,3109

Fig 132: CIE 1931 diagram for Morning Mode with measured CCT of 6222K.



Measuring Mode = Ambient	CCT = 6222K	Peak Wavelength = 463nm

Fig 133: Spectral distribution of Morning Mode showing CCT of 6222K with peak at 463 nm.

Evening Mode

The LumoGlaze system's Evening Mode was designed to simulate warm, low-stimulation lighting with a target CCT between 2700–3000K. The physical validation yielded a CCT of 2988K, confirming that the emitted light closely matched the intended target for evening use.

The spectral power distribution (SPD) graph (Figure 135) shows a dominant peak at 627 nm in the red spectrum, consistent with a warm-white output and low blue light content. This spectral profile supports the intended physiological response of minimizing circadian disruption and promoting relaxation before sleep.

The CIE 1931 chromaticity diagram (Figure 134) indicates coordinates of x = 0.4342 and y = 0.3970, firmly placing the light output in the warm region of the visible spectrum. This validates the visual and biological suitability of the Evening Mode for pre-sleep conditions in sensitive environments such as ICUs.

Together with the morning measurements, this result demonstrates that the LumoGlaze prototype is capable of producing distinct and biologically relevant lighting conditions that adhere to circadian lighting guidelines.

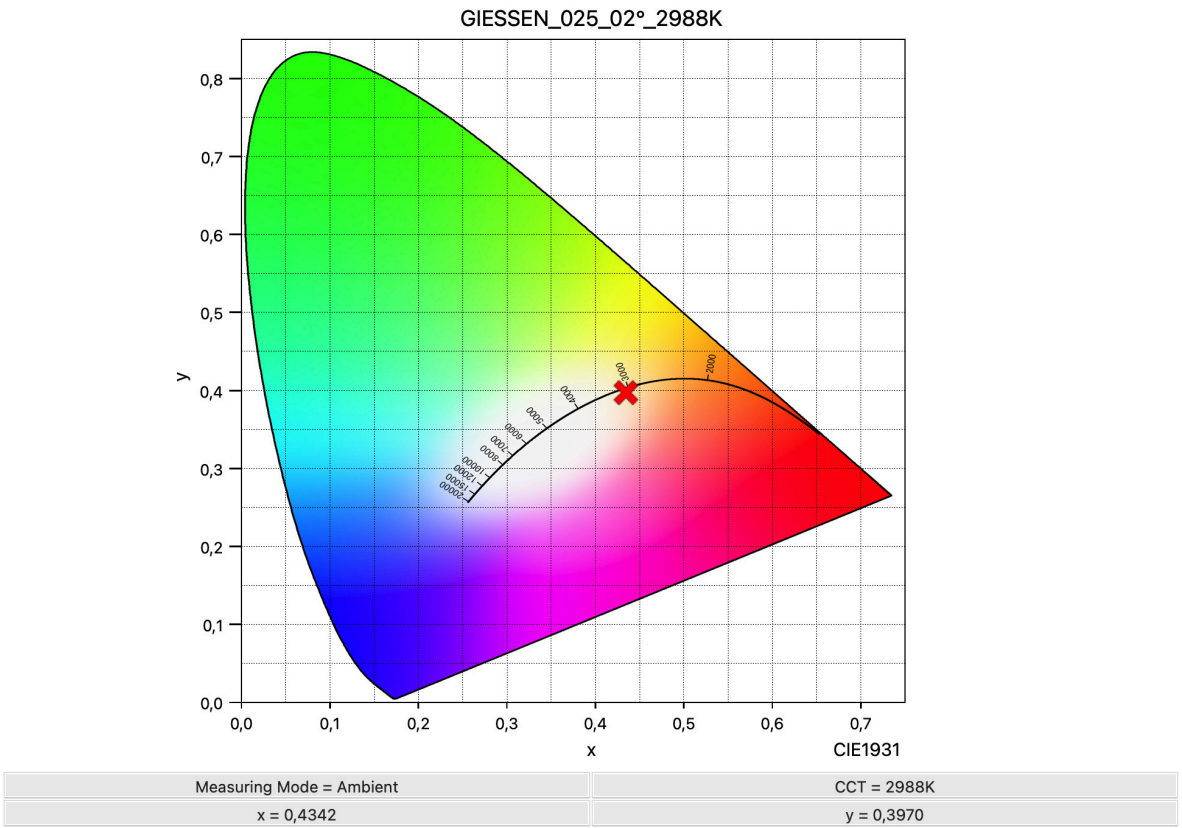


Fig 134: CIE 1931 diagram for Evening Mode with measured CCT of 2988K.

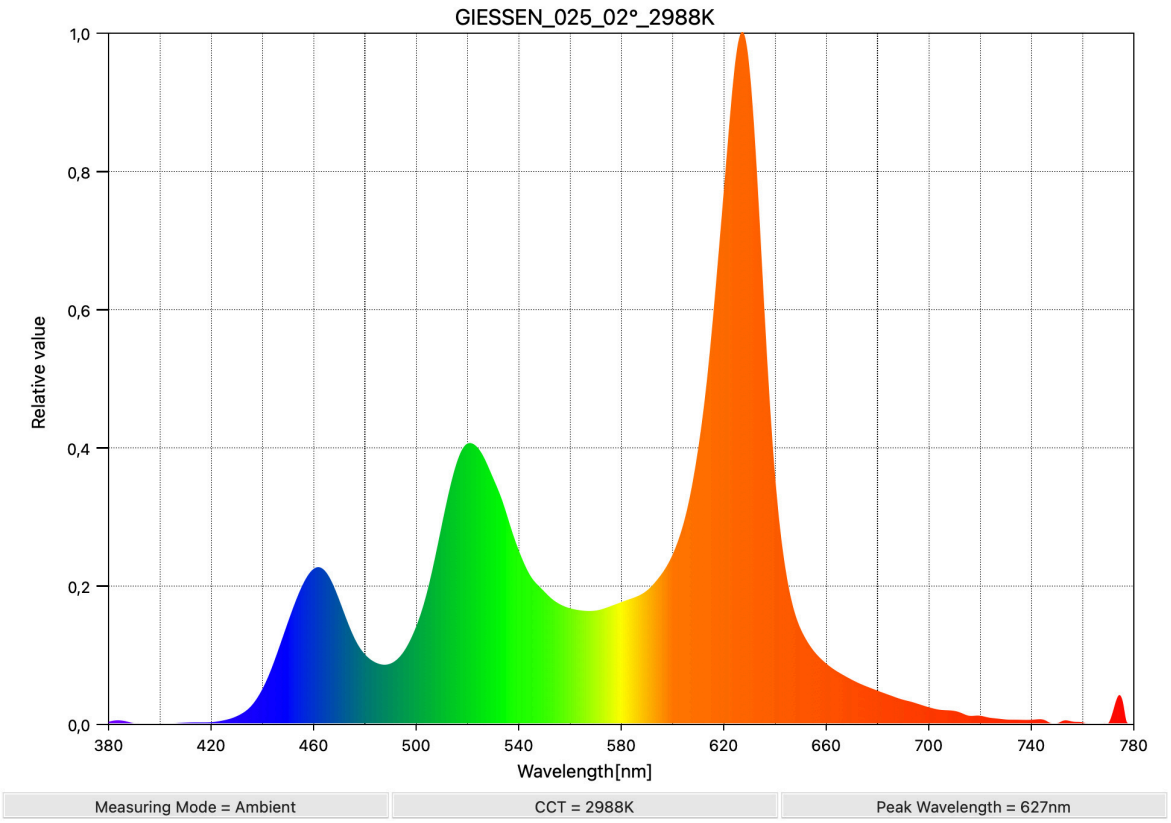


Fig 135: Spectral distribution of Morning Mode showing CCT of 2988K with peak at 627nm.

7.3 CONCLUSION

The combined evaluations affirmed the potential of the LumoGlaze system to enhance the ICU environment through circadian-supportive lighting. ICU nurses (HCPs) responded positively to the lighting concept, emphasizing its potential to support patient well-being without interfering with clinical routines. However, they also highlighted important considerations regarding comfort, patient mobility, and the need for soft, ergonomic materials.

Expert feedback (E1 and E2) provided targeted insights into design refinement and system optimization. E1 highlighted the importance of electronic integration, communication reliability, and manufacturability, while E2 offered perceptual and physiological feedback on light quality, personalization, and circadian alignment.

Finally, the physical validation confirmed that the prototype delivers accurate and distinct light outputs for morning and evening phases, with CCT and chromaticity values that fall within biologically meaningful ranges. This triangulation of feedback from users, experts, and instrumentation validates the LumoGlaze system as a viable and scalable intervention for reducing circadian disruption in ICU settings.

8.

IMPLEMENTATION

This chapter outlines the strategic deployment of the LumoGlaze system based on emotionally vulnerable - points identified along the ICU patient journey. Rather than providing continuous light exposure, the system is designed for targeted use during critical transitions, such as morning wake-up and evening wind-down, when lighting can play a meaningful role in reducing emotional distress, supporting circadian alignment, and enhancing psychological comfort.

The implementation approach is structured around typical ICU routines, ensuring that the integration of LumoGlaze into patient care is both practical and minimally disruptive. Morning and evening protocols are described in detail, with light timing, color temperature, and intensity mapped to support natural sleep–wake rhythms. These strategies are further aligned with nursing workflows, enabling seamless operation through the LumoSync app and BLE controls without adding cognitive or procedural load for healthcare providers.

8.1 TARGETED TIMING OF IMPLEMENTATION

Morning Wake-Up (High Anxiety and Disorientation)

Patients waking up in the ICU often experience anxiety, confusion, and disorientation, especially after sedation or surgical procedures. To help anchor patients to the time of day and promote circadian alignment, the LumoGlaze system will deliver bright, blue-enriched morning light as part of a structured 2-hour light therapy session, starting at 07:00 and continuing until 09:00. This simulated sunrise exposure mimics natural daylight and stimulates alertness and mood regulation, helping patients orient themselves to the beginning of the day.

Evening Rest and Reflection (Emotional Sensitivity and Isolation)

In the evening, ICU patients often report restlessness, isolation, or emotional vulnerability. To support natural melatonin production and psychological calmness, LumoGlaze delivers warm, amber-toned light beginning at 18:00. This "sunset simulation" gradually dims in intensity and shifts in color temperature every hour, gently signaling the body to prepare for rest. By 22:00, the light is fully turned off, allowing patients to fall asleep more naturally, without abrupt lighting transitions that might disturb them.

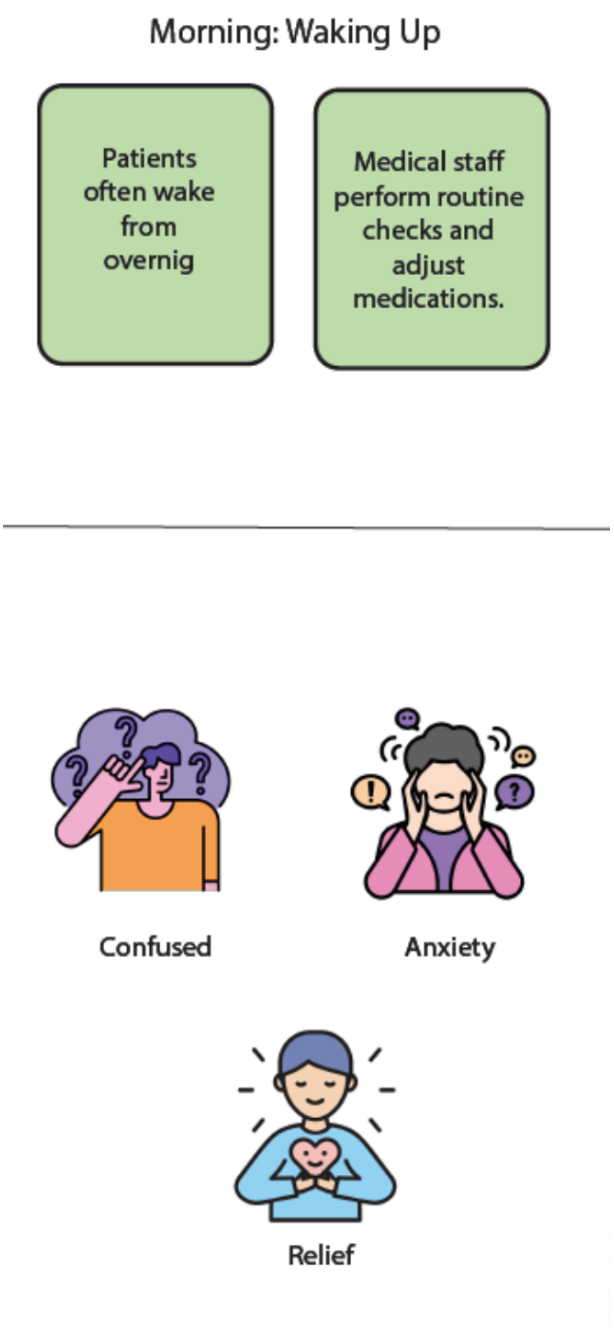


Fig 136: Morning wake-up identified as a moment of emotional vulnerability.

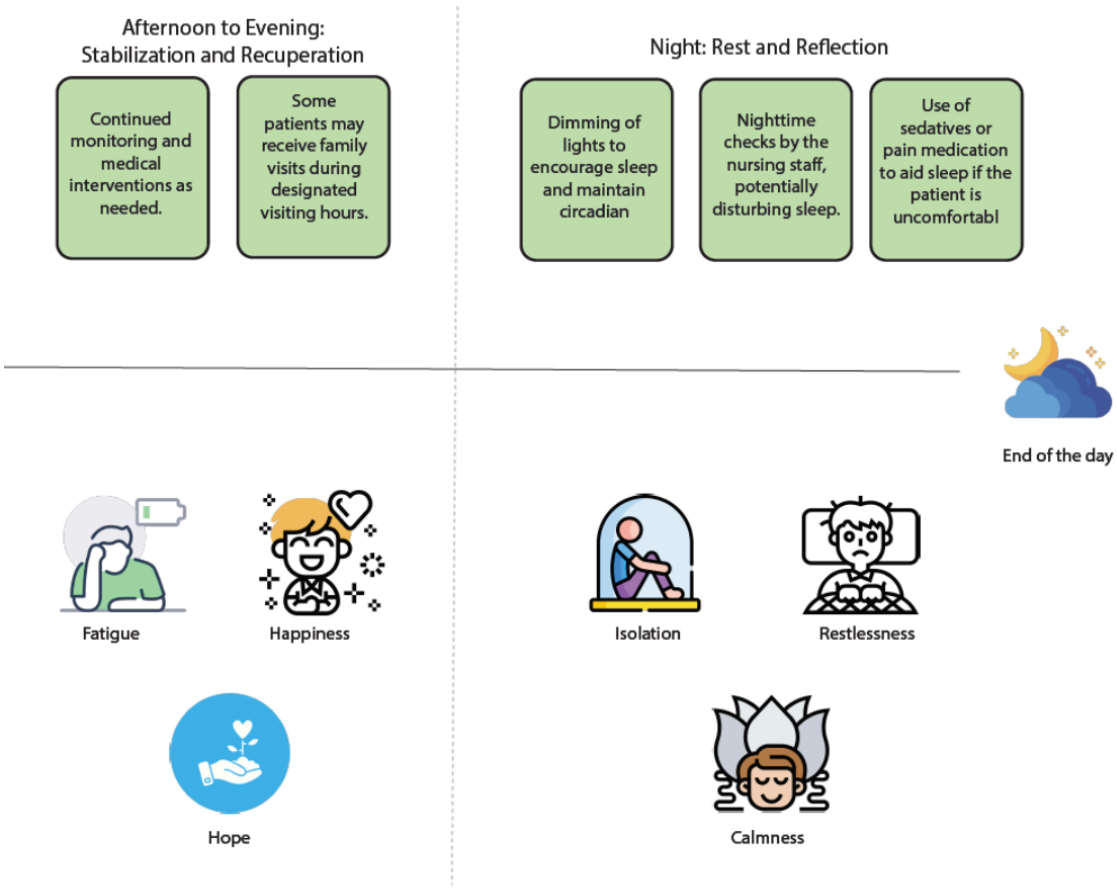


Fig 137: Evening rest and reflection identified as a moment of emotional vulnerability.

8.2 INTEGRATION INTO CLINICAL WORKFLOW

The LumoGlaze system is designed for simplicity and ease of use by healthcare providers:

Morning Routine Integration:

During vital checks or medication administration in the morning, nurses can briefly place the LumoGlaze goggles on patients before full stimulation begins. With minimal adjustment required, the nurse can activate the "Morning Mode" via the LumoSync app or BLE interface.

