Degree Project in Architectural Lighting Design

Second cycle, 15 credits

Lighting in Nordic student housing and residents’ sleep

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Abstract

Exposure to light relevantly influences human circadian rhythms, affecting not only visual perception but also physical and mental health. This thesis explores the role of architectural lighting on human health and well-being within a controlled Live-in Lab environment, focusing particularly on twilight exposure and its effects on circadian rhythms and sleep patterns. Employing a combination of environmental sensors and sleep diaries, the study quantifies light exposure and investigates its association with sleep disturbances and overall daily well-being.

The findings reveal a notable misalignment between the prevailing lighting conditions and the optimal settings for supporting natural circadian rhythms. This misalignment underscores the necessity for architectural designs that more effectively integrate natural light cycles, particularly in regions with relevant seasonal variations in daylight, such as northern latitudes. Based on these insights, the thesis recommends adopting twilight simulation technologies to enhance sleep quality and better align circadian rhythms with other light patterns that are not naturally synchronized with the extreme conditions in the Nordics.

The research contributes to the field by providing empirical evidence supporting the development of lighting strategies that promote healthier living environments, emphasizing the crucial role of lighting design in enhancing well-being. The recommendations offered aim to guide future architectural practices in creating spaces that not only meet aesthetic and functional requirements but also foster health and sustainability.

Keywords:

Twilight, Sleep Quality, Daytime Well-being, Daylight

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The Author

Stockholm, June 2024

It's better with butter

Nomenclature

Abbreviations

BL Blue lighting

BP Blood pressure

CBT Core body temperature

CL Control lighting

CSM/CSM-r Composite scale of morningness/- short form

DDsL Dusk/Dawn simulation lighting

DF Daylight Factor

DsL Dawn simulation lighting

GSQS Groningen sleep quality scale

KSS Karolinska sleepiness scale

LAN Light at night

LDC Lucio Domenico Cavallari

LEA Lighting exposure accumulation

LiL Live-in-Lab

M-EQ Morningness-eveningness questionnaire

MCTQ Munich chronotype questionnaire

PSQI Pittsburgh sleep quality index

PSS Perceived stress scale

SAD Seasonal Affective Disorder

SCN Suprachiasmatic nucleus

SPD Spectral power distribution

Contents

Chapter 1

Introduction

Exposure to light has short- and long-term effects on non-visual responses in humans [1]. This thesis proposes a theoretical investigation into the effects of twilight on sleep quality and daytime well-being.

Twilight, the transition period between day and night, plays a crucial role in setting the body's internal clock, guiding circadian rhythms synchronization [2]. The light encountered in mornings and evenings, whether natural sunlight or artificial, relevantly influences sleep patterns and overall well-being [3].

Wright et al.[4] highlight how entrainment of the human circadian clock to natural light-dark cycles, including twilight, is essential for maintaining our natural sleep schedules and well-being.

1.1 Context and Importance

The concept of circadian rhythms dates back to ancient observations, with modern chronobiology tracing the genetic underpinnings of these intrinsic timekeeping systems [5]. The transition between day and night, or twilight, has been identified as a crucial period for setting the body's internal clock, affecting sleep patterns and general well-being [2].

How can observations of existing architectural lighting designs in residential and Live-in Lab settings contribute to understanding their effect on human health and environmental sustainability?

Sub-questions/Objectives:

1. What insights can be gained from observing existing lighting conditions regarding the potential effects of twilight on human circadian rhythms and sleep patterns?
2. How do current lighting setups in residential environments align with the theoretical benefits of twilight simulation for sleep quality and daytime well-being?
3. What are the observed effects of current architectural lighting designs on sleep quality and daytime well-being, and how might these inform future enhancements tailored to diverse user demands and environmental conditions?

This research primarily aligns with the United Nations' Sustainable Development Goal 3 (Good Health and Well-being), aiming to enhance individual well-being through improved sleep patterns and overall health. To a lesser extent, it also supports Goal 7 (Affordable and Clean Energy) by promoting energy-efficient lighting solutions that contribute to sustainable architectural design.

1.2 Objectives and Goals

This research project is dedicated to observing existing architectural lighting conditions to understand their effects on sleep quality and well-being. The insights gained aim to inform potential future interventions, such as twilight simulation, to enhance residential environments for improved health and sustainability.

1.3 Methodological Framework

1.3.1 Methodology

The methodology involves observing twilight in Live-in Lab settings during 2 weeks in May 2024.

Literature Review: To understand the current state of knowledge regarding light exposure, circadian rhythms, and their effects on sleep and well-being.

Technology Assessment and Criteria Development: This study will evaluate the existing lighting setups within the KTH Live-in Lab to assess their alignment with established best practices for circadian health. Data will be collected on the current configurations to understand their effect on the residents' well-being. The insights gained will be crucial for developing criteria for future research or interventions, specifically tailored to the unique needs observed in residential environments. This approach aims to provide foundational knowledge that could inform the design of lighting systems that support circadian health in similar settings.

Framework Development: The focus will be on analyzing the observed data to suggest potential improvements. This approach will include a review of the current lighting parameters such as light intensity, distribution and exposure duration, to better understand their effect on resident well-being and to propose theoretical modifications.

1.3.2 Delimitations

The study will analyze the existing lighting conditions within the Live-in Lab. This observational focus precludes direct manipulation of variables and relies on existing setups to draw conclusions about the potential effects of optimized lighting on circadian health.

1.4 Structure of the Document

Chapter 2 will explore the detailed background of circadian rhythms, twilight's role in human health, and the historical milestones in chronobiology research. Subsequent chapters will discuss the methodology in detail, including research strategies, data collection, data analysis, and quality assurance, followed by a presentation of findings from the Stockholm KTH Live-in-Lab pilot study and implications for future research and practice.

Chapter 2

Theoretical Background

This chapter presents the findings of the literature review conducted for this thesis. It reviews current advancements in the fields of circadian biology, sleep medicine, and architectural lighting design, identifying gaps in research. It discusses the application of previous research in this thesis and reasons for excluding certain works.

2.1 Circadian Rhythm

Our daily activities are regulated by three primary clocks: the solar clock, influenced by sunlight and temperature variations marking the day; the social clock, shaped by societal norms and work schedules; and the biological clock, which becomes particularly evident during jet lag, shift work, or transitions into and out of daylight saving time. These systems collectively synchronize our daily life, weaving together the natural cycle of day and night with our social responsibilities and the intrinsic timing of our physiological processes [6]. When isolated from external cues like sunlight and societal expectations, the biological clock enters a "free-running" mode, revealing its natural periodicity, which might not align with the typical 24-hour cycle. Yet, under ordinary conditions, circadian rhythms adjust to the 24-hour cycle of the solar day, aligning internal processes with the external environment [7, 8].

This circadian system responds to natural "zeitgebers" or time cues, such as light exposure, dietary habits, and physical activity. These environmental signals recalibrate circadian rhythms, influencing both behavior and physiological functions by altering gene expression, thereby ensuring that our internal clock remains in harmony with our surroundings [5].

2.2 Circadian Milestones: From Ancient Greece to Modern Chronobiology

The historical journey of circadian rhythm research extends from ancient observations to cutting-edge molecular discoveries.

Initial recorded insights date back to the 4th century BC, with Androsthenes of Thasos documenting the diurnal leaf movements of the tamarind tree, an early hint at biological rhythms [9]. This fascination with daily patterns persisted, with notable contributions such as Jean-Jacques d'Ortous de Mairan's 18th-century discovery that plants maintain circadian rhythms in constant darkness, suggesting an innate biological clock [10, 11].

Progressing through the 20th century, the foundational work by Colin Pittendrigh, the 'father of the biological clock,' along with Franz Halberg's coining of the term 'circadian,' laid the groundwork for the modern understanding of these intrinsic timekeeping systems [12, 13]. The identification of the 'period' (PER) gene in Drosophila by Ron Konopka and Seymour Benzer marked a pivotal moment in the genetic exploration of circadian rhythms, a line of research that would lead to the 2017 Nobel Prize in Physiology or Medicine for Jeffrey Hall, Michael Rosbash, and Michael W. Young [14].

The clockΔ19 mutation was unearthed in 1994, and Joseph S. Takahashi unveiled the CLOCK gene in 1997 [15]. Later research revealed that animals lacking the CLOCK gene still exhibited normal circadian rhythms, raising intriguing questions about the gene's actual contribution to circadian regulation [16, 17].

Yet, additional in vivo experiments on mice with a complete deletion of the Clock gene (Clock−/−) identified noticeable disruptions in their behavioral rhythms. These mice showed a reduction of about 20 minutes in their circadian cycles compared to their normal siblings and exhibited altered responses to light stimuli [18].

The work by Nicolaides and Chrousos (2020) [5] encapsulates this historical progression, highlighting not only the milestones of circadian rhythm research but also the evolving complexity of understanding the molecular mechanisms underlying these rhythms.

2.3 The Effect of Dawn Lighting on Cortisol and Mood

The widespread use of electrical lighting has relevantly altered human exposure to natural light-dark cycles. This change has led to reduced sunlight exposure during the day, increased light exposure after sunset, and a consequent delay in the timing of the circadian clock compared to natural light conditions [4].

Light plays a crucial role in aligning our internal clock with the external day and night cycle, primarily by modifying the signals from our eyes to the brain's suprachiasmatic nucleus (SCN) located in the hypothalamus. Interestingly, this alignment does not rely on the retina's well-known light detectors, the rods and cones [19].

The importance of light exposure, especially during twilight, cannot be overstated in its effect on the human circadian rhythm. Given that most people are at home during dawn and dusk, the effect of both natural and artificial lighting in these settings is substantial, directly influencing our sleep patterns and overall well-being [3].

When exposed only to natural light, the human internal circadian clock synchronizes with solar time. This synchronization aligns the beginning of the internal biological night with sunset and the end of the internal biological night just after sunrise, before wake time. This adjustment suggests that the internal clock can adapt to natural light-dark cycles, promoting a timing of sleep and wakefulness that coincides with environmental light conditions [4].

Moreover, dawn simulation, by raising cortisol levels upon waking, not only signifies heightened alertness and arousal but also points to a method for adjusting the body's circadian rhythm to improve morning wakefulness and mood [20]. This practice effectively diminishes sleep inertia—the grogginess experienced upon waking—and enhances cognitive and physical performance right from the start of the day. The benefit is largely due to light exposure during the final 30 minutes of sleep, indicating that dawn simulation can simplify the waking process and render mornings more productive [21].

2.4 Twilight and Sleep Patterns in Northern Latitudes

The effects of twilight on sleep, particularly in people from different latitudes in the Northern Hemisphere, reveal complex interactions between light exposure, geographical location, and sleep patterns.