Evening Wind-Down Routine:

As part of the nighttime preparation, nurses can place the goggles on patients before sedatives are administered. The "Evening Mode" can be enabled through the app, delivering gentle, calming light.

8.3 CONCLUSION

This chapter explained how the LumoGlaze system can be used at specific times during a patient's stay in the ICU to improve their comfort and well-being. By focusing on two important moments—waking up in the morning and preparing for sleep in the evening—the system helps support the patient's natural sleep–wake cycle without using medication. The lighting is timed and adjusted to fit into the usual routine of ICU nurses, making it easy to use without adding extra work.

By fitting smoothly into the hospital environment and addressing the emotional needs of patients, LumoGlaze shows promise as a useful and patient-friendly tool in critical care. This plan helps ensure that the system can be used effectively in real ICU settings to support recovery and comfort.

Fig 138: Implementation of the LumoGlaze system during morning hours.

Fig 139: Implementation of the LumoGlaze system during evening hours.

9.

NEXT STEPS

This final chapter of the thesis provides a comprehensive conclusion of the project, summarizing its key outcomes and contributions. It then offers recommendations for future work, outlining potential directions for further development and improvement. The chapter concludes with a personal reflection, in which I share the challenges faced and the insights gained throughout the course of this thesis journey.

9.1 CONCLUSION

The LumoGlaze system was conceived with the intent to address three critical aspects of the ICU patient experience: reducing emotional stress, providing day-night orientation, and restoring a sense of control over the environment. Each of these guiding criteria informed the design decisions throughout the project, from the early-stage concept development to the final iterations of both hardware and software.

The successful integration of physiological data, Bluetooth-based lighting control, and an ergonomic wearable form factor demonstrates the feasibility of embedding such interventions into the ICU workflow without disrupting care routines. Positive user feedback from both patients and healthcare providers reaffirmed the value of this approach in supporting emotional comfort, especially during moments of disorientation such as morning wake-up and evening rest.

However, the journey was not without its challenges. One of the primary difficulties lay in designing for a highly complex and variable clinical environment where patient conditions, spatial constraints, and workflow priorities differ significantly. Balancing technical performance with user comfort, especially in a form factor worn on the face, proved particularly demanding. The nose bridge discomfort noted in the first evaluation round required multiple design iterations and compromises in internal layout and material selection. Additionally, while physiological monitoring via heart rate data provided useful trends, the short duration of testing sessions and variability in user baselines limited the conclusiveness of these findings.

Another layer of complexity arose from the need to create a system that is simultaneously robust, hygienic, and intuitive for both patients and caregivers, which often demands conflict when working with compact electronics and wearable systems. Furthermore, ethical and logistical constraints restricted access to real ICU patients, requiring simulations that may not fully reflect in-situ dynamics.

Despite these limitations, LumoGlaze demonstrates the promise of light-based interventions in critical care and sets the stage for more extensive clinical validation. The work accomplished not only meets the initial design criteria but also opens broader possibilities for future healthcare products that blend physiological intelligence with emotional sensitivity.

9.2 FUTURE RECOMMENDATIONS

While the LumoGlaze system presents a promising first step toward integrating circadian lighting interventions in critical care environments, further research is essential to validate its clinical effectiveness, improve its design, and explore broader applications. The following recommendations outline key directions for future studies:

1. Clinical Validation in Real ICU Settings

To evaluate the true impact of LumoGlaze on patient well-being, recovery, and sleep quality, future studies should involve clinical trials with actual ICU patients. This would allow researchers to observe real-time effects in high-stress, variable environments and assess long-term outcomes such as reduction in delirium incidence, improvements in sleep architecture, and emotional resilience.

2. Testing with Extended Wear Time

The current evaluation was limited to short-duration sessions. To better understand physiological and emotional responses over time, future research should include extended wear studies, ideally over multiple sleep-wake cycles. This would help in identifying adaptation phases, cumulative effects, and any potential user fatigue or discomfort with the device.

3. Integration of AI and Machine Learning for Adaptive Control

Future research should explore the use of artificial intelligence (AI) and machine learning (ML) algorithms to analyze real-time sleep and heart rate patterns. By training models on physiological data collected via wearable sensors, the system could autonomously learn optimal lighting adjustments tailored to each patient's circadian rhythm, recovery stage, and responsiveness. This would move the intervention from rule-based control to a predictive, personalized system that adapts lighting in a way that is both context-aware and clinically informed. Such intelligent adaptation could significantly enhance therapeutic effectiveness while reducing the need for manual oversight.

4. Material and Comfort Enhancements

Comfort remains a key factor influencing patient compliance and effectiveness. Future iterations should focus on soft, flexible, and skin-safe materials, potentially including textile integration or shy-tech elements that are less obtrusive and more hygienic for long-term clinical use.

5. Integration with Hospital Infrastructure

Research should explore how LumoGlaze can be embedded into broader hospital systems—such as smart room environments or existing monitoring platforms—to allow centralized control, passive data logging, and real-time alerts for healthcare staff. Seamless integration can improve clinical workflow and ensure safety.

6. Enhancing Hygiene and Infection Control

In future iterations, greater emphasis should be placed on the hygienic design of the wearable device to ensure it meets clinical infection control standards. Given the sensitive and sterile nature of ICU environments, all patient-facing surfaces of LumoGlaze should be constructed from medical-grade, wipeable, and biocompatible materials. Future studies should investigate material coatings or removable, replaceable covers that allow for safe and easy disinfection between uses. Additionally, evaluating how cleaning protocols integrate with hospital workflows will be critical for ensuring that the device is both practical and acceptable for routine clinical deployment.

7. Integration of Custom PCB and Curved LED Modules

To enhance compactness, durability, and aesthetics, future development should focus on designing a custom PCB that can be seamlessly integrated within the goggle housing. This would eliminate the need for external wiring, simplify assembly, and improve the overall user experience. In parallel, custom-designed curved LED strips mounted on flexible or semi-rigid PCBs should be explored to better conform to the contours of the face. Such an approach would ensure more uniform light distribution, improve comfort, and allow the lighting system to function more discreetly and efficiently. These advancements would also open the door to mass manufacturing and more consistent performance across units.

9.3 PERSONAL REFLECTION

This thesis has come to its end, and so has my journey as a TU Delft student. I want to dedicate this last part to sharing some thoughts about what this journey has meant to me.

Working on this thesis has been a challenging but deeply rewarding experience. Entering the healthcare domain was unfamiliar territory, and I had a steep learning curve from the very beginning. It became even more personal when I related the project to my grandmother's experience in the hospital while she was battling cancer. Thankfully, she is now cancer-free, and that emotional connection gave me even more purpose and motivation throughout the process.

There were times I questioned myself and whether I was on the right path. I remember feeling overwhelmed and panicking during those phases. Conversations with my mentor Ela helped me stay grounded, she reminded me I was doing well, which gave me the reassurance I needed to keep going.

One of the biggest challenges I faced was during the prototyping phase. I had no prior experience with APIs or electronics, but I committed to learning and applying everything from scratch. It was also difficult to find participants for user testing, as many were busy with exams or final deadlines. Still, I managed to gather valuable feedback from those who were able to help.

What I learned about myself is that I can quickly adapt to new challenges and acquire unfamiliar skills when needed. Seeing the prototype come to life, especially the moment the app worked without manual input, was a major milestone for me. And when the CCT measurements matched exactly what I had intended, it felt like everything had fallen into place.

This project has shown me that designing for the healthcare context is incredibly challenging, yet deeply meaningful. I've realised that I enjoy tackling complex, impactful problems, and it has inspired me to pursue a future in the MedTech field, developing devices that contribute to patient well-being.

Lastly, this project has allowed me to work on what motivates me: investigating, researching, and developing future systems for hospitals and the healthcare sector.

I hope I have inspired you with my thesis.
R.

Rakshith

REFERENCES

Adell, M. B., Barrachina, L. G., Andrés, E. B., Graullera, G. C., Aznar, G. P., Marmaneu, M. M., Selles, M. F., & Urendez, A. M. (2021). Factors affecting sleep quality in intensive care units. *Medicina Intensiva (English Edition), 45(8)*, 470–476. https://doi.org/10.1016/j.medine.2021.08.011

Bani Younis, M., Hayajneh, F., & Alshraideh, J. A. (2021). Effect of noise and light levels on sleep of intensive care unit patients. *Nursing in Critical Care, 26(2)*, 73-78.

Boulanger, C., & McWilliams, D. (Eds.). (2020). *Passport to Successful ICU Discharge*. Springer Nature Switzerland.

Critical Care Research Group. (2022, December 14). CCRG unveils The ICU of the Future - 14 December 2022 [Video]. YouTube. https://www.youtube.com/watch?v=zlrcnua6RjY

Cuttle, C. (2013). Research note: A practical approach to cubic illuminance measurement. *Lighting Research & Technology, 46(1)*, 31–34. https://doi.org/10.1177/1477153513498251

Danielson, S. J., Rappaport, C. A., Loher, M. K., & Gehlbach, B. K. (2018). Looking for light in the din: An examination of the circadian-disrupting properties of a medical intensive care unit. *Intensive and Critical Care Nursing, 46*, 57–63. https://doi.org/10.1016/j.iccn.2017.12.006

Desmet, P. M., Fokkinga, S. F., Ozkaramanli, D., & Yoon, J. (2016b). Emotion-Driven product design. In *Elsevier eBooks* (pp. 405–426). https://doi.org/10.1016/b978-0-08-100508-8.00016-3

Heijne, K., & Van Der Meer, H. (2019b). Road map for creative problem solving techniques: *Organizing and facilitating group sessions.*

Hosseini, S. N., Walton, J. C., SheikhAnsari, I., Kreidler, N., & Nelson, R. J. (2024). An Architectural Solution to a Biological Problem: A Systematic Review of Lighting Designs in Healthcare Environments. *Applied Sciences, 14(7)*, 2945.

Jaiswal, S. J., Garcia, S., & Owens, R. L. (2017). Sound and light levels are similarly disruptive in ICU and non-ICU wards. *Journal of Hospital Medicine, 12(10)*, 798–804. https://doi.org/10.12788/jhm.2826

Johansson, L., Bergbom, I., Persson Waye, K., Ryherd, E., & Lindahl, B. (2012). The sound environment in an ICU patient room—A content analysis of sound levels and patient experiences. *Intensive and Critical Care Nursing, 28(5)*, 269–279. https://doi.org/10.1016/j.iccn.2012.03.004

Kraneburg, A., Franke, S., Methling, R., & Griefahn, B. (2016). Effect of color temperature on melatonin production for illumination of working environments. *Applied Ergonomics, 58*, 446–453. https://doi.org/10.1016/j.apergo.2016.08.006

Latour, J. M., Kentish-Barnes, N., Jacques, T., Wysocki, M., Azoulay, E., & Metaxa, V. (2022). Improving the intensive care experience from the perspectives of different stakeholders. *Critical Care, 26(1)*, 218. https://doi.org/10.1186/s13054-022-04094-x

Leone, M. J., Dashti, H. S., Coughlin, B., Tesh, R. A., Quadri, S. A., Bucklin, A. A., Adra, N., Krishnamurthy, P. V., Ye, E. M., Hemmige, A., Rajan, S., Panneerselvam, E., Higgins, J., Ayub, M. A., Ganglberger, W., Paixao, L., Houle, T. T., Thompson, B. T., Johnson-Akeju, O., … Westover, M. B. (2023). Sound and light levels in intensive care units in a large urban hospital in the United States. *Chronobiology International, 40(6)*, 759–768. https://doi.org/10.1080/07420528.2023.2207647

Luetz, A., Spies, C., & Kervezee, L. (2024). It's about time: Circadian medicine in the intensive care unit. *Intensive Care Medicine, 50(2)*, 283–286. https://doi.org/10.1007/s00134-023-07297-0

Luther, R., & McLeod, A. (2018). The effect of chronotherapy on delirium in critical care – A systematic review. *Nursing in Critical Care, 23(6)*, 283–290.

Martinez, F. E., Poulter, A., Seneviratne, C., Chrimes, A., Havill, K., Balogh, Z. J., & Paech, G. M. (2022). ICU patients' perception of sleep and modifiable versus non-modifiable factors that affect it: A prospective observational study. *Journal of Clinical Medicine, 11(13)*, 3725. https://doi.org/10.3390/jcm11133725

Nie, J., Zou, Q., Chen, L., Chen, Z., Hu, Q., Jiao, F., Pan, Z., Deng, C., Zhang, H., Dong, B., Kang, X., Chen, W., Wang, Q., Tong, Y., Chen, X., Song, L., Wang, S., Zhang, G., & Shen, B. (2024). The lower correlated color temperature with higher illuminance nocturnal light environment improves cognitive performance and sleep quality. *Building and Environment, 251*, 111221. https://doi.org/10.1016/j.buildenv.2024.111221

Perry, H., Alight, A., & Wilcox, M. E. (2024). Light, sleep and circadian rhythm in critical illness. *Current Opinion in Critical Care, 30(4)*, 283–289. https://doi.org/10.1097/mcc.0000000000001163

Prin, M., Bertazzo, J., Walker, L. A., Scott, B., & Eckle, T. (2023). Enhancing circadian rhythms—The circadian MEGA bundle as novel approach to treat critical illness. *Annals of Translational Medicine, 11(9)*, 319.

Simons, K. S., Laheij, R. J. F., Van Den Boogaard, M., Moviat, M. A. M., Paling, A. J., Polderman, F. N., Rozendaal, F. W., Salet, G. A. M., Van Der Hoeven, J. G., Pickkers, P., & De Jager, C. P. C. (2016). Dynamic light application therapy to reduce the incidence and duration of delirium in intensive-care patients: A randomised controlled trial. *The Lancet Respiratory Medicine, 4(3)*, 194–202. https://doi.org/10.1016/s2213-2600(16)00025-4

Simons, K. S., Van Den Boogaard, M., & De Jager, C. P. C. (2019). Impact of intensive care unit light and noise exposure on critically ill patients. *Netherlands Journal of Critical Care, 27(4)*, 145–149.

Smulders, M., Van Dijk, L. N. M., Song, Y., Vink, P., & Huysmans, T. (2023). Dense 3D pressure discomfort threshold (PDT) map of the human head, face and neck: A new method for mapping human sensitivity. *Applied Ergonomics, 107*, 103919.

Telias, I., & Wilcox, M. E. (2019). Sleep and circadian rhythm in critical illness. In *Annual update in intensive care and emergency medicine* (pp. 651–664). https://doi.org/10.1007/978-3-030-06067-1_50

Tronstad, O., Flaws, D., Patterson, S., Holdsworth, R., Garcia-Hansen, V., Leonard, F. R., Ong, R., Yerkovich, S., & Fraser, J. F. (2023). Evaluation of the sensory environment in a large tertiary ICU. *Critical Care, 27(1)*. https://doi.org/10.1186/s13054-023-04744-8

Van Den Ende, E. S. (2025). *A hospital's wake-up call: Improving sleep in hospitalized patients.* https://doi.org/10.5463/thesis.866

Vethe, D., Scott, J., Engstrøm, M., Salvesen, Ø., Sand, T., Olsen, A., Morken, G., Heglum, H. S., Kjørstad, K., Faaland, P. M., Vestergaard, C. L., Langsrud, K., & Kallestad, H. (2020). The evening light environment in hospitals can be designed to produce less disruptive effects on the circadian system and improve sleep. *Sleep, 44(3)*. https://doi.org/10.1093/sleep/zsaa194

Yu, C., Wijntjes, M., Eisemann, E., & Pont, S. (2022). Effects of inter-reflections on the correlated colour temperature and colour rendition of the light field. *Lighting Research & Technology, 55*(7–8), 772–793. https://doi.org/10.1177/14771535221126902

Yu, C., Wijntjes, M., Eisemann, E., & Pont, S. (2023). Quantifying the spatial, temporal, angular and spectral structure of effective daylight in perceptually meaningful ways. *Optics Express, 31(5),* 8953–8974. https://doi.org/10.1364/oe.479715

APPENDIX

APPENDIX O

TU Delft

IDE Master Graduation Project

Projectteam,procedural checks and PersonalProject Brief

In this document the agreements made between student and supervisory team about the student's IDE Master Graduation Project are set out. This document may also include involvement of an external client, however does not cover any legal matters student and client (might) agree upon. Next to that, this document facilitates the required procedural checks:

- Student defines the team, what the student is going to do/deliver and how that will come about
- Chair of the supervisory team signs, to formally approve the project's setup / Project brief
- SSC E&SA (Shared Service Centre, Education & Student Affairs) report on the student's registration and study progress
- IDE's Board of Examiners confirms the proposed supervisory team on their eligibility, and whether the student is allowed to start the Graduation Project

STUDENT DATA&MASTERPROGRAMME
Complete all fields and indicate which master(s) you are in

Family name	[redacted]
Initials	[redacted]
Given name	[redacted]
Student number	[redacted]

IDE master(s)	IPD ✓	DfI	SPD
2nd non-IDE master			
Individual programme *(date of approval)*			
Medisign	✓		
HPM			

SUPERVISORYTEAM
Fill in he required information of supervisory team members. If applicable, company mentor is added as 2nd mentor

Chair	[redacted]	dept./section	[redacted]
mentor	[redacted]		
2nd mentor	[redacted]		
client:	[redacted]		
city:	[redacted]	country:	The Netherlands
optional comments	[redacted]		

! Ensure a heterogeneous team. In case you wish to include team members from the same section, explain why.