The length of daylight and ambient temperature relevantly influence human resting or sleeping patterns. Notably, the seasonal variation in resting periods is latitude-dependent, with more pronounced differences between summer and winter resting times at southern cities compared to northern cities. This suggests that the changing patterns of twilight and daylight duration across different latitudes can affect sleep duration and quality [22].

Studies on Syrian hamsters showed that simulated twilights, mimicking natural lighting conditions at different times of the year and latitudes, affected several circadian parameters. The inclusion of twilights resulted in activity onset times that followed dusk, suggesting that natural twilight transitions play a relevant role in aligning circadian rhythms with environmental light cycles. This finding has implications for understanding how twilight may affect human sleep patterns at different latitudes [23].

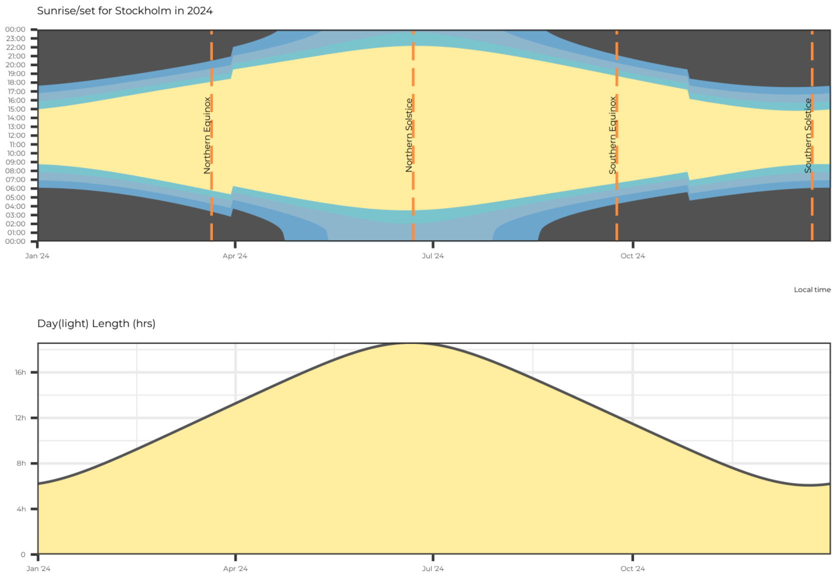
Research [24] indicates a clear relationship between exposure to natural light, sleep need, and depression at extreme latitudes. Shorter natural light exposure is associated with perceptions of insufficient sleep, with Arctic workers more prone to depression than Equatorial workers. This underscores the influence of natural light exposure, including during twilight hours, on sleep and mental health at different latitudes [24].

Studies have tracked the natural patterns of illumination experienced by individuals, highlighting relevant seasonal differences in exposure to bright light. The amount of time spent in bright illumination (> 1000 lux) was substantially longer in summer compared to winter, suggesting that seasonal variations in natural light exposure, including the extended twilight periods in summer at higher latitudes, can relevantly affect human circadian rhythms and potentially sleep patterns [25].

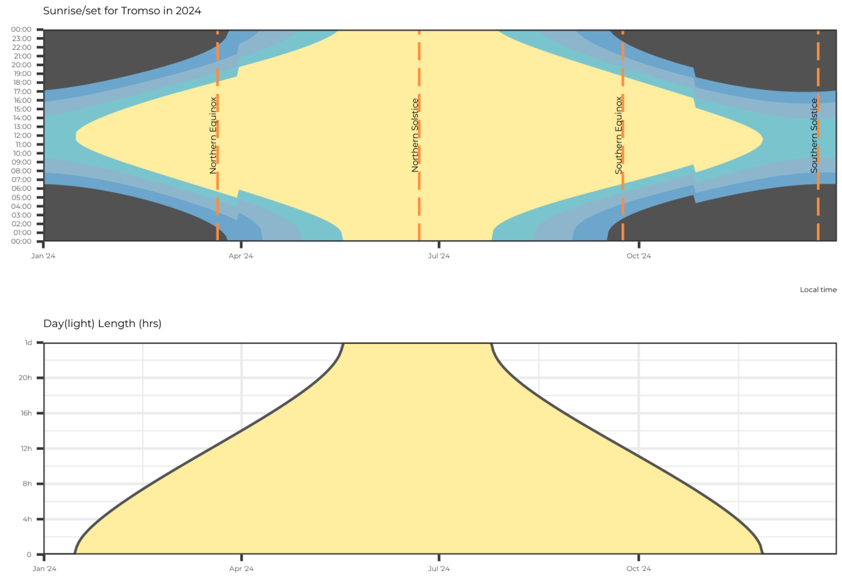
2.4.1 Light Exposure Across Latitudes

Table 2.4.1: Light Exposure across Latitudes

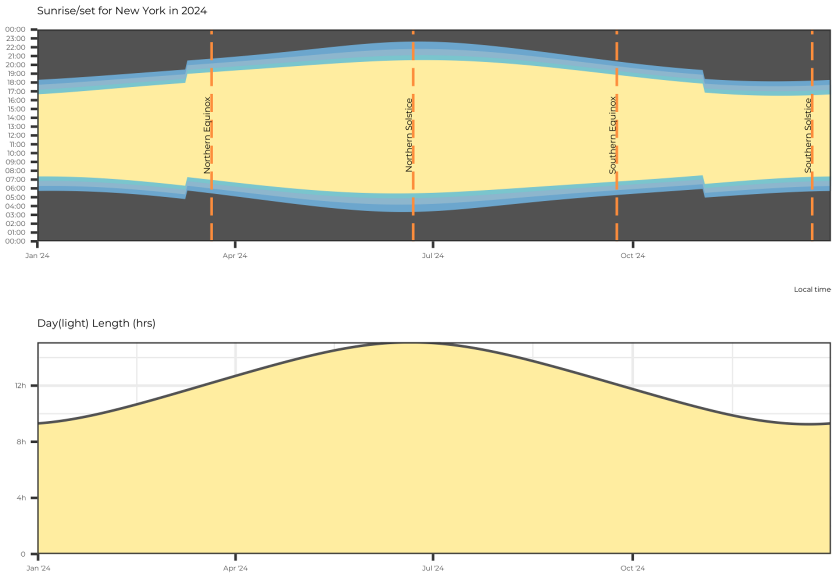
Latitude	Impact on Light Exposure
High Latitudes (e.g., Scandinavia, Northern Canada)	**Long Summer Days:** Extremely long days during summer with twilight lasting until late at night or never fully transitioning to complete darkness (Figures 2.4.1a, 2.4.1b). Delays in melatonin production can disrupt sleep patterns. **Short Winter Days:** Very short days and long nights in winter, leading to Seasonal Affective Disorder (SAD) due to insufficient natural light.
Mid-Latitudes (e.g., United States, Southern Europe)	**Moderate Variation:** More moderate variations in day length (Figure 2.4.1c). Changes in twilight times throughout the year are less extreme, supporting more stable light exposure patterns. **Adaptation:** Easier maintenance of regular sleep schedules, though daylight saving time shifts can temporarily disrupt sleep.
Low Latitudes (e.g., Near the Equator)	**Consistent Day Length:** Consistent day lengths and twilight times throughout the year (Figure 2.4.1d). This consistency helps stabilize circadian rhythms and supports regular sleep patterns. **Less Seasonal Impact:** Fewer seasonal impacts on sleep, with challenges more related to daytime heat and light intensity.



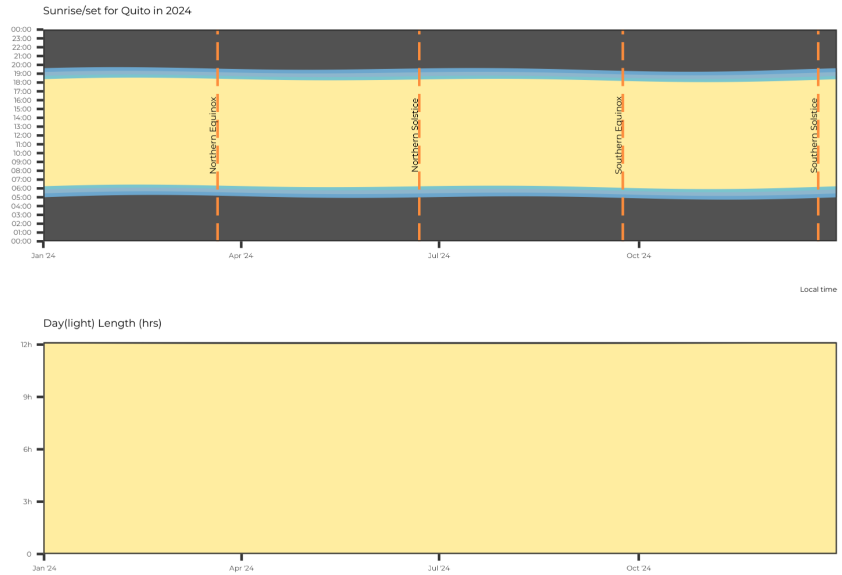
(a) Stockholm (Coordinates: 59.3293° N, 18.0686° E).



(b) Tromso (Coordinates: 69.6492° N, 18.9553° E).



(c) New York (Coordinates: 40.7128° N, 74.0060° W).



(d) Quito (Coordinates: 0.1807° S, 78.4678° W)

Figure 2.4.1: Daylight and Twilight yearly rhythms in Stockholm, Tromso, New York and Quito. Source: Emanuele Messori

Table 2.4.2: Approximate Twilight Durations Across Different Dates and Latitudes

Event	**High Latitudes (> 60°)**	**Mid Latitudes (23.5°-60°)**	**Low Latitudes (< 23.5°)**
Winter Solstice			
Civil Twilight	1-2 hours	20-40 min	$\leq$ 20 min
Nautical Twilight	Several hours	30-60 min	20-30 min
Astronomical Twilight	2.5+ hours	1-1.5 hours	30-40 min
Summer Solstice			
Civil Twilight	Indefinite	20-40 min	$\leq$ 20 min
Nautical Twilight	Indefinite	30-60 min	20-30 min
Astronomical Twilight	All night	1-1.5 hours	30-40 min
Spring/Autumn Equinox			
Civil Twilight	1-2 hours	20-30 min	$\approx$ 20 min
Nautical Twilight	2-3 hours	30-45 min	20-30 min
Astronomical Twilight	3-4 hours	45-60 min	30-40 min

2.5 Circadian Rhythms and Homeostatic Sleep Drive

Photoentrainment refers to the syncing of an organism's internal clock with the environmental light-dark cycle and is crucial for sustaining and enhancing health and well-being [2].