! Chair should request the IDE Board of Examiners for approval when a non-IDE mentor is proposed. Include CV and motivation letter.

! 2nd mentor only applies when a client is involved.

APPROVAL OF CHAIR on PROJECT PROPOSAL / PROJECT BRIEF -> to be filled in **by the Chair** of the supervisory team

Sign for approval (Chair)

Name [redacted] Date [redacted] Signature [redacted]

CHECK ON STUDY PROGRESS

To be filled in **by SSC E&SA** (Shared Service Centre, Education & Student Affairs), after approval of the project brief by the chair. The study progress will be checked for a 2nd time just before the green light meeting.

Master electives no. of EC accumulated in total _____ EC

Of which, taking conditional requirements into account, can be part of the exam programme _____ EC

★	**YES**	all 1st year master courses passed
	NO	missing 1st year courses

Comments:

Sign for approval (SSC E&SA)

[redacted]

Name [redacted] Date [redacted] Signature _____

APPROVAL OF BOARD OF EXAMINERS IDE on SUPERVISORY TEAM -> to be checked and filled in by IDE's Board of Examiners

Does the composition of the Supervisory Team comply with regulations?

YES	★	Supervisory Team approved
NO		Supervisory Team not approved

Comments:

Based on study progress, students is …

★	**ALLOWED** to start the graduation project
	NOT allowed to start the graduation project

Comments:

Sign for approval (BoEx)

[redacted]

Name [redacted] Date [redacted] Signature _____

Personal Project Brief – IDE Master Graduation Project

Name student [redacted] **Student number** [redacted]

PROJECTTITLE,INTRODUCTION,PROBLEMDEFINITIONand ASSIGNMENT

Complete all fields, keep information clear, specific and concise

Project title Enhancing calmness and creating a stress-free environment for patients in ICU through an lighting system

Please state the title of your graduation project (above). Keep the title compact and simple. Do not use abbreviations. The remainder of this document allows you to define and clarify your graduation project.

Introduction

Describe the context of your project here; What is the domain in which your project takes place? Who are the main stakeholders and what interests are at stake? Describe the opportunities (and limitations) in this domain to better serve the stakeholder interests. (max 250 words)

The Intensive Care Unit (ICU) environment is critical for patient survival, yet it presents a significant challenge to emotional and psychological well-being of the patient. Patients often experience distress due to excessive , unwanted noise and persistent artificial lighting, which disrupts sleep, circadian rhythms, and cognitive stability. This project aims to address these issues by introducing a lighting system that adapts to natural lighting to create a more relaxed and stress-free environment.

The opportunities this project investigates include potentially improving patient recovery rates by promoting better sleep and reducing stress, crucial for positive outcomes in critical care. Additionally, this project aligns with increasing interest in healthcare innovations that focus on patient-centered care. However, challenges include integrating new technology into existing ICU structures and ensuring that these innovations do not disrupt medical equipment and procedures. This thesis will explore these challenges and aim to demonstrate the feasibility and benefits of a multisensory approach in critical care environments.

This project is a collaboration between IDE's Critical Alarms lab at TU Delft and the Leiden University Medical Centre at Leiden which aligns with LUMC's commitment to patient-centered care and innovation in medical practices. The focus of my thesis is the development of an Lighting System specifically designed for intensive care units (ICUs). The primary stakeholders include critically ill ICU patients , healthcare providers (nurses and intensivists) and family members.(Patients are the main focus for the design, HCPs interact and control the system according to the need , and family inputs/ wishes enhances value).

→ *space available for images / figures on next page*

introduction (continued): space for images

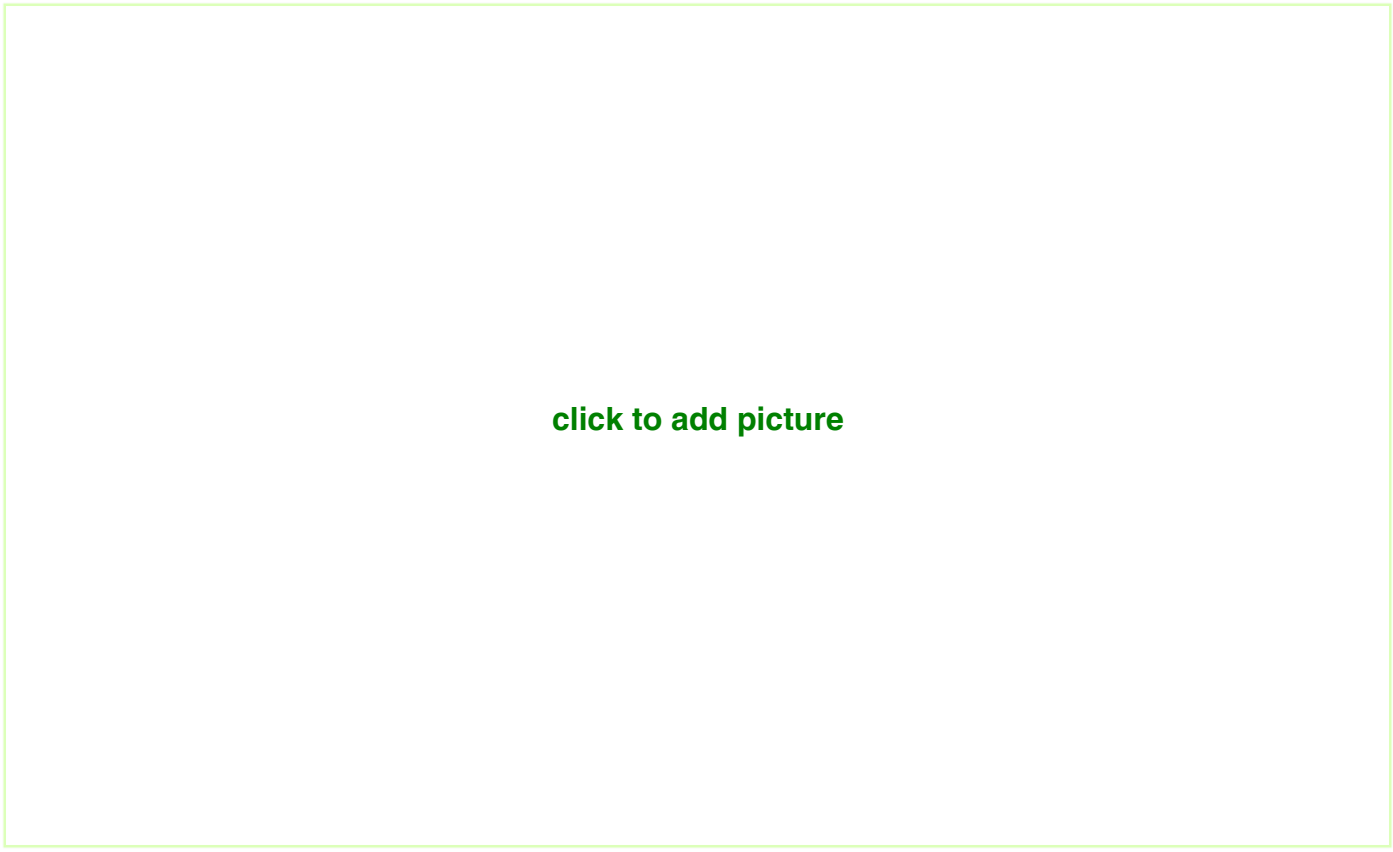


image / figure 1 Equipments in ICU Environment.(Where intervention will be done)

image / figure 2

Problem Definition

What problem do you want to solve in the context described in the introduction, and within the available time frame of 100 working days? (= Master Graduation Project of 30 EC). What opportunities do you see to create added value for the described stakeholders? Substantiate your choice.
(max 200 words)

The main problem my thesis addresses is the negative impact of environmental factors like harsh lighting and continuous noise on the sleep quality of patients in Intensive Care Units (ICUs). These environmental conditions are not conducive to the natural sleep-wake cycles essential for recovery, as they can significantly disrupt patients' circadian rhythms.

In ICUs, proper sleep is crucial because it aids in healing and overall well-being. However, the typical ICU setup—with its constant lighting and high noise levels—increases stress, impairs immune function, and prolongs the time patients need to recover. While there are some solutions aimed at improving these conditions, they are often not integrated or specifically tailored to the unique requirements of ICU settings.

This thesis not only explores the specific environmental challenges that impact sleep in ICUs but also aims to develop a prototype that can effectively mitigate these disruptive factors. The goal is to create a better environment that aligns with the natural biological cycles of patients, thereby enhancing their calmness and reducing stress for both patients and healthcare providers. This focus on both problem analysis and solution development highlights the comprehensive approach of the thesis to improve patient care in ICUs.

Assignment

This is the most important part of the project brief because it will give a clear direction of what you are heading for. Formulate an assignment to yourself regarding what you expect to deliver as result at the end of your project. (1 sentence) As you graduate as an industrial design engineer, your assignment will start with a verb (Design/Investigate/Validate/Create), and you may use the green text format*:*

"Develop and evaluate an lighting system for the adult ICU to ensure critically ill patients feel calm, relaxed, and stress-free, while supporting their natural day-night rhythm throughout their ICU stay."

Then explain your project approach to carrying out your graduation project and what research and design methods you plan to use to generate your design solution (max 150 words)

My project approach will utilize the Double Diamond design process to develop the Adaptive Lighting System. In the Discover phase, I will conduct qualitative research, including interviews with healthcare professionals and observations in ICU settings, to identify key pain points related to patient recovery environments. During the Define phase, I'll synthesize insights from the survey and the co-creation session with students to establish clear design requirements and objectives using the HMW (How Might We) method. The Develop phase will involve prototyping the lighting systems, testing these with stakeholders, and iteratively refining based on feedback. Finally, in the Deliver phase, I will finalize the design for implementation, ensuring it meets the needs of both patients and healthcare providers in enhancing recovery experiences in ICUs. This structured approach will ensure a comprehensive understanding and innovative solution that aligns with user needs and technical feasibility.

Project planning and key moments

To make visible how you plan to spend your time, you must make a planning for the full project. You are advised to use a Gantt chart format to show the different phases of your project, deliverables you have in mind, meetings and in-between deadlines. Keep in mind that all activities should fit within the given run time of 100 working days. Your planning should include a ***kick-off meeting***, ***mid-term evaluation meeting***, ***green light meeting*** *and* ***graduation ceremony****. Please indicate periods of part-time activities and/or periods of not spending time on your graduation project, if any (for instance because of holidays or parallel course activities).*

Make sure to attach the full plan to this project brief.
The four key moment dates must be filled in below

Kick off meeting	11th February 2025
Mid-term evaluation	14 Apr 2025
Green light meeting	2 Jun 2025
Graduation ceremony	1 Jul 2025

In exceptional cases (part of) the Graduation Project may need to be scheduled part-time. Indicate here if such applies to your project

Part of project scheduled part-time	
For how many project weeks	
Number of project days per week	

Comments:

Motivation and personal ambitions

Explain why you wish to start this project, what competencies you want to prove or develop (e.g. competencies acquired in your MSc programme, electives, extra-curricular activities or other).

Optionally, describe whether you have some personal learning ambitions which you explicitly want to address in this project, on top of the learning objectives of the Graduation Project itself. You might think of e.g. acquiring in depth knowledge on a specific subject, broadening your competencies or experimenting with a specific tool or methodology. Personal learning ambitions are limited to a maximum number of five.
(200 words max)

My motivation to embark on this project stems from a profound interest in improving healthcare environments through innovative technology, a passion cultivated during my MSc program. This thesis presents an opportunity to apply and expand my knowledge in designing systems that enhance patient well-being in critical care settings.

This project specifically allows me to further develop competencies in interdisciplinary design and user experience research, crucial skills I intend to carry forward into my professional career. My ambition is to create a prototype that not only meets technical specifications but also resonates deeply with user needs, particularly for those in vulnerable conditions such as ICU patients.

Additionally, I aim to deepen my understanding of circadian rhythms and their impact on health—a subject that has intrigued me throughout my studies. By integrating this scientific aspect with practical design skills, I aspire to pioneer solutions that offer tangible benefits to both patients and healthcare providers. Experimenting with the Double Diamond design process in this real-world application will enhance my ability to manage complex design challenges and foster innovation in healthcare technology.

APPENDIX A

Recorded luminance values

1st HOUR 4pm							
Points	Light Direction						
	E(x+)	E(x-)	E(y+)	E(y-)	E(z+)	E(z-)	
1	62	78,4	51,9	41,2	79,1	24,4	56,1667
2	137,8	105,5	86,5	41,9	144,7	36,4	92,1333
3	45,1	66,6	53	49,6	35,93	23,25	45,58
4	42,6	64,6	53,8	73	34,03	24,24	48,7117
5	66,6	114,9	41,2	51,5	53,8	25,31	58,885
6	252	37,27	61,2	86,1	127	36,08	99,9417
7	62,4	35,52	55	64,4	53	22,73	48,8417
8	71,3	41,9	53,8	108	53,5	25,78	59,0467
9							
10							
11	69,3	63,6	50,3	30,9	57	24,43	49,255
12	55	49,8	34,7	25,51	55,5	19,93	40,0733

2nd HOUR. 5pm. Sunset 5:01pm							
Points	Light Direction						
	E(x+)	E(x-)	E(y+)	E(y-)	E(z+)	E(z-)	
1	44,9	71	66,3	32,03	55,9	18,01	48,0233
2	70	61,2	62,6	33,64	47,3	18,4	48,8567
3	36,7	34,8	33,8	41,9	26,1	16,6	31,65
4	36,3	35,6	40,5	39,06	24,3	17,8	32,26
5	35,2	114	29,9	25,77	39,39	16,7	43,4933
6	145,7	27,73	29,4	38,03	68,5	22,97	55,3883
7	57	31,68	32,73	51,3	36,31	15	37,3367
8	35,97	39,8	29,85	90,02	40,7	18,28	42,4367
9							
10							
11	65,8	54,7	33,08	25,24	53,8	20,54	42,1933
12	51,8	73	35,18	22,73	51,5	20,6	42,4683

3rd HOUR. 6pm							
Points	Light Direction						
	E(x+)	E(x-)	E(y+)	E(y-)	E(z+)	E(z-)	
1	47,3	68,5	66,6	31,55	60,9	17,78	48,7717
2	63,6	54,7	67,1	33,06	56,5	19,6	49,0933
3	40,4	34,8	32,9	64,6	25,24	21,5	36,5733
4	33,4	34,7	40,4	38,8	23,19	16,88	31,2283
5	37,38	93,2	28,56	21,88	35,36	17,09	38,9117
6	135,9	26,78	33,05	34,2	51,5	22,17	50,6
7	51,3	29,5	31,8	58,7	34,98	16,06	37,0567
8	34,11	40,9	29,29	82	40,4	17,85	40,7583
9							
10							
11	55,2	53	29,85	25,15	55,5	19,9	39,7667
12	47,8	68,8	31,6	21,29	52,3	19,7	40,2483

4th HOUR. 7pm							
Points	**Light Direction**						
	E(x+)	**E(x-)**	**E(y+)**	**E(y-)**	**E(z+)**	**E(z-)**	
1	1,99	4,07	2,4	1,84	1,98	0,99	2,21167
2	3,42	2,11	2,27	3,06	1,82	0,89	2,26167
3	2,52	1,89	2,13	3,5	1,4	1,17	2,10167
4	1,88	2,8	2,91	1,67	1,47	1,02	1,95833
5	8,54	3,14	1,78	2,6	1,83	1,21	3,18333
6	4,57	3,4	1,7	2,22	2,12	1,04	2,50833
7	3,87	1,66	3,09	2,96	1,96	1,3	2,47333
8	5,04	1,8	5,01	4,26	1,98	1,86	3,325
9							
10							
11	2,51	1,63	2,47	1,96	1,56	1,07	1,86667
12	1,37	2,96	2,25	0,88	1,62	0,84	1,65333

5th HOUR. 8pm							
Points	**Light Direction**						
	E(x+)	**E(x-)**	**E(y+)**	**E(y-)**	**E(z+)**	**E(z-)**	
1	2,58	4,28	2,99	7,68	2,98	1,37	3,64667
2	3,37	2,19	2,28	2,94	1,89	0,88	2,25833
3	2,54	1,75	2,27	3,82	1,58	1,21	2,195
4	1,87	2,8	3,2	1,84	1,5	0,98	2,03167
5	6,78	4,07	2,6	5,8	2,35	1,16	3,79333
6	4,31	3,55	1,72	1,9	1,96	0,99	2,405
7	3,54	2,03	5,87	3,77	3,46	1,35	3,33667
8	4,9	2,49	5,05	4,35	2,89	1,41	3,515
9							
10							
11	2,7	1,99	4,78	2,4	2,5	1,46	2,63833
12	1,49	2,74	2,53	0,87	1,46	0,92	1,66833

Average values										
	Point 1	Point 2	Point 3	Point 4	Point 5	Point 6	Point 7	Point 8	Point 11	Point 12
4pm	56	92	46	49	59	100	49	59	49	40
5pm	48	49	32	32	43	55	37	42	42	42
6pm	49	49	37	31	39	51	37	41	40	40
7pm	2	2	2	2	3	3	2	3	2	2
8pm	4	2	2	2	4	2	3	4	3	2

B. ANALYSIS DONE IN LUMC

C. SEMI STRUCTURED INTERVIEW QUESTIONS

1. Patient's Emotional Journey:
- How does the patient's journey differ in terms of their emotions throughout the day?
- What are the emotional impacts of waking up from sedation or undergoing surgery?
- How do fluctuations in patient emotions occur throughout the day?
- What causes feelings of isolation, fear, or anxiety in patients?

2. Patient Sleep and Comfort:
- Do ICU patients sleep well? How does the ICU environment impact their sleep?
- How do light and sound affect the quality of sleep?
- What helps patients sleep or feel less anxious?
- Does the ICU environment (sound, light, medical interventions) disrupt the patient's ability to sleep or rest?

3. Sound and Its Impact:
- How do sounds in the ICU affect the patient's mental state?
- Can soothing music or sound therapy be beneficial in ICU?
- Are there specific sounds or lighting conditions that cause distress or comfort to patients?

4. Control Over Environment:
- Do patients feel isolated or disconnected? How can environmental control help alleviate this?
- Should patients be given more control over the ICU environment (lighting, sound)?

5. The Role of Family:
- How does the presence (or absence) of family affect the patient's emotional state?
- What impact does family interaction have on patient recovery?

D. SURVEY QUESTIONS

1. Are you a Nurse or a Doctor at LUMC? How many years of experience do you have in ICU?

2. Mention your gender

3. What are the patients' experiences around the lighting conditions in single/ double patient ICU rooms in terms of their mood and emotions?

- Patients appear more calm and relaxed under current lighting conditions.
- Patients often appear agitated or restless under current lighting conditions.
- Patients show no noticeable change in mood due to lighting conditions.
- Patients seem to experience discomfort or difficulty sleeping due to lighting conditions.

4. Which of the following sounds causes the most distress to patients?

- Alarm / machine sounds
- Talking sounds
- Sounds from an emergency
- Sounds from the corridor
- Sounds from a different patient

5. How do the current sounds in the ICU affect the patients' experiences (mood) and how do they respond to them?

- Patients appear calmer and more relaxed when the ICU is quieter.
- Patients often show signs of confusion or agitation when the ICU is noisy.
- No noticeable change in patients' mood in response to different sound levels.
- Patients seem to experience discomfort or have trouble sleeping due to ICU sounds.
- The implementation of soothing sounds could benefit patients' emotional well-being.

6. What are the specific times during your shift when patients seem sensitive or vulnerable?
After waking up from sedation

- During care-giving activities (e.g., bathing, dressing changes, repositioning)
- During shift changes or handovers
- During night-time or early morning hours
- When receiving distressing medical news
- Before or after medical procedures (e.g., intubation, injections, catheterization)
- When experiencing pain or discomfort
- When family members leave after visiting hours
- During moments of isolation or loneliness
- Other (Please specify):

7. How do patients' emotional states vary throughout the day in the ICU, and what are the possible triggers for these changes?

8. Please describe a potential new lighting intervention designed to improve patient comfort in the ICU. What specific features should it include, and how would it function throughout the day?

9. Who should have the ability to control this potential lighting intervention?

- Patient themselves.
- Only Staff
- Or Both

10. Please describe a potential sound-based intervention aimed at improving patient well-being in the ICU. What specific elements should it include, and how would it function through out the day?

11. Should the patients be given the option to chose from a library of different types of sounds (Natural sounds, Calming sounds, Human sounds)

12. Which types of sounds do you think will make the patients feel more connected and familiar in the ICU space?

13. Have you ever experienced or heard about the use of natural sounds in healthcare settings?

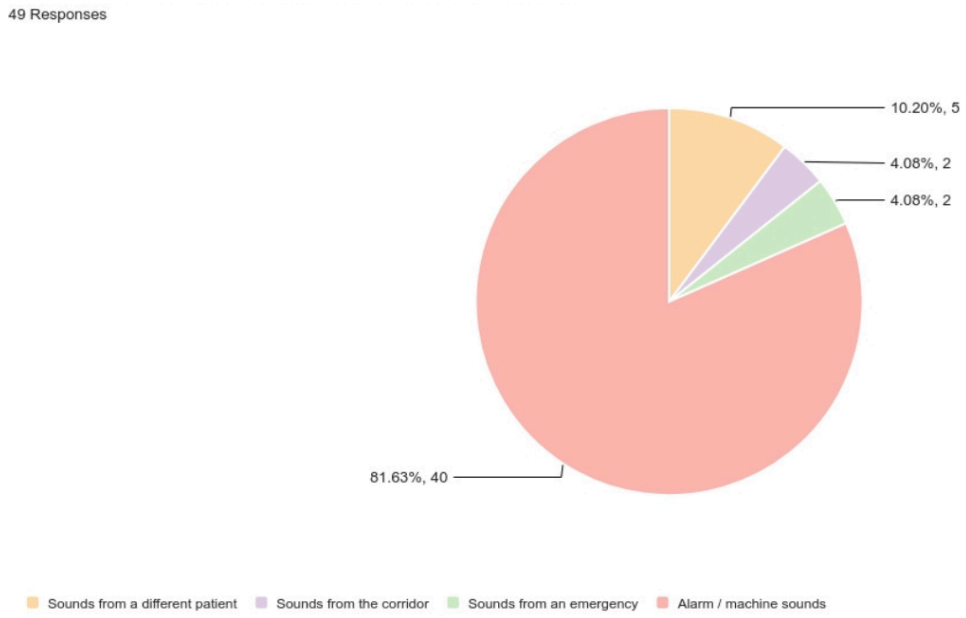
- Yes
- No
- If yes, can you describe how did you experienced it.

14. Have you had any preferences or suggestions related to music/ sound from patients / family members?

- Yes
- No
- If yes, can you elaborate.

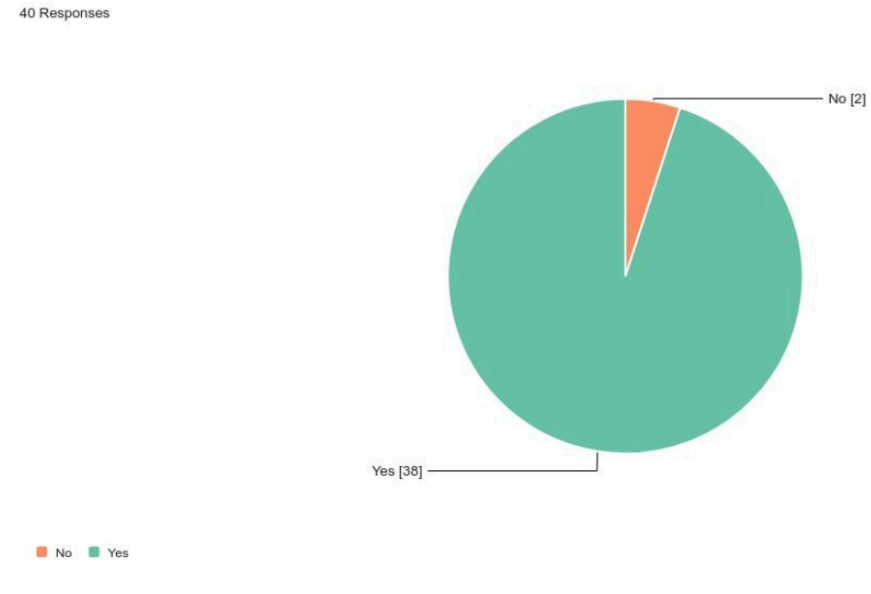
E. SURVEY ANALYSIS

Q2 - Which of the following sounds cause most distress to patients?



- Most healthcare providers said that sounds from alarms and machines distress patients a lot. These sounds include beeps and buzzes from medical devices.
- A smaller proportion of respondents noted that noises made by other patients, such as talking, or medical interventions, are distressing.

Q9 - Should the patients be given the option to chose from a library of different types of sounds



- The vast majority believe that patients should have the autonomy to select sounds that they find comforting or familiar. This could significantly enhance their sense of control and personal comfort within the ICU environment, which is often seen as a key factor in patient-centered care.

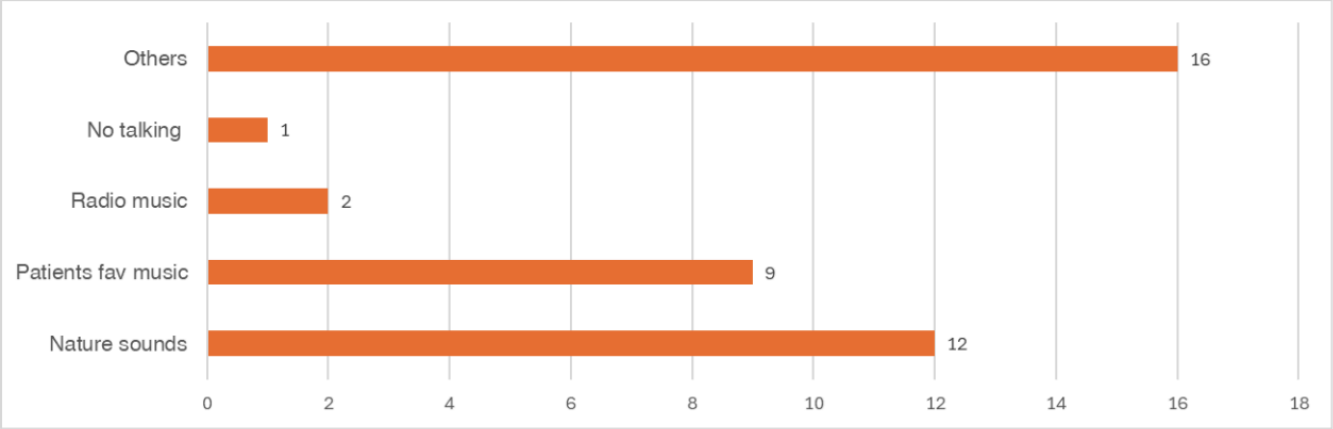
Q10 - Which types of sounds do you think will make the patients feel more connected and familiar in the ICU space?

Bird sounds

Sea noise

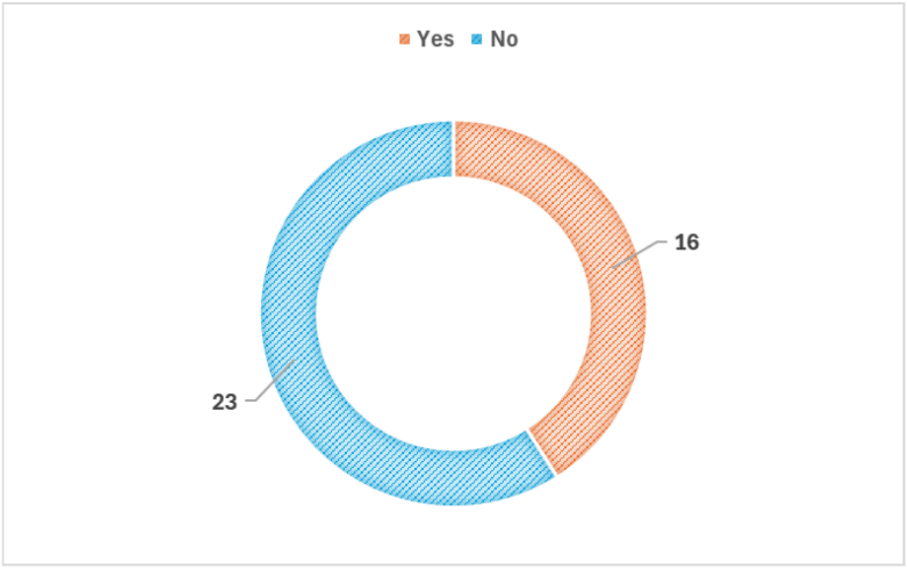
water stream

Rain/thunder



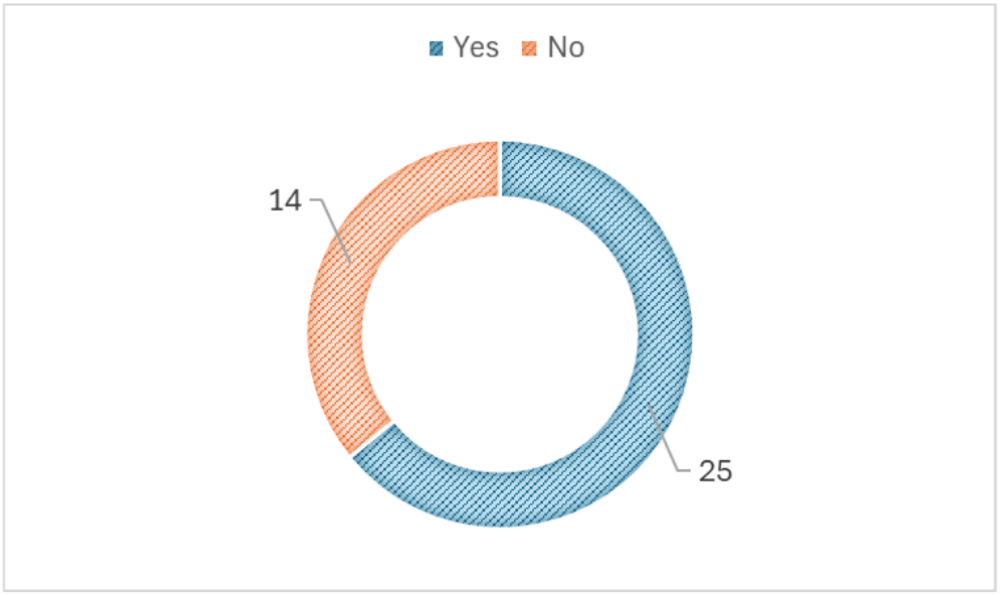
- **Nature Sounds**: Many responses highlighted the calming effect of nature sounds, such as rain, thunder, sea noises, bird sounds, and water streams. These sounds are often used in therapeutic settings due to their proven effectiveness in reducing stress and enhancing relaxation.
- **Music**: There's a strong preference for music, specifically music loved by the patients, classical music, and soothing tones. Personalizing music choices to fit individual patient preferences can provide comfort and a sense of normalcy.
- **Personal and Familiar Sounds**: Several responses indicated the importance of incorporating sounds from the patient's home or familiar environments, such as own music or sounds from their daily life.

Q11 - Have you ever experienced or heard about the use of natural sounds in healthcare settings?