In the comprehensive exploration of sleep regulation, it is acknowledged that the sleep-wake cycle is intricately governed by two predominant mechanisms: the circadian rhythm and the homeostatic sleep drive. The circadian rhythm, an internal biological clock running on a near-24-hour cycle, orchestrates periods of wakefulness and sleepiness throughout the day in response to external light-dark cues. This rhythmic process ensures that physiological states are optimally aligned with day-night cycles. Complementarily, the homeostatic sleep drive accounts for the accumulation of sleep pressure during wakefulness, compelling the body towards rest to counterbalance prolonged periods of alertness. This sleep pressure dissipates during sleep, resetting the system for the next wakeful period. Together, these mechanisms ensure the maintenance of sleep patterns that are crucial for health and well-being [22].

2.6 Chronotypes

Chronotype encapsulates the timing of an individual's internal clock or circadian rhythm, influencing their daily schedule of physical activity, mental alertness, and rest. This innate timing affects when a person is most alert, when they prefer to eat, and their peak bodily functions and hormone levels within a 24-hour period. Individuals often fall into categories such as ”morning larks,” who are active early in the day, or ”night owls,” who peak later. Interestingly, exposure to natural light has been found to diminish these differences, aligning the internal clocks of ”night owls” more closely with those of ”morning larks”, suggesting a form of adaptability in our circadian timings [4]. These chronotype preferences are distributed broadly and consistently across populations, unaffected by geographical or cultural factors, and remain stable irrespective of the methods used for their assessment [26]. Thus, while our chronotypes may have a genetic and biological foundation, environmental factors like light exposure can play a relevant role in modulating our internal daily rhythms.

The concept of chronotype has sparked considerable debate within scientific literature, often being simplified to refer to an individual's sleep patterns, where ”early birds” rise and sleep early, and ”night owls” have a propensity for later sleep and wake times [26]. However, a more nuanced definition in the field considers chronotype as the synchronization or entrainment of the body's internal clock to the 24-hour day. This perspective is centered on a reference point within the circadian rhythm that dictates how internal processes align with external cues, like the light-dark cycle [27].

Chapter 3

Methodology and Methods

This chapter outlines the methodology applied to address the research questions, integrating theoretical insights and empirical observations.

3.1 Methodology

This study utilizes an observational approach to critically analyze existing lighting setups at the KTH Live-in Lab, employing both sensor data for quantitative assessment and participant feedback for qualitative insights. The combination of these methods enables a holistic evaluation of how lighting influences circadian rhythms and sleep quality, providing a foundation for potential future interventions (Figure 3.1.1).

Figure 3.1.1: Methodology Diagram. Graphical interpretation of the study on twilight observation and its impact on sleep quality and well-being.

3.2 Methodological Choices for Validity and Reliability

Internal Validity: The research focuses on the current lighting setups within the KTH Live-in-Lab without manipulating the environment. This approach ensures that observations and data collected are a direct result of the existing conditions, which allows for a clear understanding of how these conditions impact sleep quality and well-being.

External Validity: The KTH Live-in-Lab is chosen for this study because it reflects typical modern residential environments, enhancing the applicability of the findings to similar settings.

Reliability: Reliability is supported through the use of rigorous data collection methods, including environmental monitoring sensors and detailed resident questionnaires. By maintaining consistent data collection methods throughout the study, the results are expected to be reproducible in similar settings. However, it is important to note that for true reliability, a larger sample size would be necessary. As this is a pilot study with an N=4 sample size, the findings provide valuable preliminary insights but should be validated with a larger cohort in future research.

3.3 Contextual Background: Twilight Timing

Twilight, the period before sunrise and after sunset, is categorized into three distinct phases based on the sun's position below the horizon: astronomical twilight occurs when the sun is between 12 and 18 degrees below the horizon; nautical twilight occurs when the sun is between 6 and 12 degrees below the horizon; and civil twilight occurs when the sun is less than 6 degrees below the horizon. The graph below illustrates the changes in the duration of each twilight phase over the observation period (Figure 3.3.1). Notably, the astronomical twilight phases disappear after May 13, leaving only nautical and civil twilight.

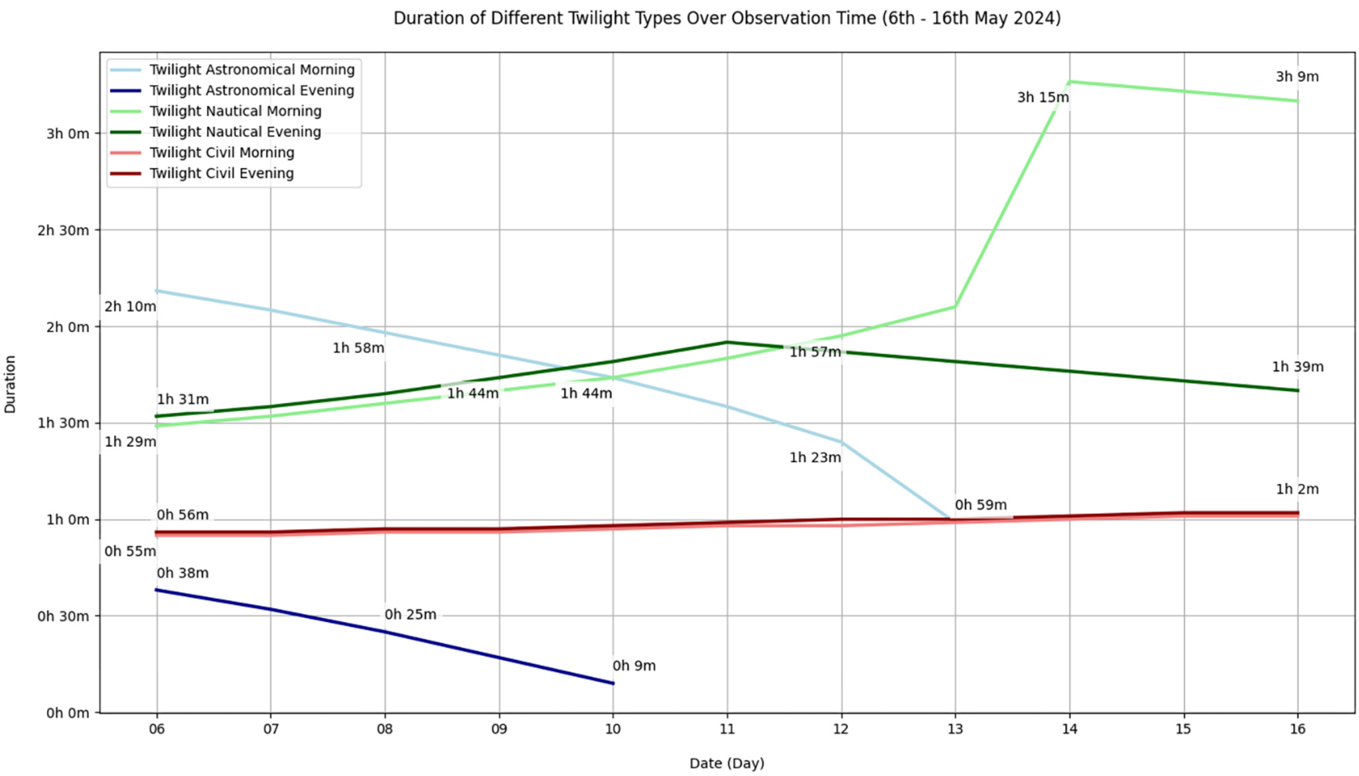


Figure 3.3.1: Duration of Twilight Phases in Stockholm from May 6th to May 16th, 2024.
Data Source: Time & Date

3.4 Study Schedule and Key Activities

The study was conducted over a period from May 6th to May 16th, 2024, focusing on several key activities:

- **Twilight Observation:** This involved monitoring the changes in twilight phases in Stockholm, categorized into astronomical, nautical, and civil twilight, to understand their duration and impact on residents.
- **Interviews:** On May 9th, semi-structured interviews were conducted with the residents to gather in-depth information on their sleep habits, daily light exposure, and overall well-being. These interviews aimed to explore residents' perceptions and experiences, particularly how they believe lighting conditions affected their daily activities and psychological comfort (Figure B.1.1).

3.5 Data Collection and Tools

Existing Sensors: Air Temperature, CO2, Occupancy, Luminous Intensity, Relative Humidity, Water Measurements, and Electricity Usage Sensors.
Additional Enhancements: Temperature/Illuminance Data Logger to refine data accuracy and scope [28].
Sleep Diary and Personal Interviews: Participants will maintain sleep diaries during two-week period, documenting sleep patterns, disturbances, and subjective sleep quality daily [29]. Semi-structured interviews explore participants' experiences and perceptions regarding the effects of lighting on their daily activities and overall well-being .

3.6 Dataset and Metadata

This section provides detailed information about the datasets used in this study, including their temporal resolution, data type, acquisition dates, variables measured, and sources (Table 3.6.1).

Table 3.6.1: Dataset and metadata used in the thesis.

DATA SET	**TEMPORAL RESOLUTION**	**DATA TYPE**	**DAY OF AQUISITION**	**VARIABLES**	**SOURCE**
Hobo sensors	Every minute	Quantitative	6-16 May 2024	Lux, Celsius	Primary
Interviews	1 time	Qualitative	9 May 2024	Responses	Primary
Sleep diary	2 inputs every day for 11 days	Qualitative, Quantitative	6-16 May 2024	Sleep times, Sleep quality, Mood, Well-being	Primary
Daylight Analysis	Annual, Daily	Quantitative	N/A	DF, sDA, ASE	Gregor Ruta
CO_2, Pressure	N/A	Quantitative	6-16 May 2024	CO_2 levels, Pressure	KTH Live-in-Lab
Spectrometer	Various times	Quantitative	9 May 2024	Light spectrum	Primary

3.7 Current Artificial Light Setup

The floor plan (Figure 3.7.1) shows various types of lighting fixtures placed throughout the facility to cater different functional and aesthetic needs. Each fixture's location is indicated by the yellow circles on the plan.

3.7.1 Types and Placements of Lighting Fixtures

The lighting setup includes a combination of overhead lights, task lighting, and ambient lights. Overhead lights are primarily located in common areas, bedrooms, and hallways to provide general illumination. Task lighting is found near workspaces such as kitchen counters and study areas, designed to offer focused light that enhances visual clarity for specific tasks. Ambient lighting is used in living areas and bedrooms, providing a softer light that contributes to a cozy and relaxing atmosphere.

3.7.2 Control Systems

The lighting is controlled via standard wall switches with some areas equipped with dimming capabilities. This allows residents to adjust the light intensity according to their needs and preferences, thereby impacting their interaction with the space and potentially influencing their circadian rhythms.

Figure 3.7.1: Lighting fixtures distribution.

3.8 Sensors Configuration

Table 3.8.1: Sensor Overview and Data Availability

Category	**Details**
Existing Sensors	Air Temperature Sensor, CO_2 Sensor, Occupancy Sensor, Luminous Intensity Sensor, Relative Humidity Sensor, Electricity Usage Sensors (Figure 3.8.1).
Available Datasets as of 22/05/2024	Due to recent reconfiguration of LiL, the only datasets available are CO_2 and Relative Humidity.
Additional Enhancements	Temperature/Illuminance Data Logger (Figure 3.8.2). **Specs:** Light Sensor (MX2202) **|** Range: 0 to 167,731 lux **|** Accuracy: ±10% typical for direct sunlight

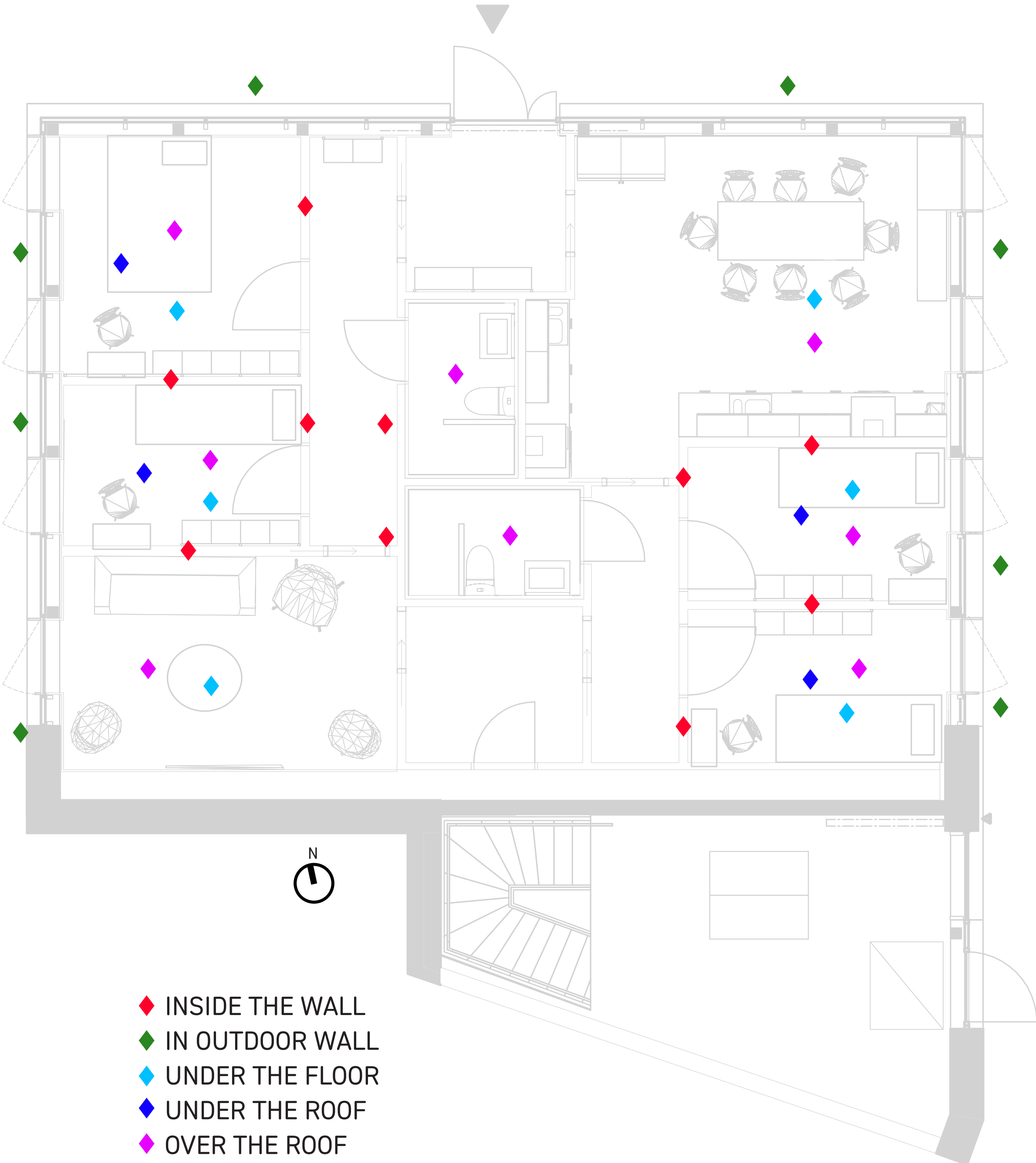


Figure 3.8.1: Temperature and Pressure sensors position.

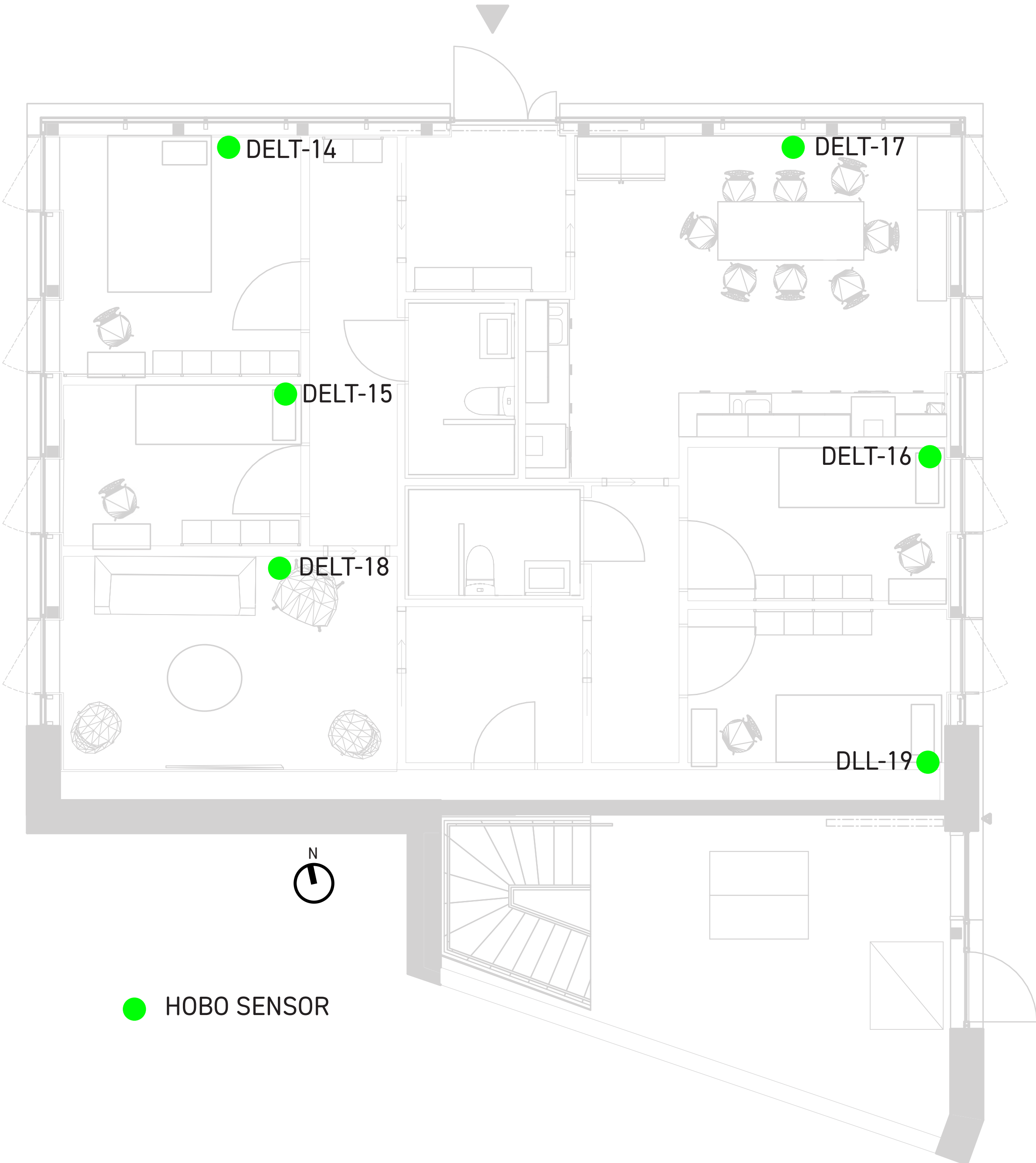


Figure 3.8.2: Hobo Pendant MX2202 Data Logger position.

3.9 Participant Engagement

Daily Diary Entries: Residents were expected to log various aspects of their daily experiences, including sleep quality, mood, and overall well-being, throughout the study period from May 6th to May 16th, 2024. This qualitative data helped assess the subjective effects of the lighting environment. Specifically, participants were asked to record:

Sleep and Wake Times: Including the time they went to bed and the time they woke up.
Sleep Quality: Subjective assessment of how well they slept each night, noting any disturbances or factors that affected their sleep.
Mood: Daily mood ratings to understand the psychological impact of lighting conditions.
Well-being: Items related to their overall well-being during the day, such as levels of alertness, fatigue, and general comfort.
Environmental Factors: Any notable environmental factors or changes that may have influenced their sleep or daily experiences.

This comprehensive data collection aimed to correlate environmental lighting conditions with residents' subjective experiences. Figures 3.9.1 and 3.9.2 illustrate the participant locations and sample sleep diary used for data collection.

Figure 3.9.1: Sleep Diary, Participant Diagram and Room location.

Sleep Diary

Use this sleep diary to record the quality and quantity of your sleep and how sleepy you feel during the day.
Bring the diary with you if you don't sleep at KTH Live-in-Lab.

Fill out before going to bed

Today's date:	April 28*	May 6	May 7	May 8	May 9	May 10	May 11	May 12
Did anything significant happen today that excited or upset me?	no							
How might it impact my sleep tonight? 3—Positively 2—Negatively 1—No impact	1							
Naptimes and lengths today:	3:30 p.m., 45 minutes							
Exercise times and lengths today:	None							
How sleepy did I feel during the day today? 4—So sleepy I hadto struggle to stay awake during much of the day 3—Somewhat tired 2—Fairly alert 1—Alert	1							

Fill out in the morning

Today's date:	April 29*	May 7	May 8	May 9	May 10	May 11	May 12	May 13
• TimeI went to bed last night: • Time I got out of bed this morning: • Hours spent in bed last night:	11 p.m. 7 a.m. 8							
Number of awakenings and total time awake last night:	5 times, 2 hours							
How long I took to fall asleep last night:	30 minutes							
Did I sleep at KTH Live-in-Lab?	Yes							
How alert did I feel when I got up This morning? 1—Alert 2—Alert but a little tired 3—Sleepy	2							

* This column shows an example of the diary entries.