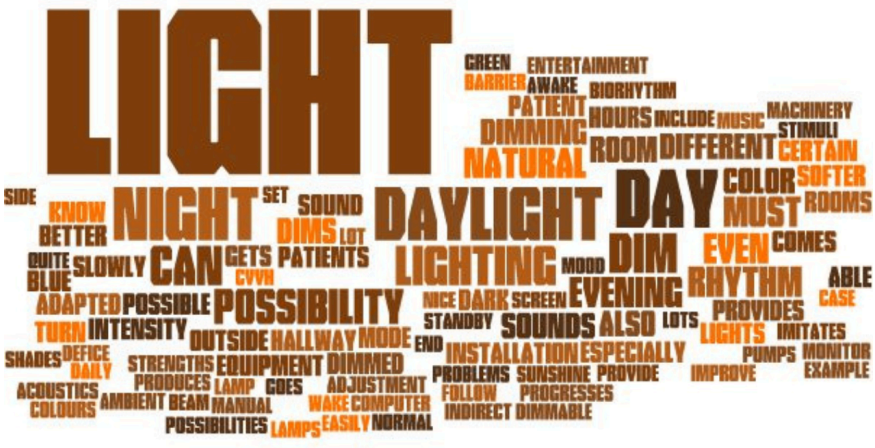


- Several responses indicate that natural sounds are already being used in pediatric and neonatal ICUs. This suggests that there is an established practice of using nature-based soundscapes to provide comfort, particularly for young patients.
- Some respondents explicitly mention that natural sounds have a soothing and calming effect, reinforcing the idea that such interventions positively impact patient well-being.
- **Ceiling Projectors**: The mention of ceiling projectors with natural sounds and videos suggests the integration of multisensory experiences (sound and visuals) to enhance relaxation.

Q12 - Have you had any preferences or suggestions related to music/ sound from patients / family members?



- A majority of healthcare providers (64%) reported that patients or their families have expressed preferences or suggestions regarding music and sound.



F. CO CREATIVE SESSION

Co-creative session planning

Brain writing (Diverging)

- Use **Brainwriting 6-3-5 worksheets**.
- Each student writes **3 ideas** in **5 minutes.**
- After **5 minutes**, they pass the sheet to the right or ask students to change places.
- The next person **builds on those ideas**.
- Repeat **6 times**. (Based on number of participants)

Spontaneous Clustering (Reverging)

Setup

- **Stick all ideas on a wall or board.**
- **Ask students to walk around and read the ideas.**
- **Begin grouping similar ideas into clusters.**
-

(Instruction or tell them in prior)

- Grab a post-it, read the option and try to find a similar option. Put them on the wall closely together.
- You will find that after just starting the clusters of similar ideas will emerge.
- Feel free to reposition options if needed
- After clustering, ask RG to give a catchy name, and write names for that cluster.
- Some options belongs to two or more clusters, duplicate them on posit it and add it to both the clusters

Hits or dots (Converging)

Setup

- Each participant receives **5 dot stickers**. (3 for good, 2 for best)
- They vote on the **ideas per clusters they find most compelling**.

(Instruction or tell them in prior)

- Read out the problem before starting the procedure.
- Provide the stickers and mention them about the criteria and frame questions on spot.
- Three dots for **hits** ideas and two dots for the **novel** or best ones.

SCAMPER (Diverging)

- From the top ideas from hits or dots, keep everything together.
- In break have a quick glances at the selected ones and then formulate the questions based on SCAMPER.
- Give post its, with sheets to write and paste.

Substitute
Combine
Adapt
Modify
Put to another use
Eliminate
Reverse

- What if we substitute....?
- What is we combine...and...?
-

Sequencing (Reverging)

Setup

- **Stick all lighting ideas on a wall or board**.
- Ask students to **walk around and read** the ideas.
- Begin **grouping similar ideas** into clusters.

(Instruction or tell them in prior)

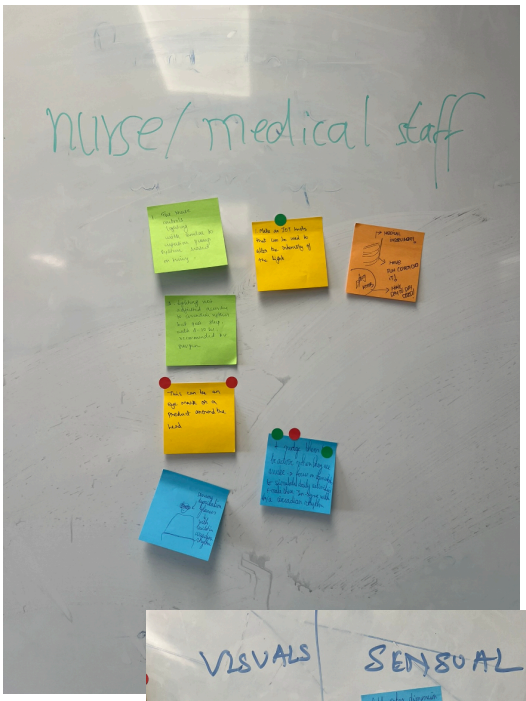
- Have a quick glance at the post its and come with 2x2 matrix axes and ask RG to name the axes.
- Eg of axes -
    - **Ease of Implementation vs. Impact on Patient Well-being**
    - **Cost vs. Effectiveness**
    - **Technology Readiness vs. Comfort Level**

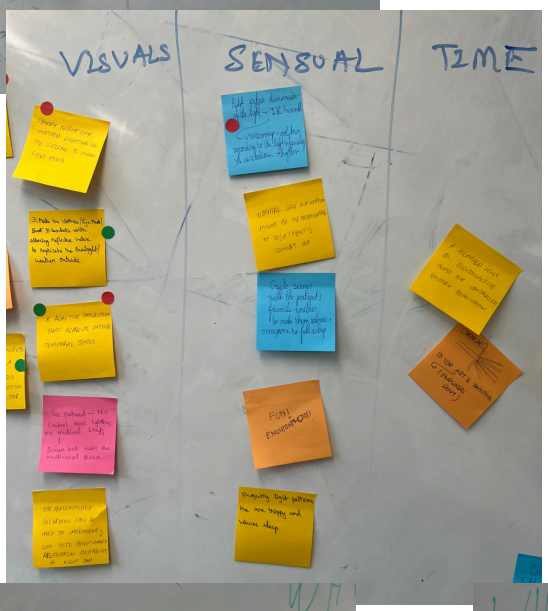
Making a poster (Converging)

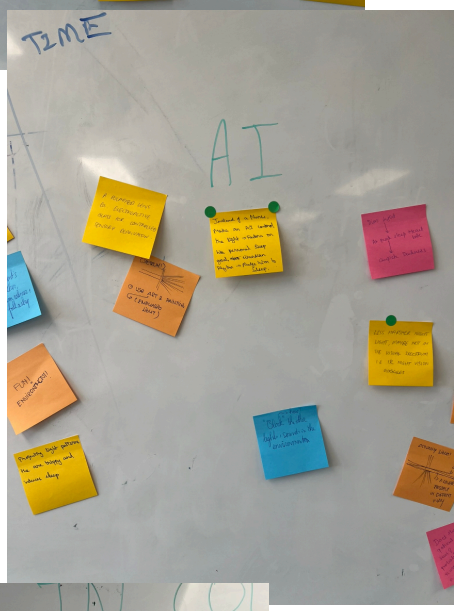
Setup

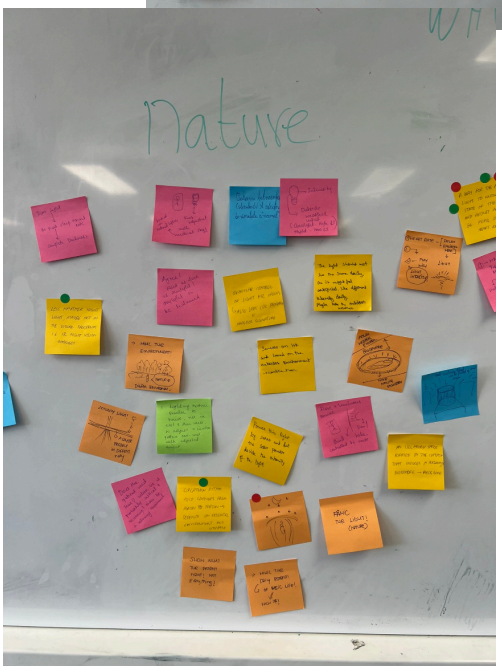
- Arrange workstations, provide A3 papers and markers for poster making.
- Mention that poster should have titles, problem statement, proposed solutions.
- Ask RG to select ideas from matrix and later divide groups and then ask the group to choose one idea and come with a poster.

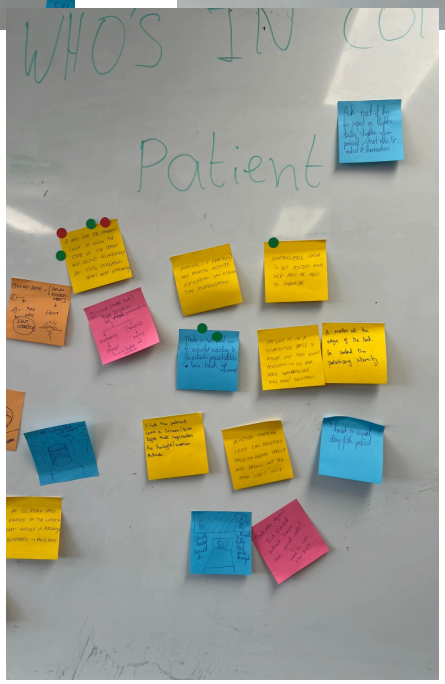
Outcome of HITS & DOTS method.







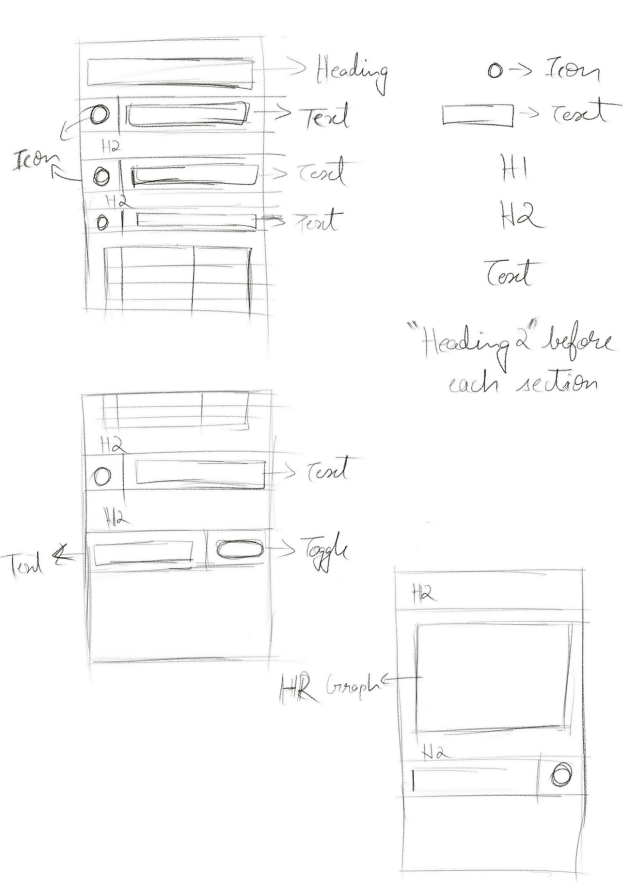


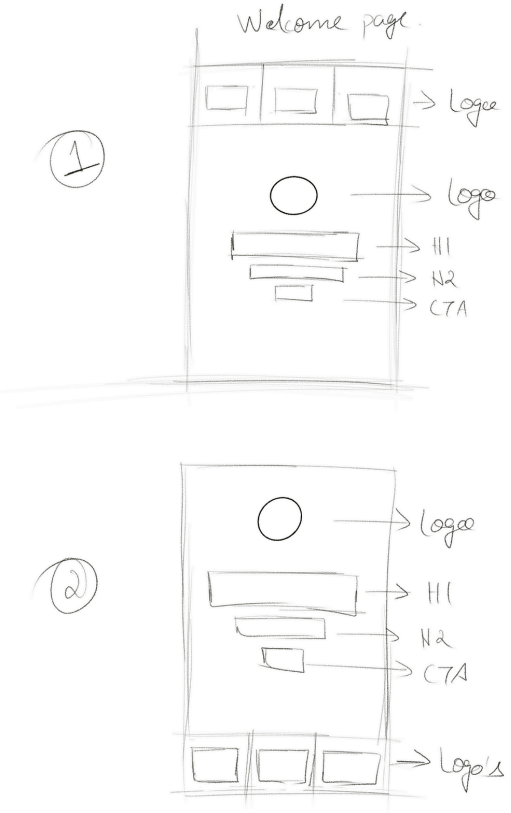


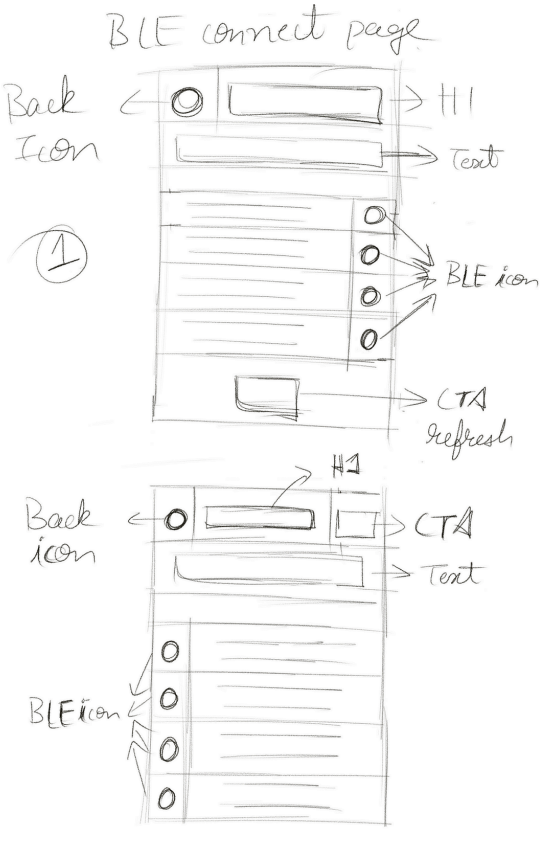
Outcome of the SCAMPER method.

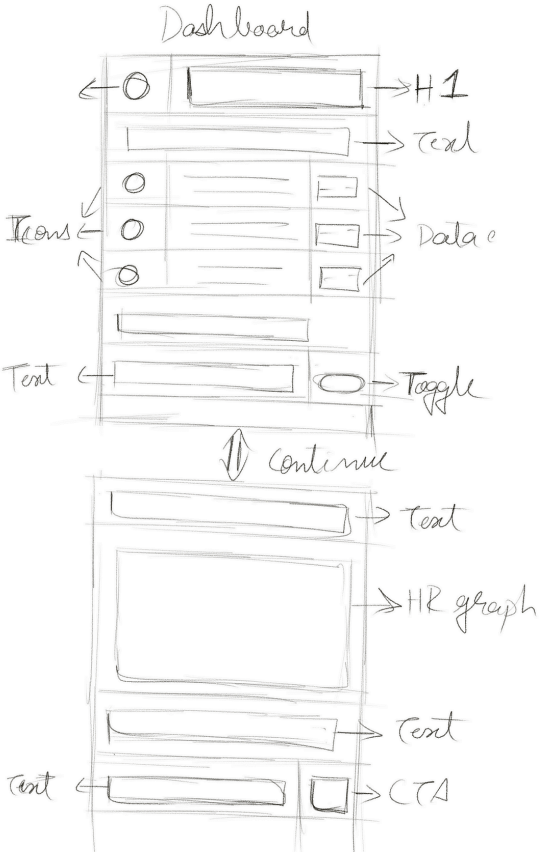
Participants engaging in different activities during the co-creative session.