Figure 3.9.2: Sample sleep diary used to track daily sleep patterns, relevant events impacting sleep, and daytime alertness for participants at the KTH Live-in Lab. This diary helps in documenting the correlation between sleep quality and environmental factors over the observation period from May 6th - May 16th, 2024. Based on the original document from: NIH National Heart, Lung, and Blood Institute.

3.10 Ethical Consideration and GDPR Compliance

Purpose of Data Collection: Enhance understanding of environmental conditions, usage patterns to potentially optimize energy efficiency, space utilization and collect input for personalized twilight simulation protocols.

Protection of Personal Data: Data anonymity is ensured, with provisions for participants to withdraw consent at any time.

Chapter 4

Results and Analysis

This chapter presents the findings from the observational study at the KTH Live-in Lab, detailing how the existing lighting setups impact circadian rhythm and sleep quality of the residents.

4.1 Data Analysis

4.1.1 Overview

Beginning with a review of the raw data gathered from both the environmental sensors, sleep diaries, and interviews, key metrics such as average illuminance levels, temperature variations, and notable entries from the sleep diaries and interviews are presented to provide an initial understanding of the data set (Table: 4.1.1).

Table 4.1.1: Summary of Key Findings

Aspect	**Finding**
Twilight Impact	Observerved low illuminance levels during civil twilight. Variability in illuminance levels before bedtime, especially in rooms with higher averages, highlights the need for environmental adjustments to reduce light exposure and protect sleep quality (Figure 4.4.1, 4.2.2 and Figure 4.7.3).
Temperature Correlation	Correlations between light exposure and sleep metrics such as sleep duration and awakenings are generally weak. The analysis highlights that room temperature and light exposure are interconnected but do not strongly impact sleep quality directly (Table 4.3.1 and Figure 4.3.1).
Sleep Patterns	Observations in Rooms A and B showed more awakenings, indicating disruptive factors unique to these areas. Sleep habits of the residents don't align with twilight phases. Unclear if this is related to light exposure (Figure 4.5.1).
Variability of Light Intensity Across Twilight Phases	Light intensity shows significant fluctuations across twilight phases, peaking during daylight and decreasing markedly during evening twilight. (Figure 4.2.3).
Cityscape Lighting Impact	The impact of artificial street lighting was found to be minimal, as HOBO sensors indicated low illuminance levels during Civil Twilight. This suggests that the internal lighting strategies are more critical to study (Figure 4.2.1).
Biometric Data	The findings underscore the importance of incorporating biometric data in future research to gain deeper insights into how circadian rhythms are influenced by environmental factors.

4.2 Twilight Phases and Light Intensities

This section examines light intensity variations during different twilight phases highlighting how natural light transitions impact indoor environments at the KTH Live-in Lab (Figure 4.2.1, 4.2.2 and 4.2.3).

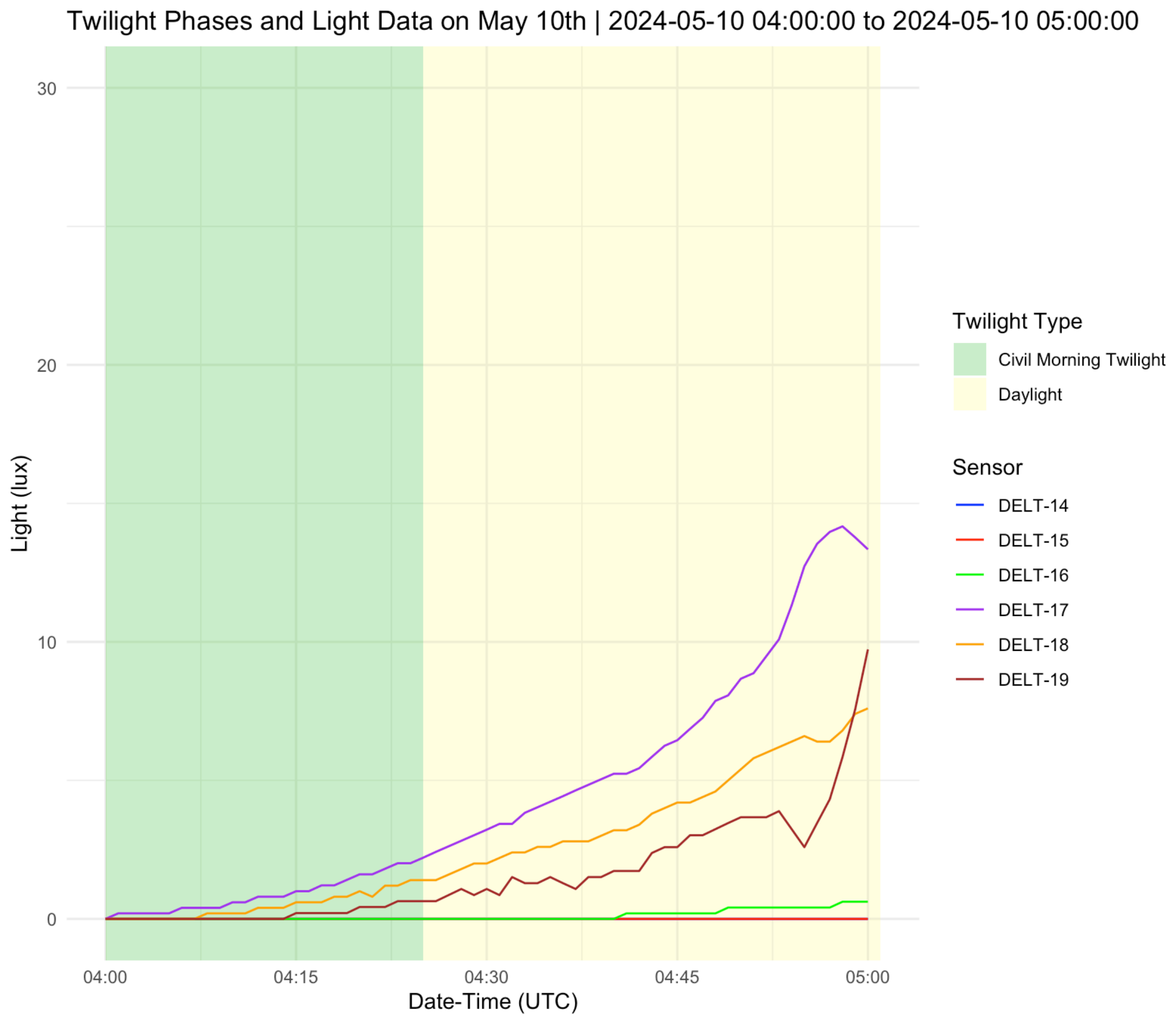


Figure 4.2.1: Twilight Phases and Light Intensity on May 10th, 2024. This graph displays the light intensity readings from multiple sensors (DELT-14 to DELT-19) during the early morning hours of 04:00 to 05:00 UTC. The shaded areas represent different twilight phases: Civil Morning Twilight (green) transitioning into Daylight (light yellow). Notably, the light intensity levels during the Civil Morning Twilight remain relatively low across all sensors, typically under 10 lux, before a sharp increase as daylight approaches. This visual evidence supports the hypothesis that light exposure levels during Civil Morning Twilight might be insufficient to relevantly influence sleep patterns, as indicated by the relatively stable and low lux readings prior to sunrise.

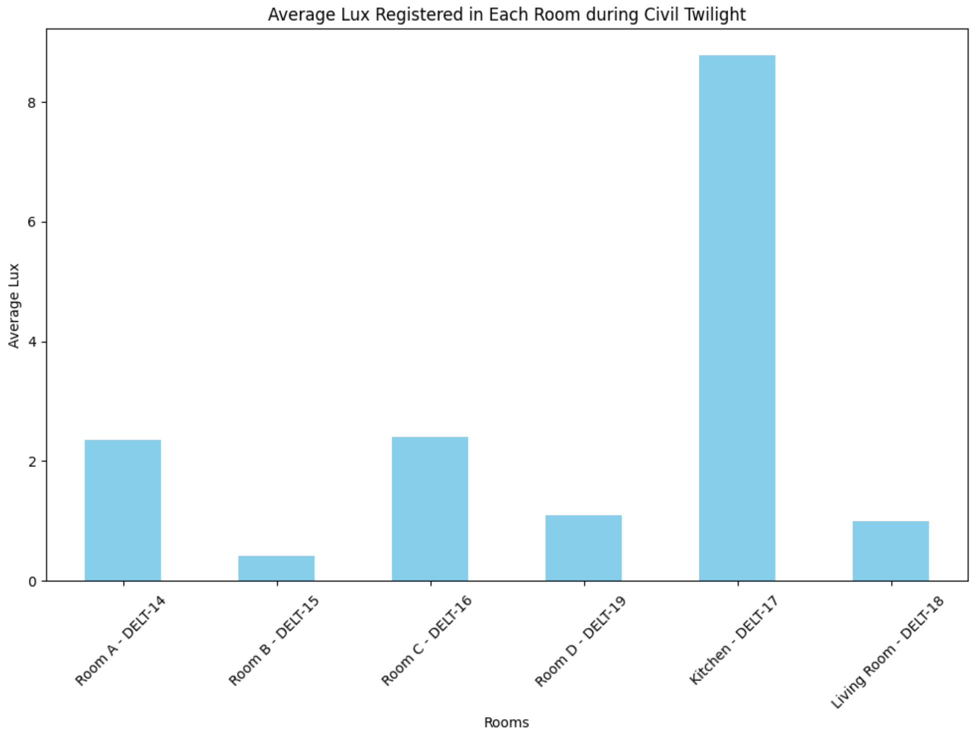


Figure 4.2.2: Average lux registered in each room during Civil Twilight. The plot shows that Kitchen - DELT-17 has the highest average illuminance level during twilight periods.