G. WIREFRAME IDEATION

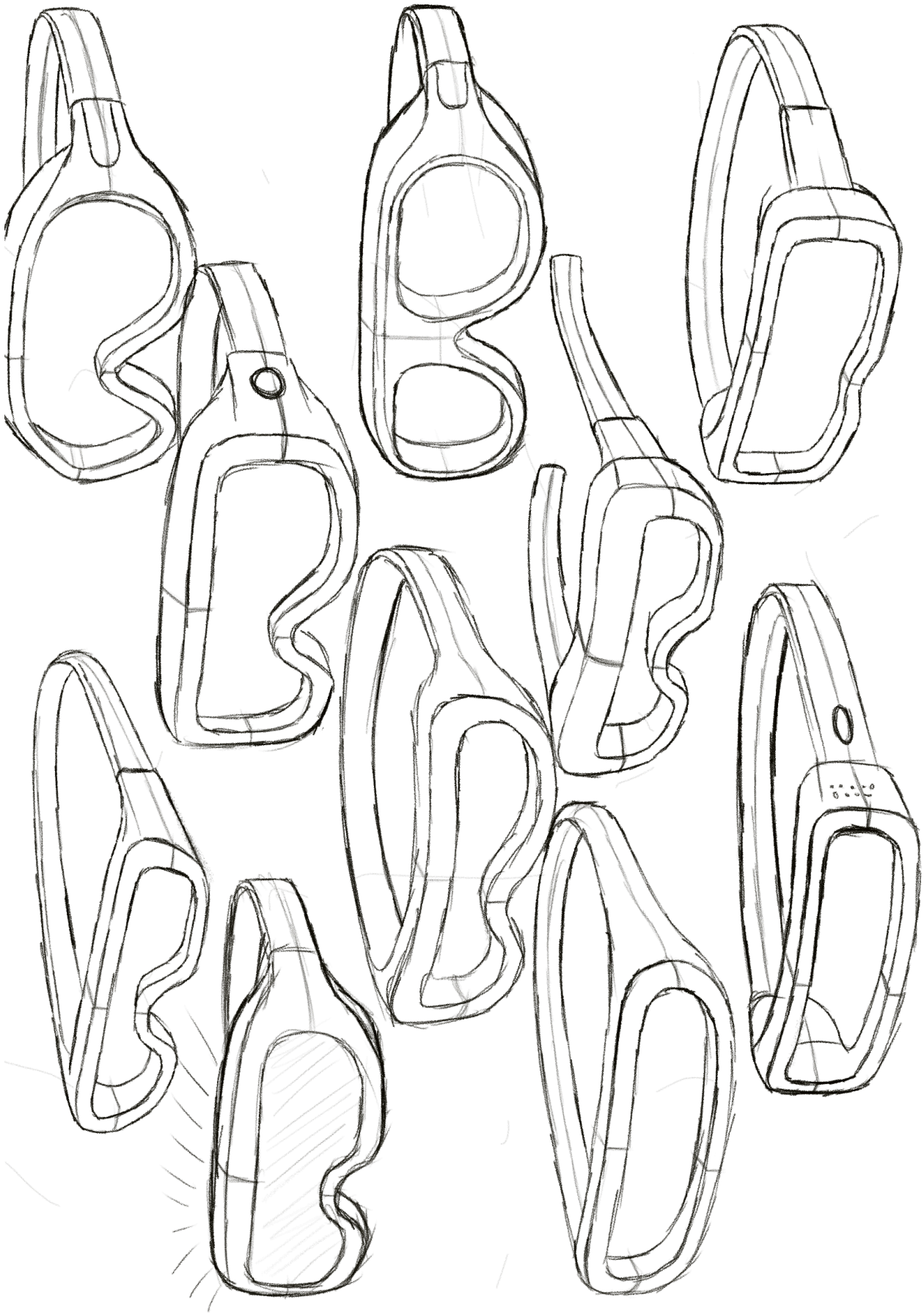








H. IDEATION SKETCHES

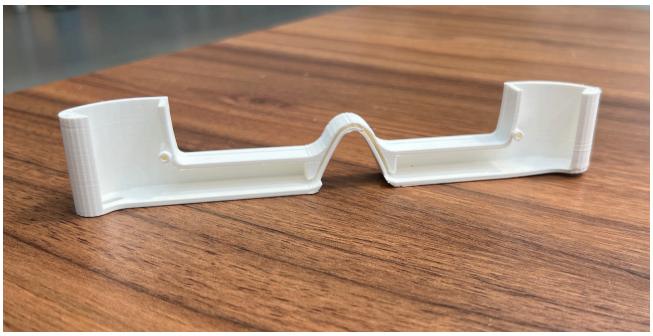
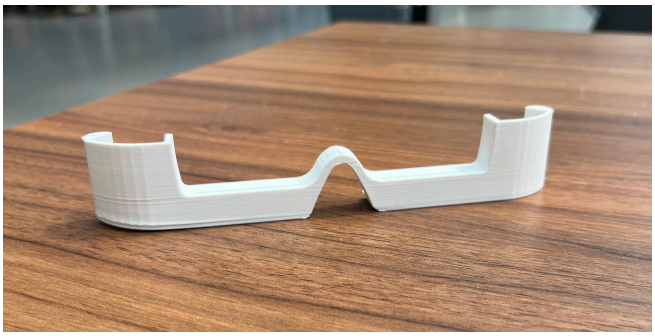


I. LUMOGLAZE ITERATIONS

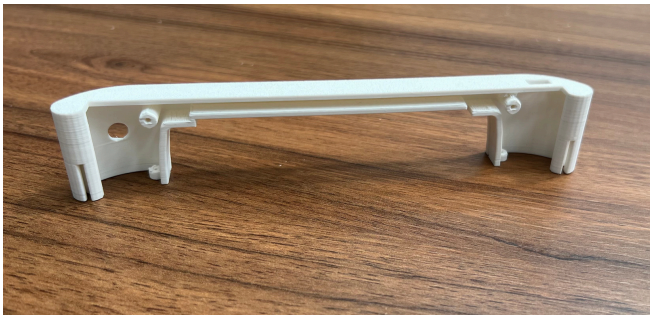
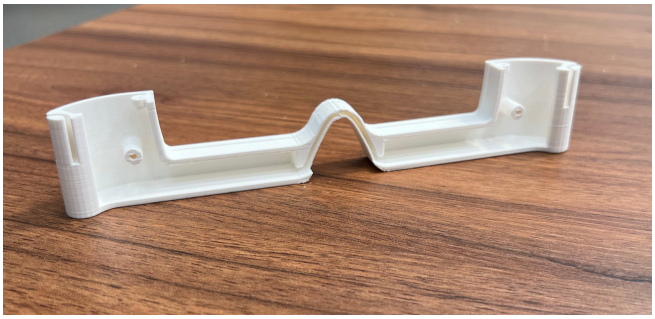
First Iteration

Second Iteration

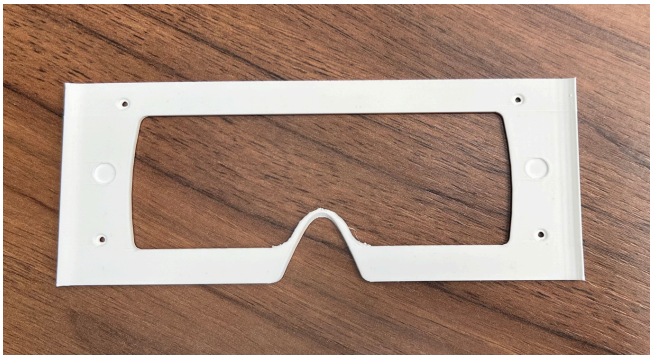
Third Iteration

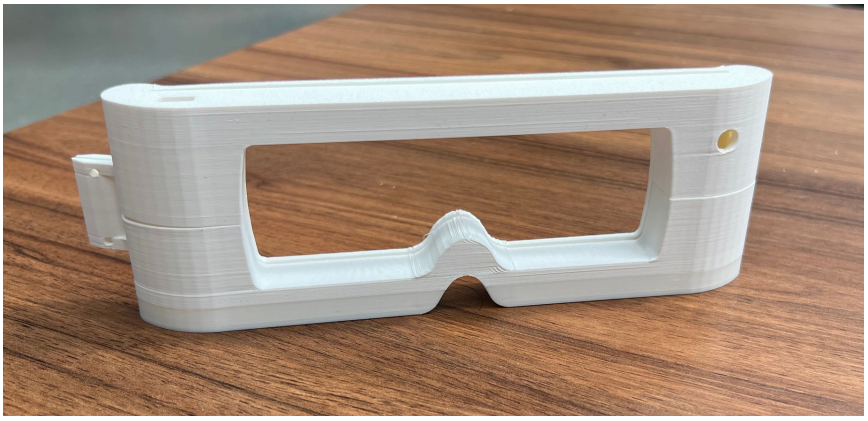



Fourth Iteration

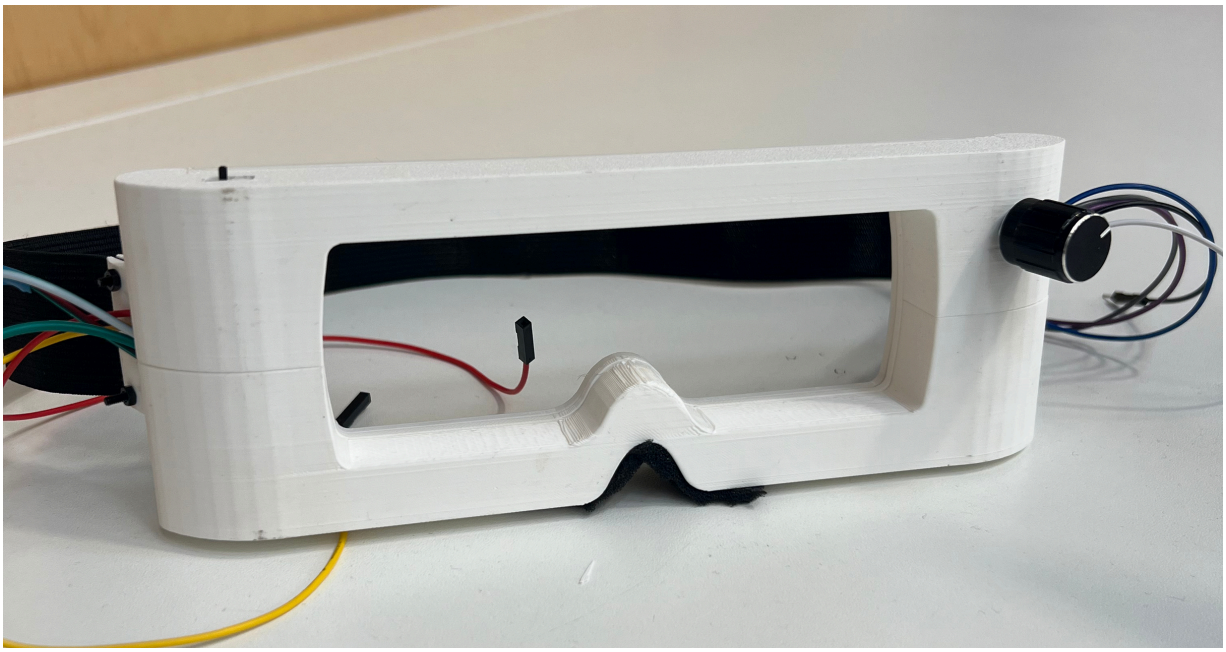



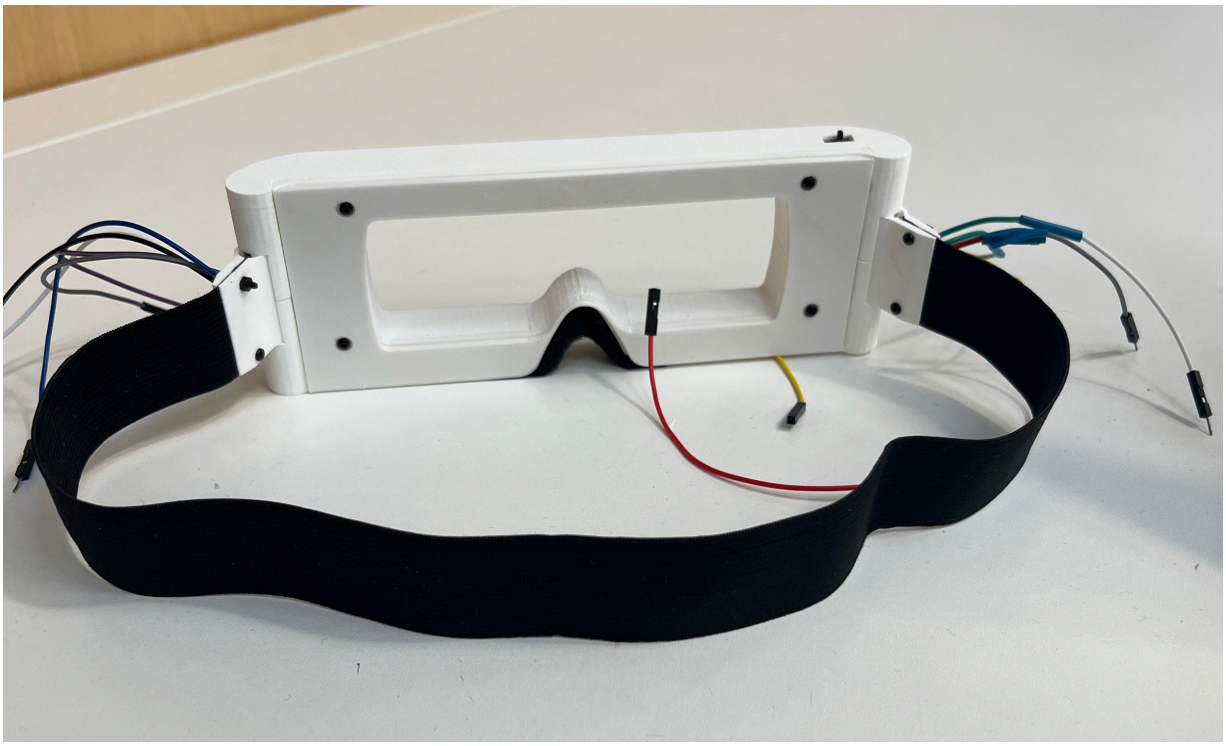
Sixth Iteration



Fully assembled LumoGlaze





J. USER TESTING

Questions asked

1. Did you find the brightness level of the morning light comfortable and appropriate?
-Strongly disagree -Somewhat disagree -Neither agree nor disagree -Somewhat agree -Strongly agree

2. Did the light make you feel more alert or energized?
-Strongly disagree -Somewhat disagree -Neither agree nor disagree -Somewhat agree -Strongly agree

3. Any discomfort or feedback about the morning light?

4. Did the evening light feel gentle and non-intrusive?
-Strongly disagree -Somewhat disagree -Neither agree nor disagree -Somewhat agree -Strongly agree

5. Did you feel relaxed or sleepy while experiencing this light?
-Strongly disagree -Somewhat disagree -Neither agree nor disagree -Somewhat agree -Strongly agree

6. Would you consider using this light before sleep?
- Yes
- No

7. The goggles felt comfortable to wear during the session.
-Strongly disagree -Somewhat disagree -Neither agree nor disagree -Somewhat agree -Strongly agree

8. Did the goggles feel physically discomfort at any particular place? If any mention them.

9. What was your overall impression of the lighting effects?

10. I could clearly perceive the difference between morning and evening light.
-Strongly disagree -Somewhat disagree -Neither agree nor disagree -Somewhat agree -Strongly agree

11. Was the rotary control intuitive to use? Any suggestions?

12. The toggle between auto/manual modes was easy to understand.
-Strongly disagree -Somewhat disagree -Neither agree nor disagree -Somewhat agree -Strongly agree

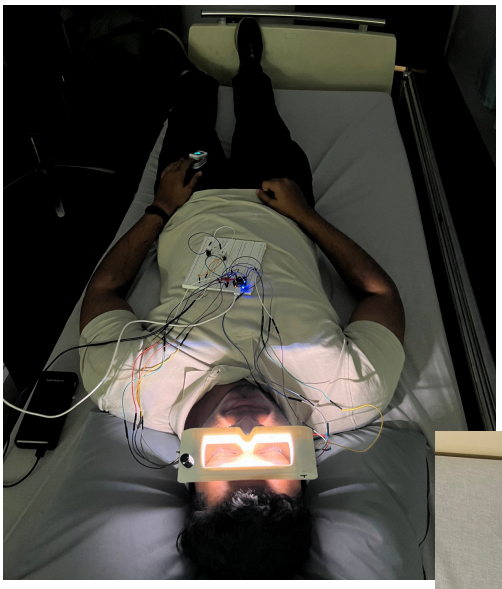
13. Did any phase feel too intense or too dim? Which one and why?