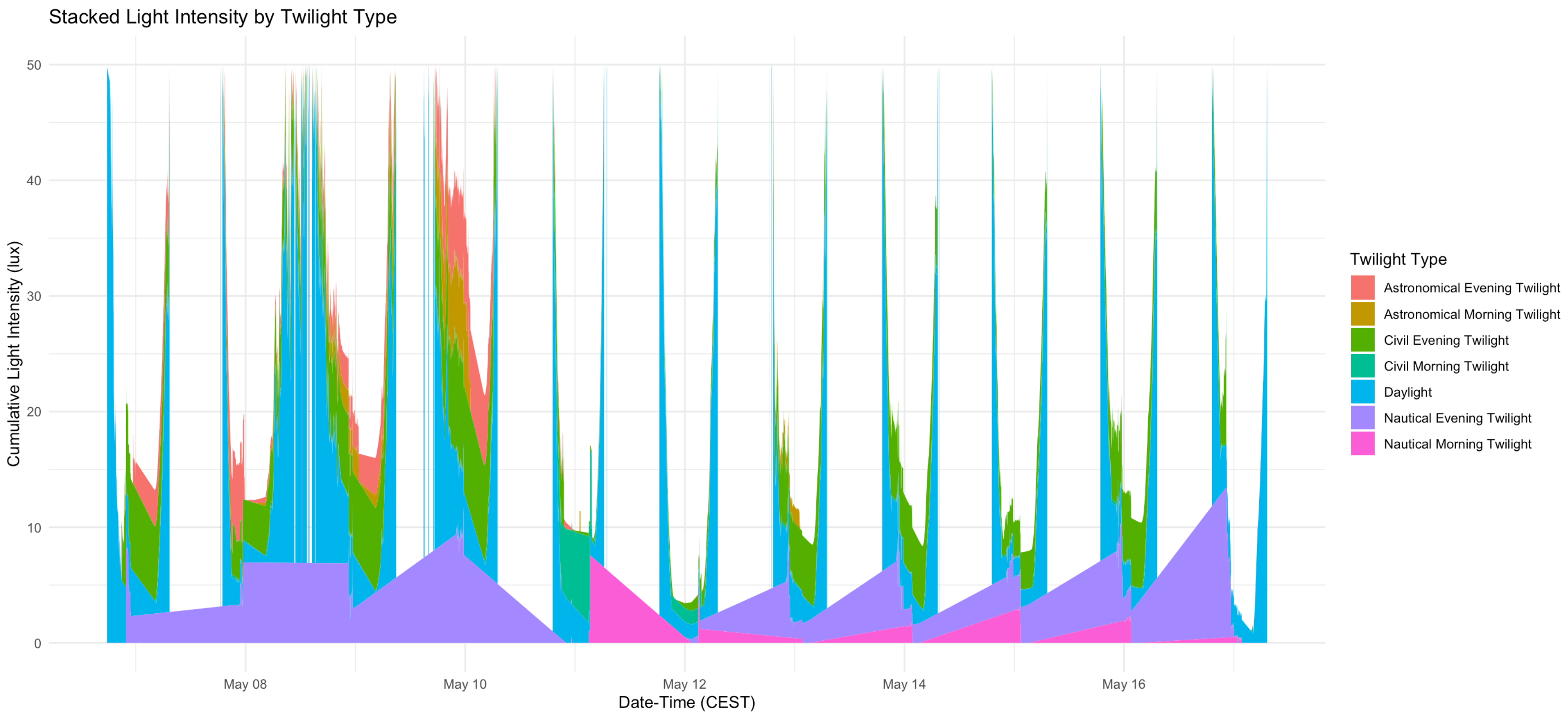


Figure 4.2.3: Cumulative Light Intensity by Twilight Type from May 8th to May 16th, 2024. This graph depicts the variation in light intensity measured in lux, stacked by different twilight phases over several days in May. Each color represents a distinct phase of twilight, illustrating how light levels change through the transition from night to day and back. Notably, the layers show relevant fluctuations in light intensity during the early morning hours (Civil and Nautical Morning Twilight) and late evening hours (Civil and Nautical Evening Twilight). The graph highlights peaks of light intensity during the Daylight phase, demonstrating the maximum light exposure, which then progressively decreases during the evening twilight phases. This visualization provides insights into the dynamic nature of ambient light across different times of the day and its potential implications for environmental and behavioral studies.

4.3 Temperature and light correlation

This examination underscores how room temperatures correspond with varying light exposures and informs on the thermal performance across different building zones (Figure 4.3.1). Tables 4.3.1 and 4.3.2 present these findings, offering a nuanced view of the interplay between environmental factors.

Table 4.3.1: Temperature Heatmap Relevant Reasons

Identifying Relationships: Highlights positive and negative correlations between temperature and light levels across various rooms.
Thermal Performance Insights: Provides insights into how different rooms respond to light exposure.
Data-Driven Decisions: Supports decisions for shading, insulation, or ventilation strategies based on quantitative data.
Comparing Different Zones: Allows comparison of different building zones, showing how various areas are influenced by external and internal factors. light exposure.

Table 4.3.2: Key Findings from Correlation Analysis

Room	Key Findings
Room A	Moderate positive correlation between temperature and light (0.24). Strong correlations with Living Room (0.94) and Room B (0.79) temperatures.
Room B	Strong correlation between temperature and light (0.76). Significant temperature correlations with Room A (0.79) and Living Room (0.77).
Room C	Notable correlation between temperature and light (0.26). Strong correlations with Room D (0.90) and Kitchen (0.89) temperatures.
Room D	Mild correlation between temperature and light (0.23). Significant correlations with Room C (0.90) and Kitchen (0.86).

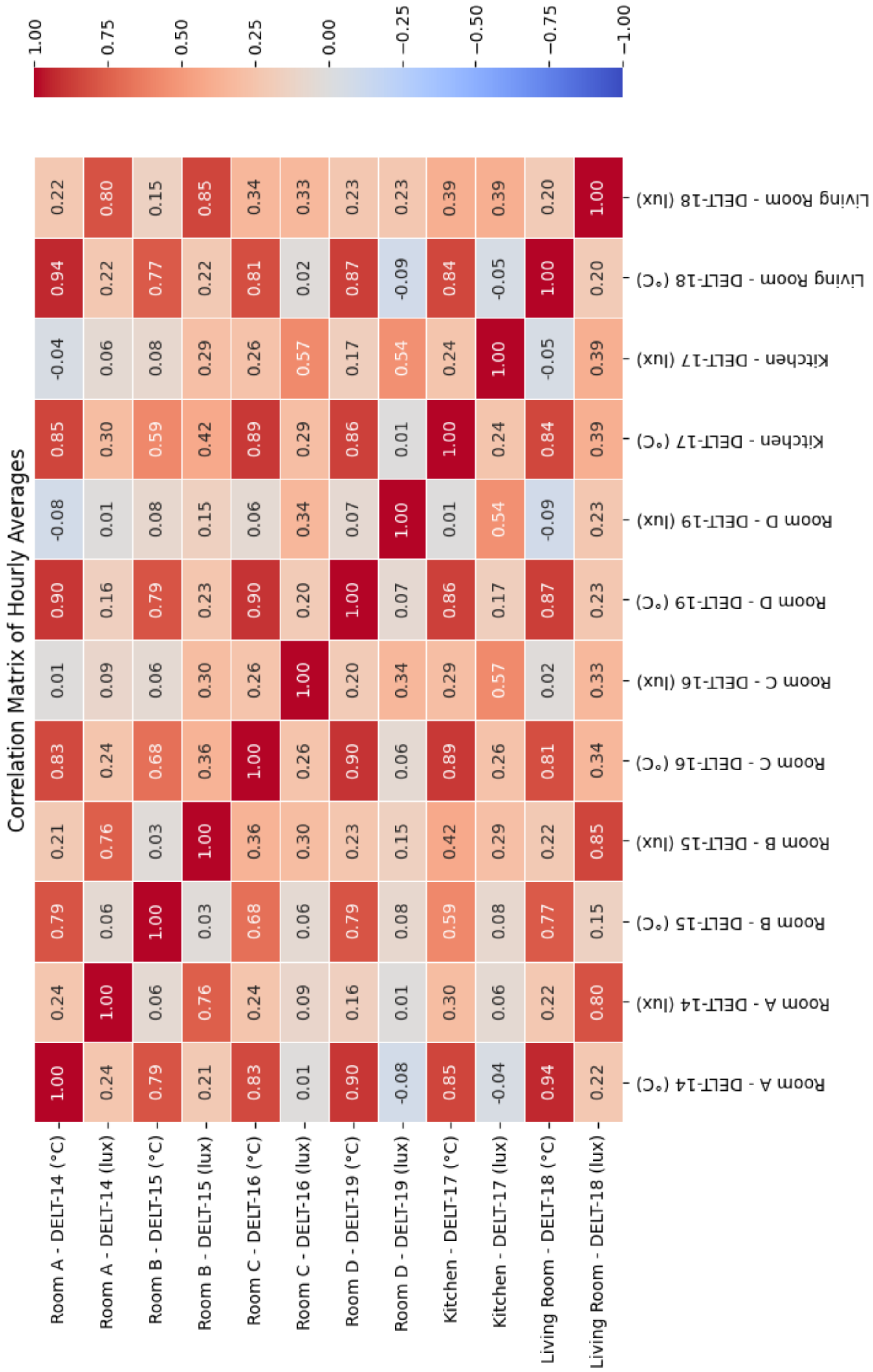


Figure 4.3.1: Correlation Matrix of Hourly Averages for Temperature and Light Intensity across Different Rooms.

4.4 Sleep Patterns

The aggregate statistics indicate diverse sleep patterns across the rooms:

Room A: Shows a high average sleep duration coupled with the highest average awakenings, suggesting potential disturbances or interruptions in sleep.

Room B and C: Feature high sleep durations with relatively fewer awakenings, indicating a more restful sleep environment compared to other rooms.

Room D: Has the shortest sleep duration and no recorded awakenings.

Table 4.4.1: Summary of Sleep Statistics by Room

Room	Average Sleep (h)	Median Sleep (h)	SD Sleep (h)	IQR Sleep (h)	Total Awaken-ings	Average Awaken-ings
A	8.58	8.50	1.30	1.88	25	2.27
B	8.67	8.25	1.38	1.21	8	0.727
C	9.29	9.50	0.997	1.17	5	0.455
D	7.61	7.50	0.564	0.875	0	0.000

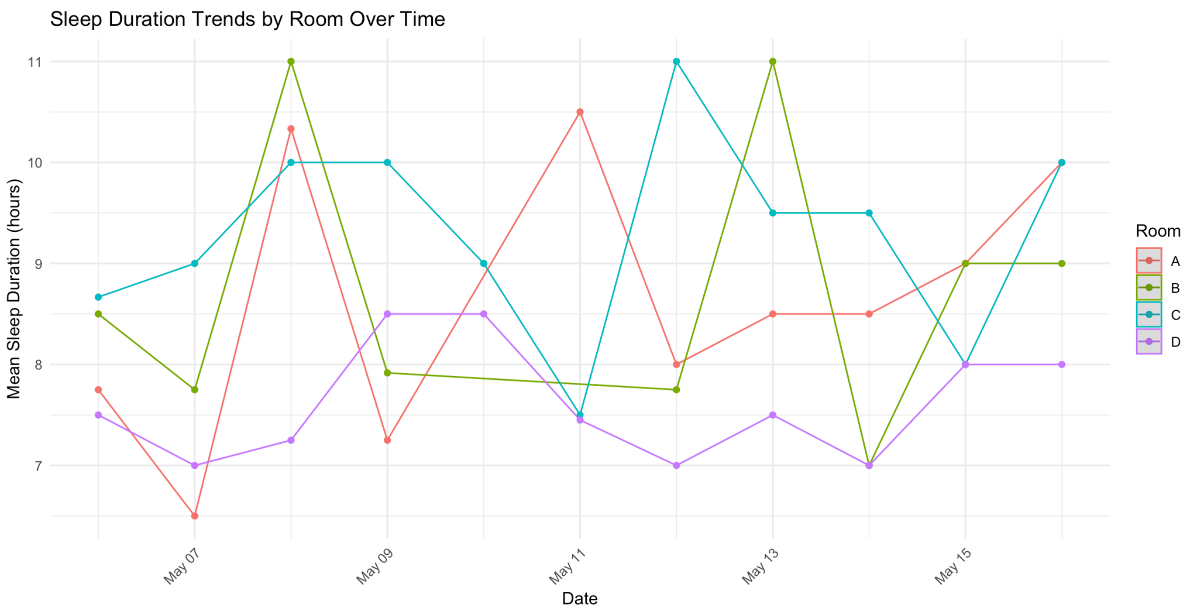


Figure 4.4.1: Sleep Duration Trends by Room Over Time. This figure shows the sleep duration in hours across different rooms (A, B, C, and D) over a series of dates in May. Each line represents a different room, highlighting the variability in sleep duration over time.

Table 4.4.2: Light vs Sleep Duration and Awakenings & Inter-sensor Correlation

Light vs Sleep Duration and Awakenings
The correlations between light exposure and sleep metrics such as duration and awakenings are generally low. Nonetheless, a notable exception is observed with Avg_Lux_14 (light in Room A), which exhibits a slight positive correlation with sleep duration (Figure 4.4.2).
Inter-sensor Correlation
There is moderate to high positive correlation between the light readings across several rooms, particularly between Avg_Lux_14, Avg_Lux_15, and Avg_Lux_18, which might indicate similar environmental lighting conditions or patterns affecting these areas.

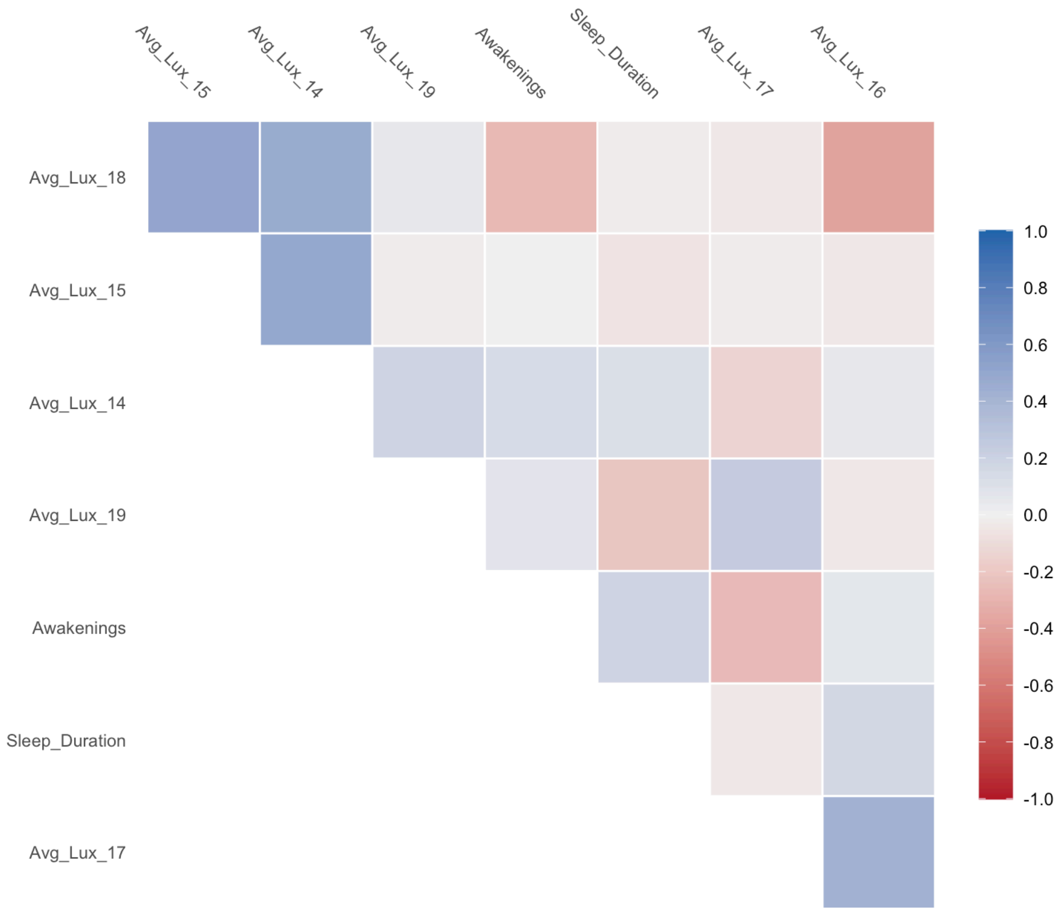


Figure 4.4.2: Light vs Sleep Duration and Awakenings & Inter-sensor Correlation

4.5 Awakenings by Room

Sleep diaries were analyzed to sum the number of awakenings reported by residents for each room. Figure 4.5.1 shows the total number of awakenings by room. Room A had the highest number of awakenings and Figure 4.5.1 the relationship between sleep duration and awakenings by room.

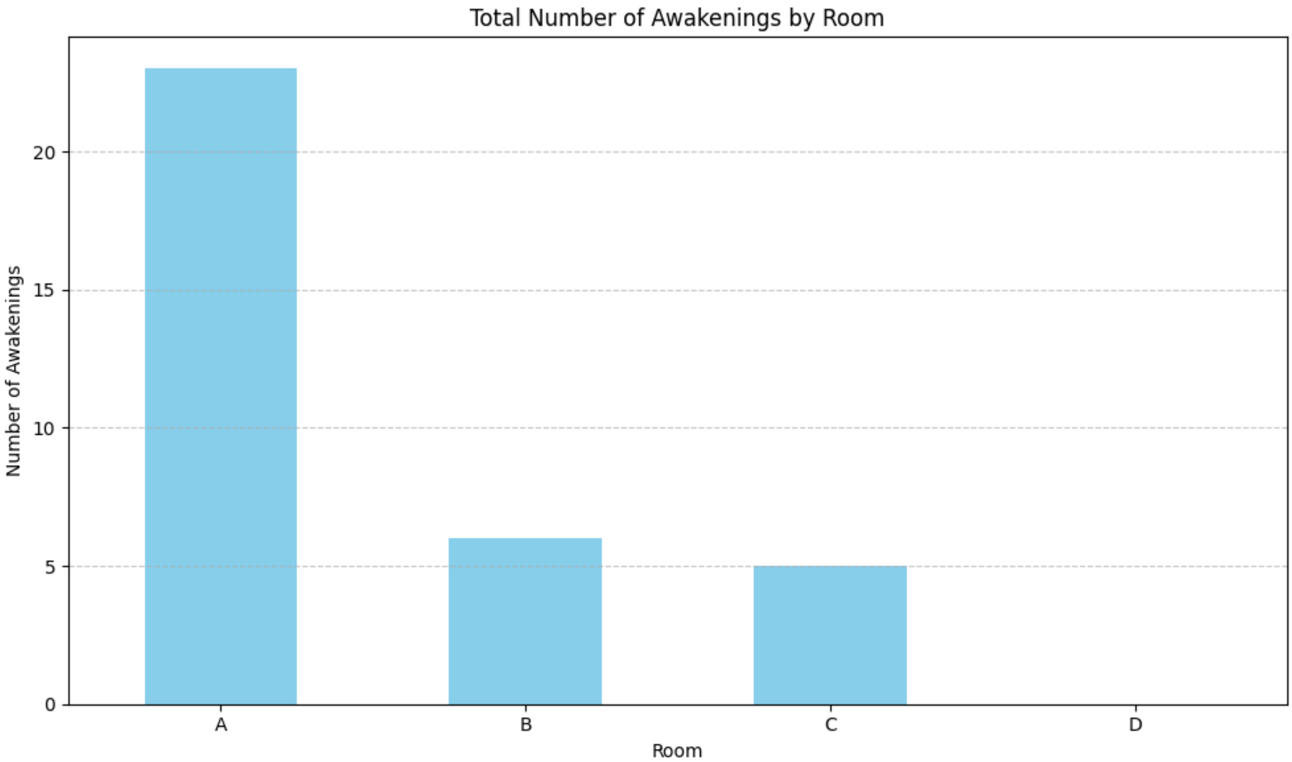


Figure 4.5.1: Total Number of Awakenings by Room.

4.5.1 Impact of Daylight on Sleep and Well-being

Data from the annual daylight analysis provides quantifiable insights into how daylight may affect indoor living environments. The figures show May 10th as a representative day within the observation period.

Daylight Autonomy (sDA): Achieved a score of 51.4%, indicating that over half of the living spaces received sufficient daylight for at least half of the year (Figure 4.5.2).
Annual Sunlight Exposure (ASE): Registered at 9.1%, suggesting that a small portion of the area received excessive sunlight, which could contribute to glare and overheating (Figure 4.5.3).
Illuminance Levels: The average illuminance was recorded at 855 Lux, reflecting the intensity of light that residents might be exposed to during daytime hours (Figure 4.5.4).