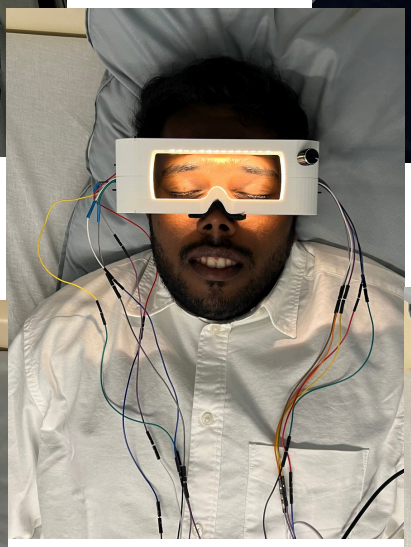
14. I noticed a change in how I felt (alertness or calm) during the test.
-Strongly disagree -Somewhat disagree -Neither agree nor disagree -Somewhat agree -Strongly agree

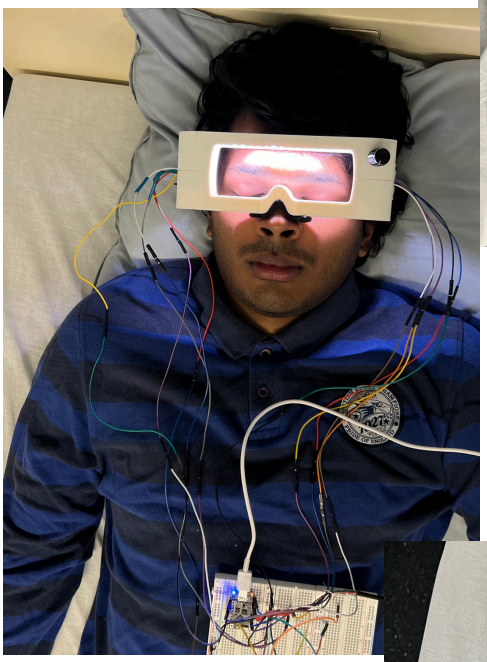
15. How did your body feel during the different lighting phases
- Morning Light
- Evening Light

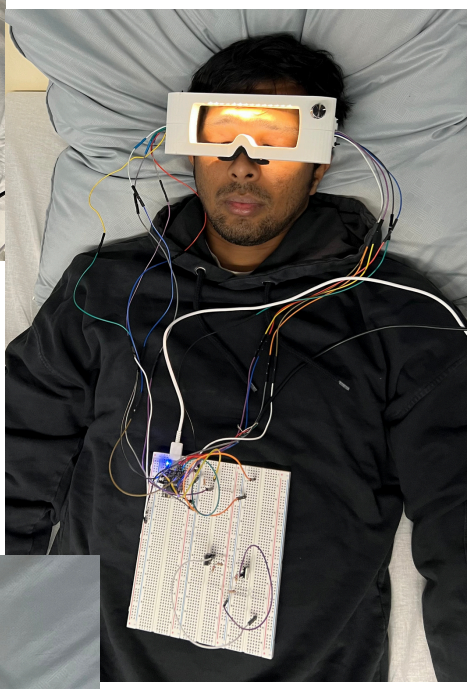
16. If you had to use this for an extended period, how likely would you be to accept it as part of your environment?

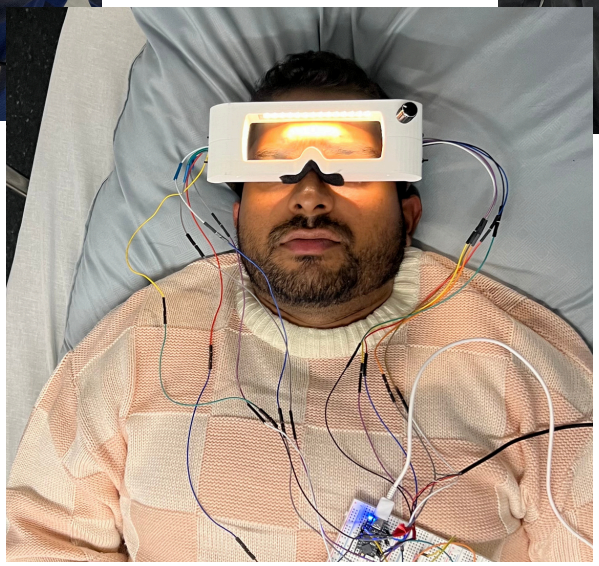
K. IMAGES FROM USER TESTING SESSIONS.











L. DATA ANALYSIS

	User interview results new graph					
Q1						
		Strongly Disagree	Somehwhat disagree	Neither agree nor disagree	Somewhat agree	Strongly agree
	No of participants	0	1	2	8	1

		Strongly Disagree	Somehwhat disagree	Neither agree nor disagree	Somewhat agree	Strongly agree
Q2	No of participants	0	1	2	8	1

		Strongly Disagree	Somehwhat disagree	Neither agree nor disagree	Somewhat agree	Strongly agree
Q3	No of participants	0	1	4	4	3
	Mean	3,75				
	SD	0,92				

		Strongly Disagree	Somehwhat disagree	Neither agree nor disagree	Somewhat agree	Strongly agree
Q4	No of participants	1	0	2	5	4
	Mean	3,91				
	SD	-1,2				

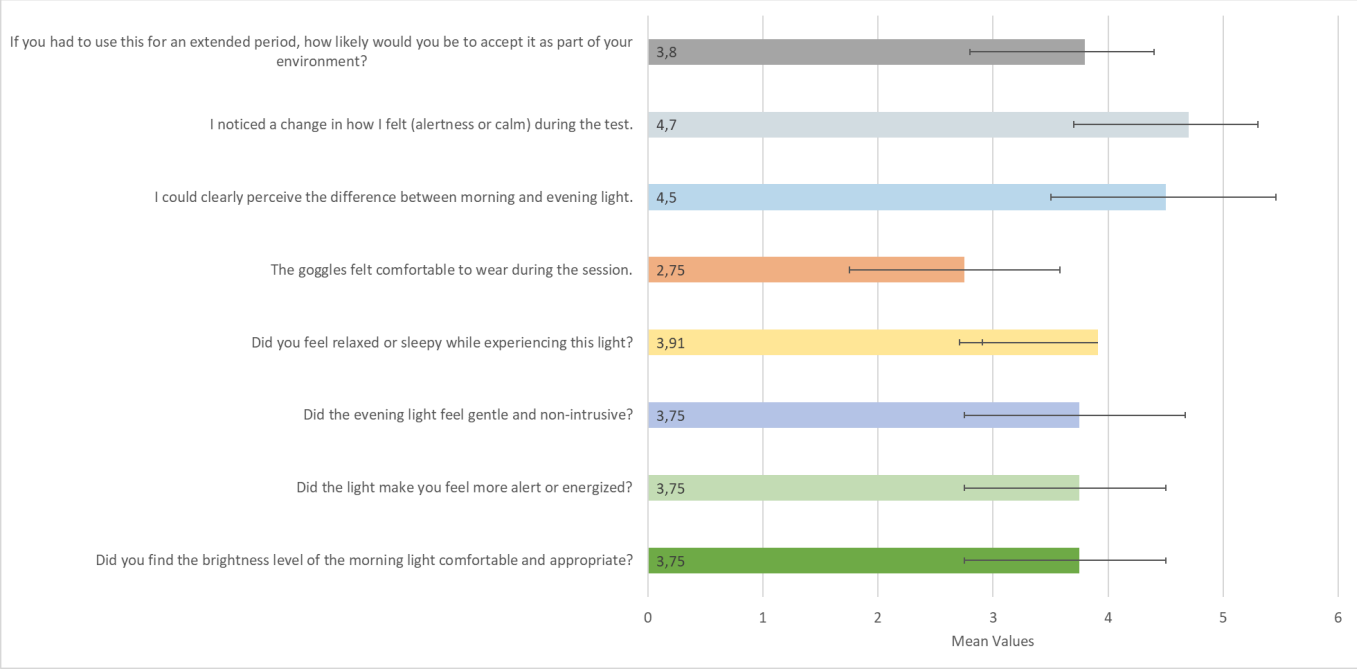
		Strongly Disagree	Somehwhat disagree	Neither agree nor disagree	Somewhat agree	Strongly agree
Q5	No of participants	1	3	6	2	0
	Mean	2,75				
	SD	0,83				

		Strongly Disagree	Somehwhat disagree	Neither agree nor disagree	Somewhat agree	Strongly agree
Q6	No of participants	0	1	1	1	9
	Mean	4,5				
	SD	0,96				

		Strongly Disagree	Somehwhat disagree	Neither agree nor disagree	Somewhat agree	Strongly agree
Q7	No of participants	0	0	1	2	9
	Mean	4,7				
	SD	0,6				

		Strongly Disagree	Somehwhat disagree	Neither agree nor disagree	Somewhat agree	Strongly agree
Q8	No of participants	0	0	3	8	1
	Mean	3,8				
	SD	0,6				

	Mean	SD
Did you find the brightness level of the morning light comfortable and appropriate?	3,75	0,753778
Did the light make you feel more alert or energized?	3,75	0,753778
Did the evening light feel gentle and non-intrusive?	3,75	0,92
Did you feel relaxed or sleepy while experiencing this light?	3,91	-1,2
The goggles felt comfortable to wear during the session.	2,75	0,83
I could clearly perceive the difference between morning and evening light.	4,5	0,96
I noticed a change in how I felt (alertness or calm) during the test.	4,7	0,6
If you had to use this for an extended period, how likely would you be to accept it as part of your environment?	3,8	0,6



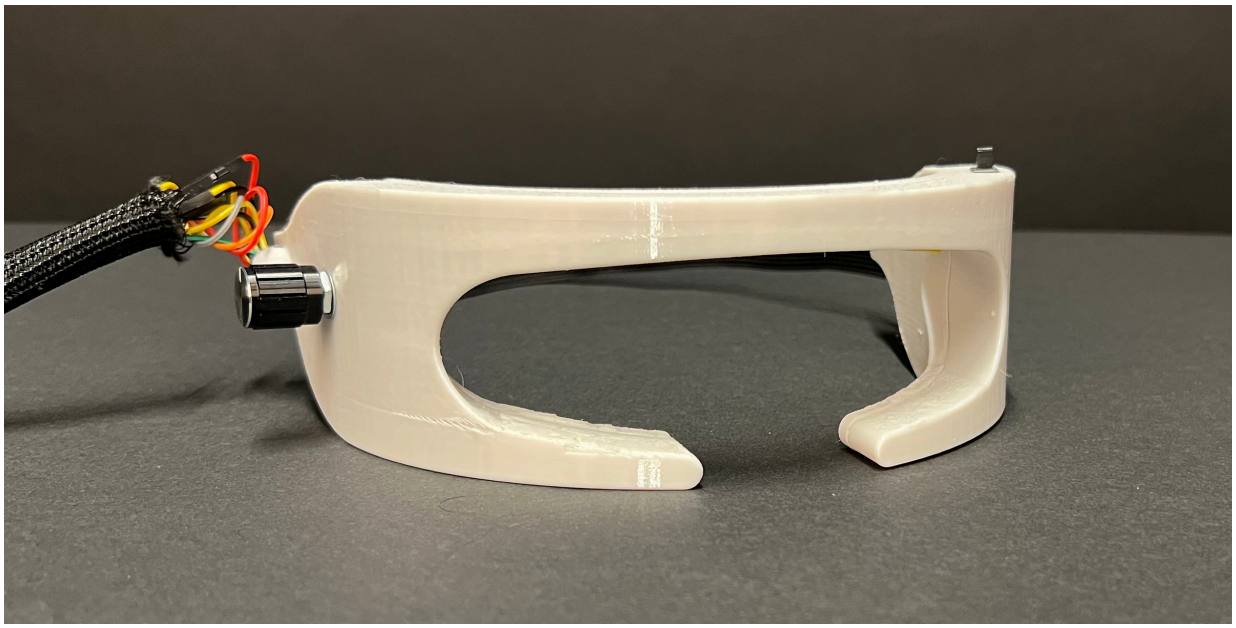
Heart rate analysis

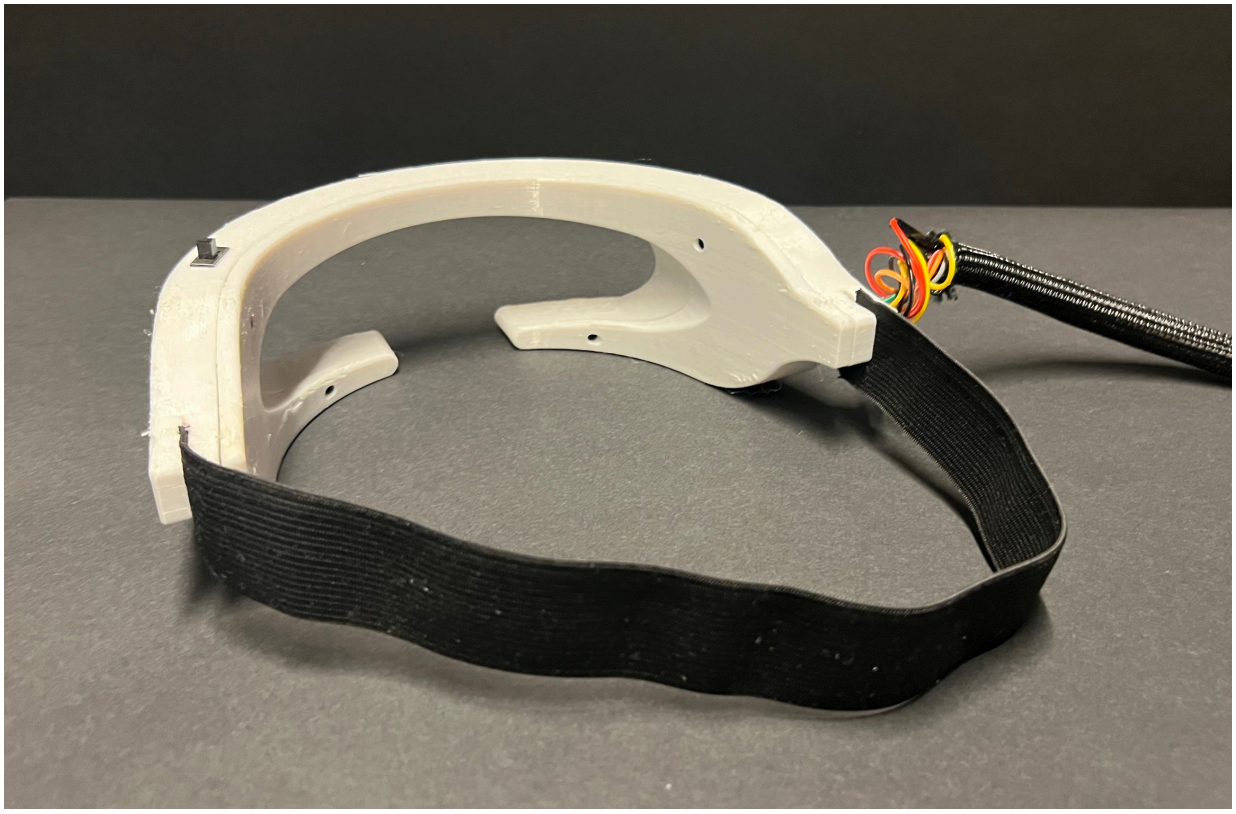
Morning mode									
Time stamp(min:sec)	00:30	01:00	01:30	02:00	02:30	03:00	03:30	04:00	04:30
Participant 1	64	66	63	62	64	61	65	61	61
Participant 2	83	85	85	84	84	87	85	81	80
Participant 3	73	73	72	75	76	73	73	72	73
Participant 4	66	67	72	71	69	71	68	69	71
Participant 5	65	62	62	58	64	58	58	61	60
Participant 6	62	61	60	61	63	61	68	69	69
Participant 7	72	67	65	66	71	74	65	66	70
Participant 8	65	65	66	73	75	71	71	70	72
Participant 9	76	70	69	71	69	70	70	68	75
Participant 10	72	71	71	71	74	72	76	76	74
Participant 11	67	61	67	71	70	68	77	74	72
Participant 12	81	82	81	78	79	78	80	78	79
Average	71	69	69	70	72	70	71	70	71

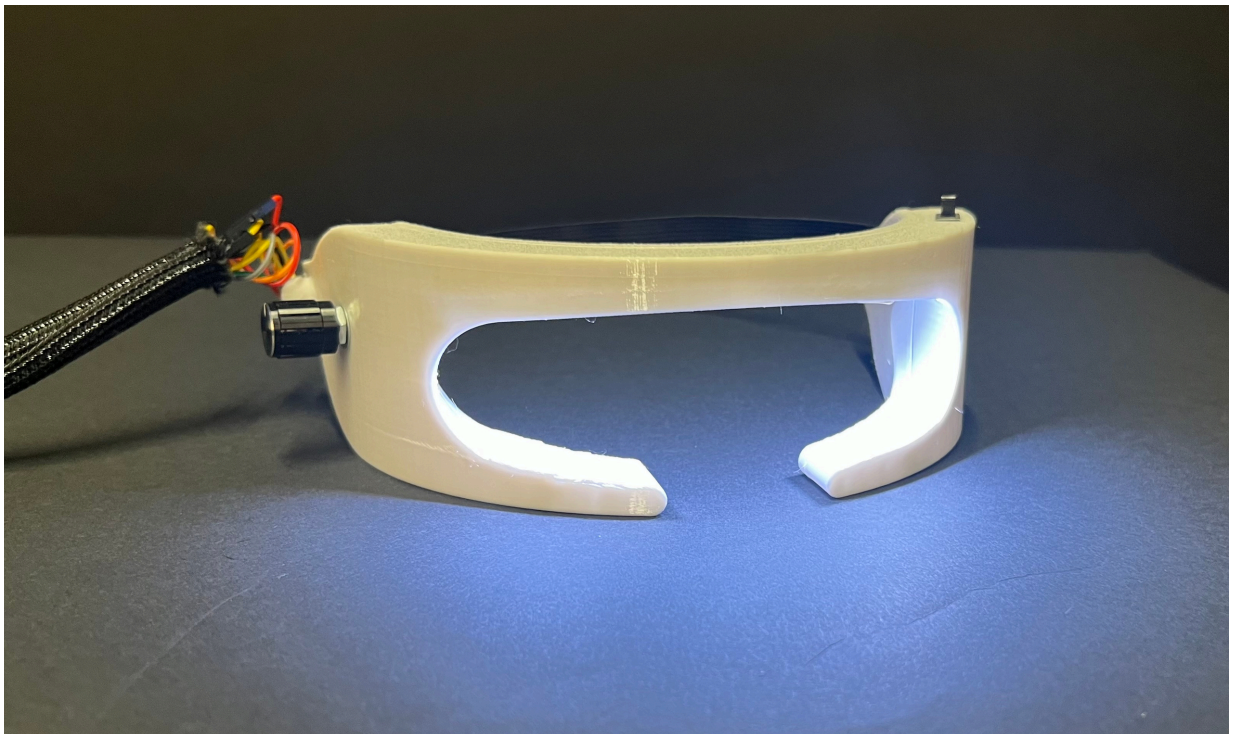
Evening									
Time stamp(min:sec)	00:30	01:00	01:30	02:00	02:30	03:00	03:30	04:00	04:30
Participant 1	61	59	59	60	62	61	62	62	61
Participant 2	79	77	74	82	77	74	70	68	66
Participant 3	71	73	76	75	74	73	73	75	71
Participant 4	65	64	64	69	68	72	67	69	64
Participant 5	67	56	61	61	55	56	58	55	52
Participant 6	65	61	63	67	66	64	64	62	64
Participant 7	63	66	69	66	67	65	68	64	64
Participant 8	69	64	70	64	66	71	69	66	66
Participant 9	71	64	65	66	70	66	68	71	64
Participant 10	75	74	74	89	71	73	73	73	73
Participant 11	70	71	79	74	74	74	70	75	72
Participant 12	81	78	77	80	77	76	77	72	69
Average	70	67	69	71	69	69	68	68	66

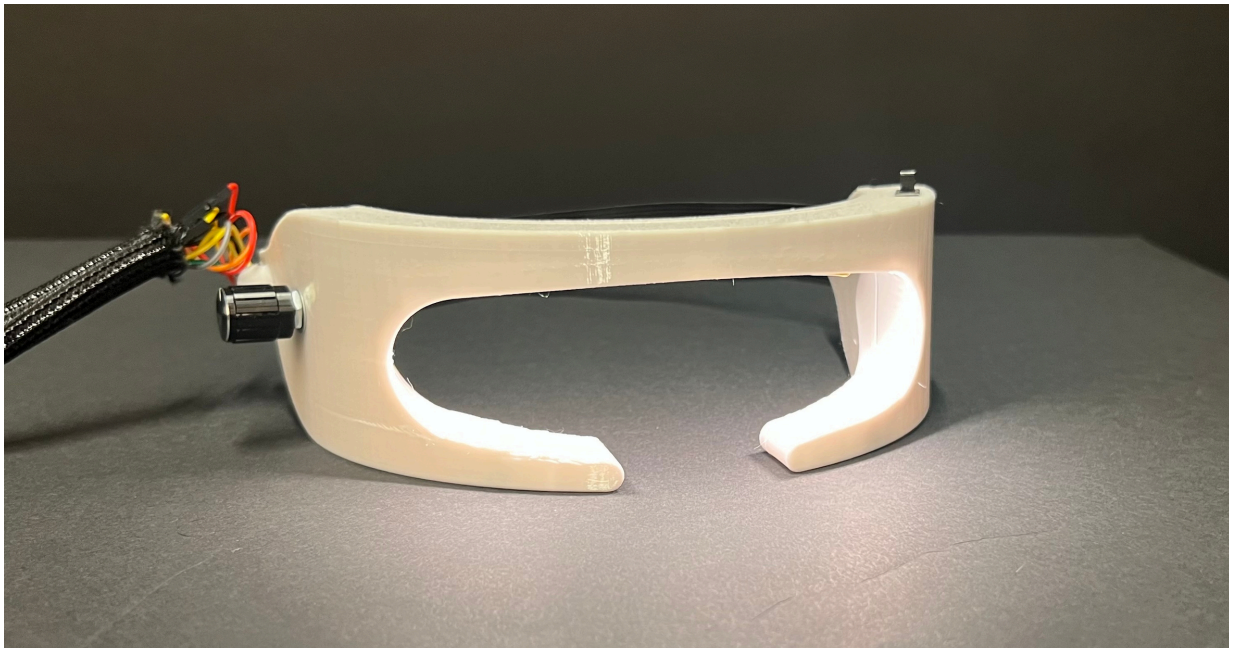
	00:30	01:00	01:30	02:00	02:30	03:00	03:30	04:00	04:30
Morning	71	69	69	70	72	70	71	70	71
Evening	70	67	69	71	69	69	68	68	66

M. FULLY ASSEMBLED NEW LUMOGLAZE









N. USER TESTING 2

Questions asked

1. The goggles felt comfortable to wear during the session.
-Strongly disagree -Somewhat disagree -Neither agree nor disagree -Somewhat agree -Strongly agree

2. How would you rate the overall brightness level of the light?

3. Did the app give clear feedback when you interacted with it (e.g., button pressed, lighting changed)?
-Strongly disagree -Somewhat disagree -Neither agree nor disagree -Somewhat agree -Strongly agree

5. Was it easy or difficult for you to navigate the app?

Data analysis

The goggles felt comfortable to wear during the session.					
	Strongly Disagree	Somehwhat disagree	Neither agree nor disagree	Somewhat agree	Strongly agree
No of participants	0	0	0	2	6

How would you rate the overall brightness level of the light?	Strongly Disagree	Somehwhat disagree	Neither agree nor disagree	Somewhat agree	Strongly agree
No of participants	0	0	0	5	3

Did the app give clear feedback when you interacted with it (e.g., button pressed, lighting changed)?	Strongly Disagree	Somehwhat disagree	Neither agree nor disagree	Somewhat agree	Strongly agree
No of participants	0	0	0	3	5

How easy or difficult was it for you to navigate the app?	Strongly Disagree	Somehwhat disagre	Neither agree nor disagree	Somewhat agree	Strongly agree
No of participants	0	0	0	3	5

Morning

HR	0	00:30	01:00	01:30	02:00	02:30	03:00	03:30	04:00	04:30	05:00	05:30	06:00	06:30	07:00	07:30	08:00	08:30	09:00	09:30	10:00	10:30	11:00	11:30	12:00	12:30	13:00	13:30	14:00	14:30	15:00
Participant 1	71	70	75	70	73	72	75	75	74	75	73	75	72	71	70	73	74	82	75	75	74	75	77	72	74	73	82	94	71	76	75
Participant 2	67	70	71	70	75	73	68	68	75	76	74	76	76	74	70	68	72	73	77	74	70	68	74	77	76	76	74	75	75	70	70
Participant 3	77	80	70	70	68	78	78	71	72	71	72	68	72	74	70	74	74	71	70	73	73	70	68	69	72	75	75	68	72	70	70
Participant 4	71	69	71	77	76	72	73	71	71	71	72	78	70	71	74	78	74	71	72	71	73	75	74	71	73	71	71	72	71	72	71
Participant 5	74	80	78	75	72	72	76	72	69	76	71	72	73	72	75	76	71	70	74	86	76	72	70	69	75	88	71	70	71	78	75
Participant 6	83	83	79	75	76	77	74	79	78	78	80	81	76	78	73	80	77	75	77	71	73	72	74	73	71	71	72	70	72	72	71
Participant 7	74	72	72	70	74	74	72	69	68	72	72	75	74	70	69	68	72	74	78	80	78	78	74	75	73	69	70	72	72	70	69
Participant 8	75	73	72	71	71	75	70	73	69	71	69	71	69	72	71	74	71	74	72	69	71	71	71	71	72	70	71	71	69	68	69
	74	75	74	72	73	74	73	72	72	74	73	75	73	73	72	74	73	74	74	75	74	73	73	72	73	74	73	74	72	72	71

Evening

HR		00:30	01:00	01:30	02:00	02:30	03:00	03:30	04:00	04:30	05:00	05:30	06:00	06:30	07:00	07:30	08:00	08:30	09:00	09:30	10:00	10:30	11:00	11:30	12:00	12:30	13:00	13:30	14:00	14:30	15:00
Participant 1	79	58	66	64	63	65	65	62	63	67	63	63	68	63	59	56	54	51	50	60	64	65	66	60	58	58	58	53	52	51	52
Participant 2	55	56	55	61	61	58	59	58	59	60	65	66	66	65	63	59	58	61	62	59	65	70	70	66	63	64	61	59	57	59	59
Participant 3	70	62	55	57	57	55	60	54	55	59	57	60	55	57	56	53	60	56	56	59	58	57	57	55	54	57	57	59	60	55	58
Participant 4	71	69	70	72	69	72	65	66	67	70	70	71	68	69	70	69	72	76	71	71	68	69	71	69	67	68	71	69	70	72	68
Participant 5	67	68	71	73	65	68	75	68	69	72	70	71	73	71	69	76	72	65	70	70	72	75	70	74	74	72	70	70	72	72	71
Participant 6	85	78	76	75	78	75	76	78	79	78	78	80	75	77	77	74	77	75	80	76	76	78	78	78	77	83	78	78	77	74	76
Participant 7	71	64	65	64	65	68	69	75	66	65	65	64	70	65	69	76	64	70	69	61	70	64	60	69	71	69	64	61	59	63	69
Participant 8	73	69	70	71	69	69	71	72	73	70	71	70	71	71	70	68	72	71	72	74	76	72	70	68	70	67	69	69	67	70	72
	71	66	66	67	66	66	68	67	66	68	67	68	68	67	67	66	66	66	66	66	69	69	68	67	67	67	66	65	64	65	66

	0	00:30	01:00	01:30	02:00	02:30	03:00	03:30	04:00	04:30	05:00	05:30	06:00	06:30	07:00	07:30	08:00	08:30	09:00	09:30	10:00	10:30	11:00	11:30	12:00	12:30	13:00	13:30	14:00	14:30	15:00	
Morning	74	75	74	72	73	74	73	72	72	74	73	75	73	73	72	74	73	74	74	75	74	73	73	72	73	74	73	74	72	72	71	73
Evening	71	66	66	67	66	66	68	67	66	68	67	68	68	67	67	66	66	66	66	66	69	69	68	67	67	67	66	65	64	65	66	67

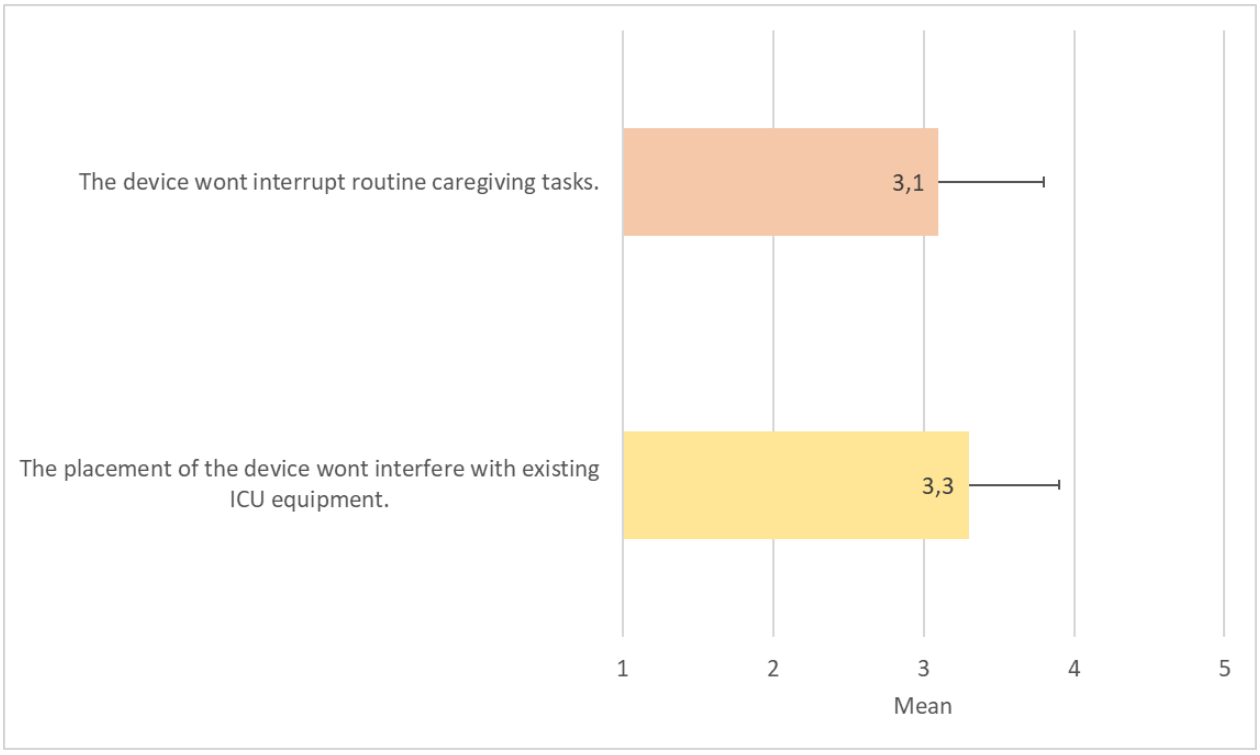
O. EXPERT INTERVIEW

Data analysis

The placement of the device wont interfere with existing ICU equipment.				
Strongly Disagree	Somehwhat disagree	Neither agree nor disagree	Somewhat agree	Strongly agree
0	1	7	5	0

The device wont interrupt routine caregiving tasks.				
Strongly Disagree	Somehwhat disagree	Neither agree nor disagree	Somewhat agree	Strongly agree
0	3	6	4	0

	Mean	STD
The placement of the device wont interfere with existing ICU equipment.	3,3	0,6
The device wont interrupt routine caregiving tasks.	3,1	0,7



Questions asked

Expert 1

1. The app interface is clear and easy to navigate for first-time users.
☐1 ☐2 ☐3 ☐4 ☐5.

2. BLE commands are processed quickly and without delay.
☐1 ☐2 ☐3 ☐4 ☐5

3. The brightness slider and demo buttons function as expected.
1.☐1 ☐2 ☐3 ☐4 ☐5

4. Are there any improvements you would suggest regarding the app.

5. Does the wearable's form factor and technical design seem feasible for use in real settings

6. Do you see any concerns with heat generation, power consumption, or circuit complexity?

7. What suggestions do you have for improving the device itself in terms of design?

8. The use of BLE is appropriate for the system's responsiveness and reliability.
☐1 ☐2 ☐3 ☐4 ☐5

9. What features would you consider important for scaling this system to a clinical pilot?

10. Do you see this system scaling to more complex settings (multi-patient, multi-room)?

11. Are there any ethical or practical challenges with using sleep/HR data for light control?

Expert 2

1.Do 2-hour morning light sessions and gradual dimming from 18:00 to 22:00 align well with best practices in light therapy for circadian support?

2.Although heart rate changes were minor, users perceived benefits—how should we weigh these perceptions in validating circadian lighting design?

3.From a lighting perspective, what materials would best diffuse light while maintaining therapeutic intensity and comfort?

4.What are your thoughts on using LED light therapy close to the face for long durations in vulnerable ICU patients? Are there safety certifications or shielding considerations we might be missing?

5.What metrics, beyond heart rate and subjective feedback, would you recommend for evaluating circadian lighting interventions in healthcare environments?

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