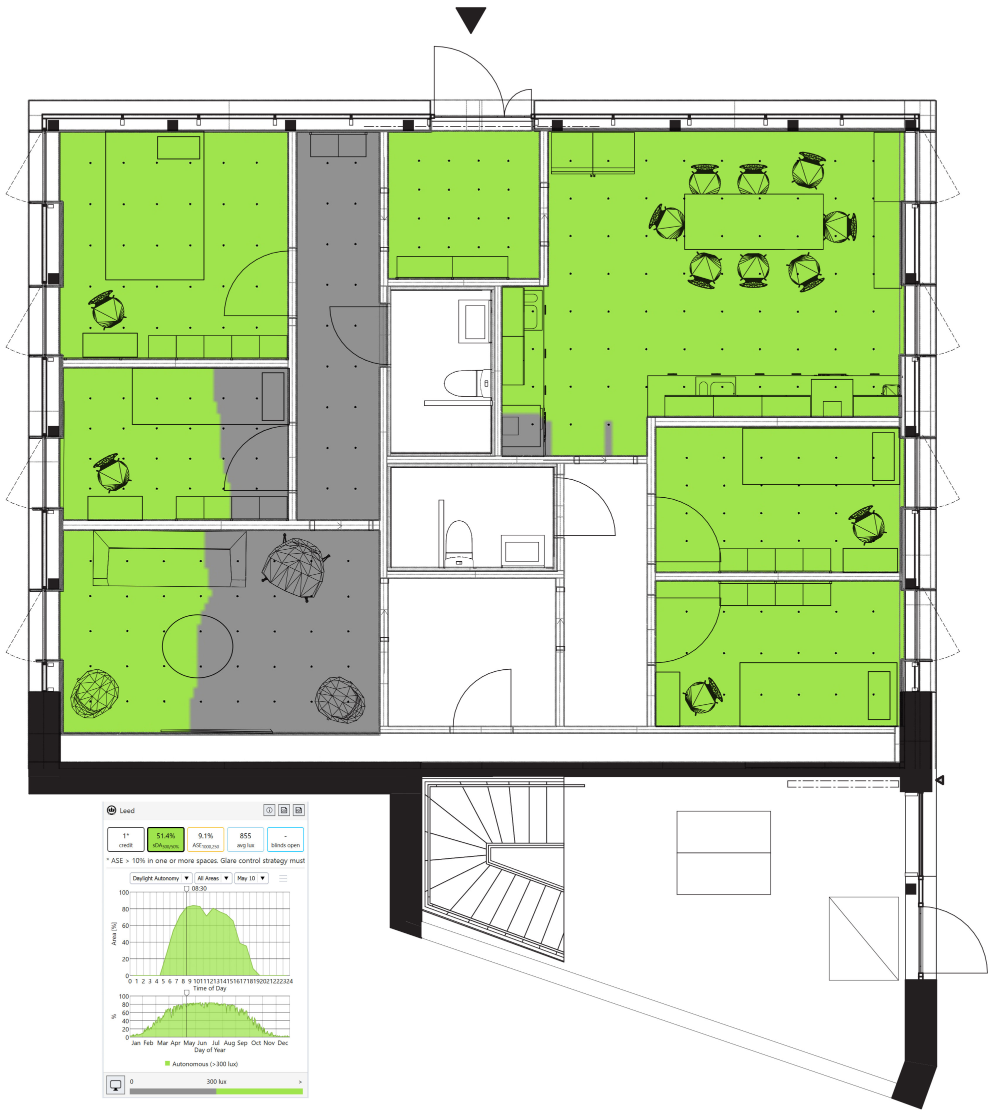


Figure 4.5.2: Daylight Autonomy (sDA) achieved score of 51.4% at 8:30 on May 10th | LEED Daylight Analysis. Source: Gregor Ruta.

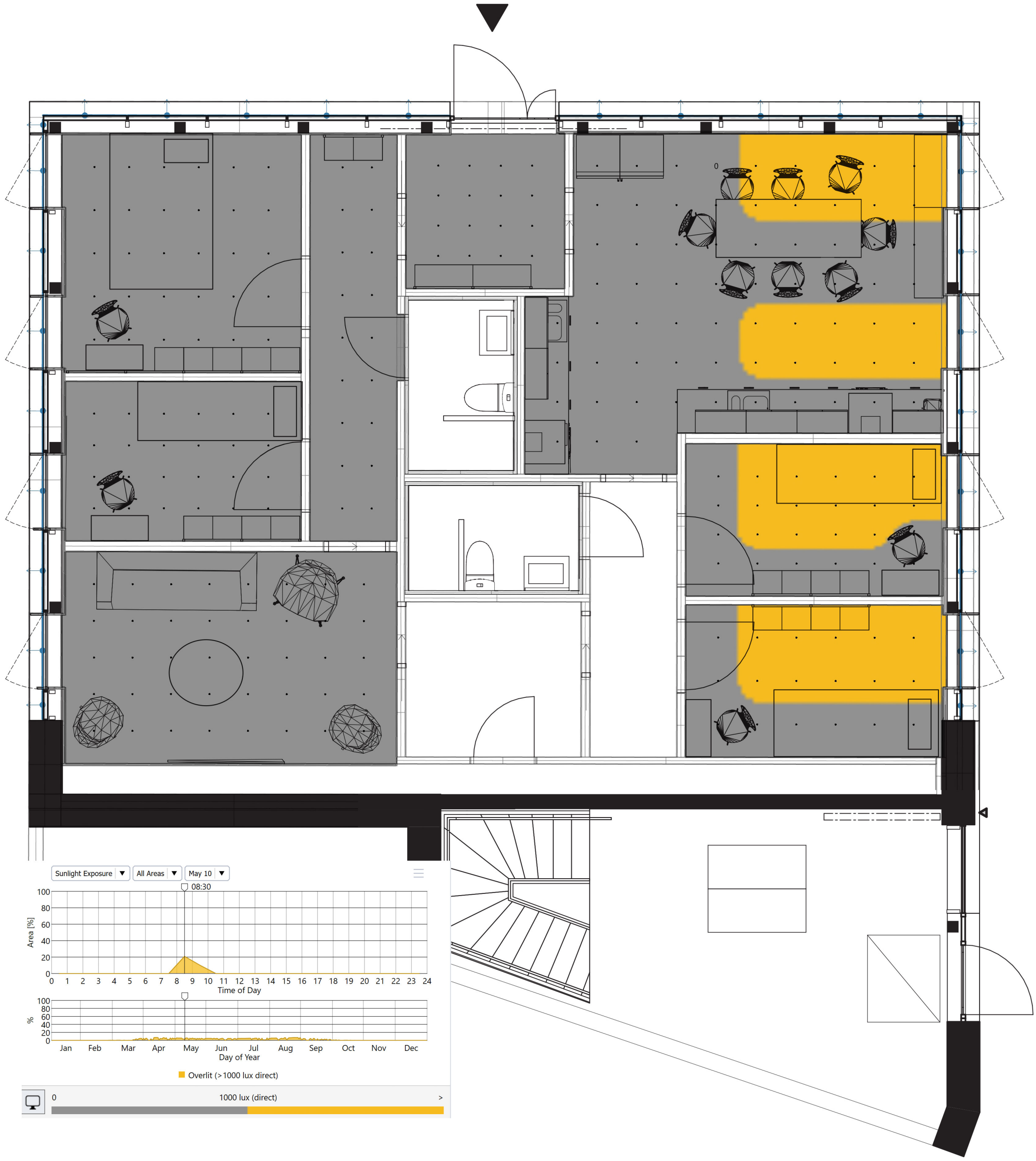


Figure 4.5.3: ASE Sunlight Exposure 9.1% at 8:30 on May 10th | LEED Daylight Analysis. Source: Gregor Ruta.

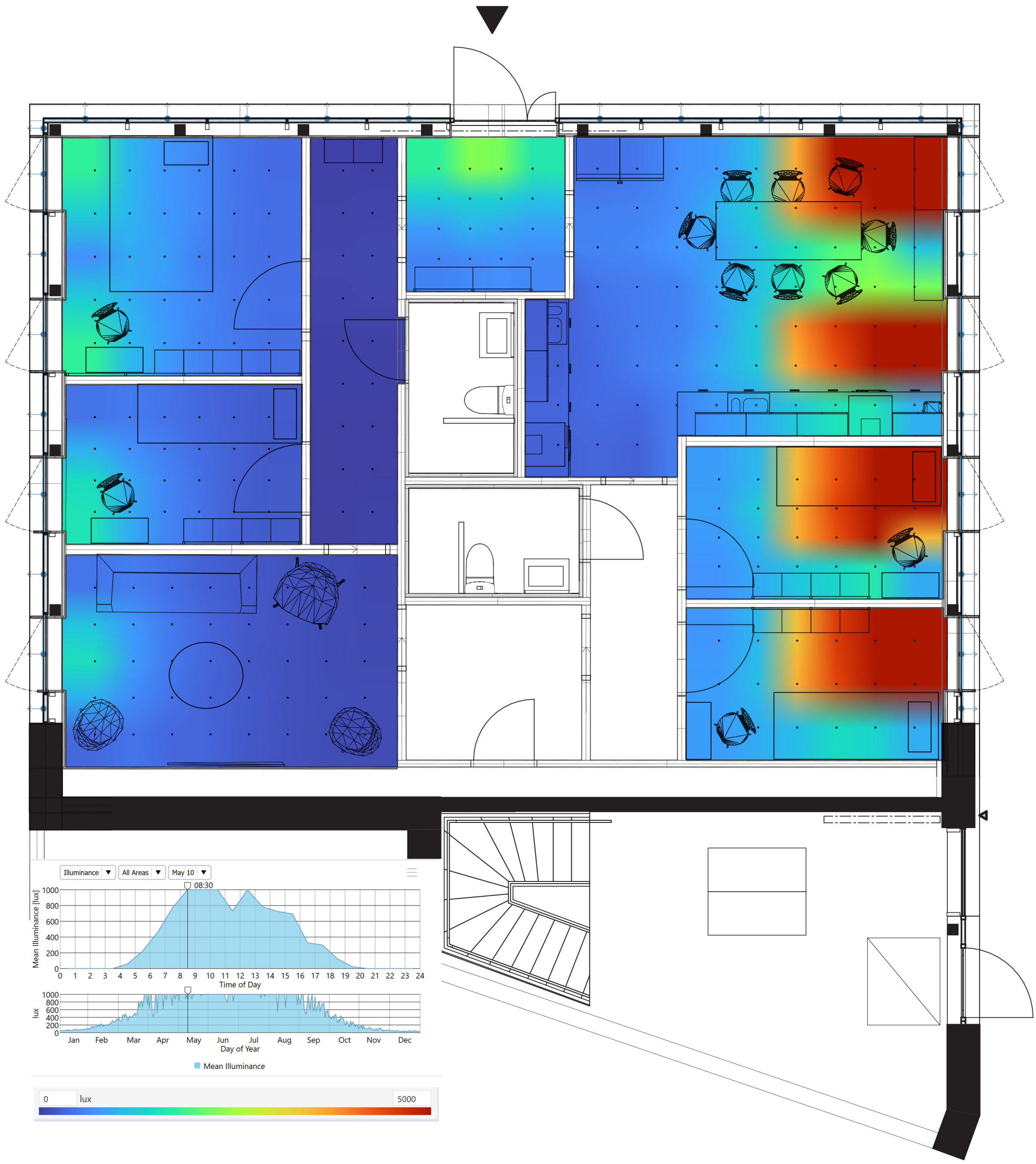
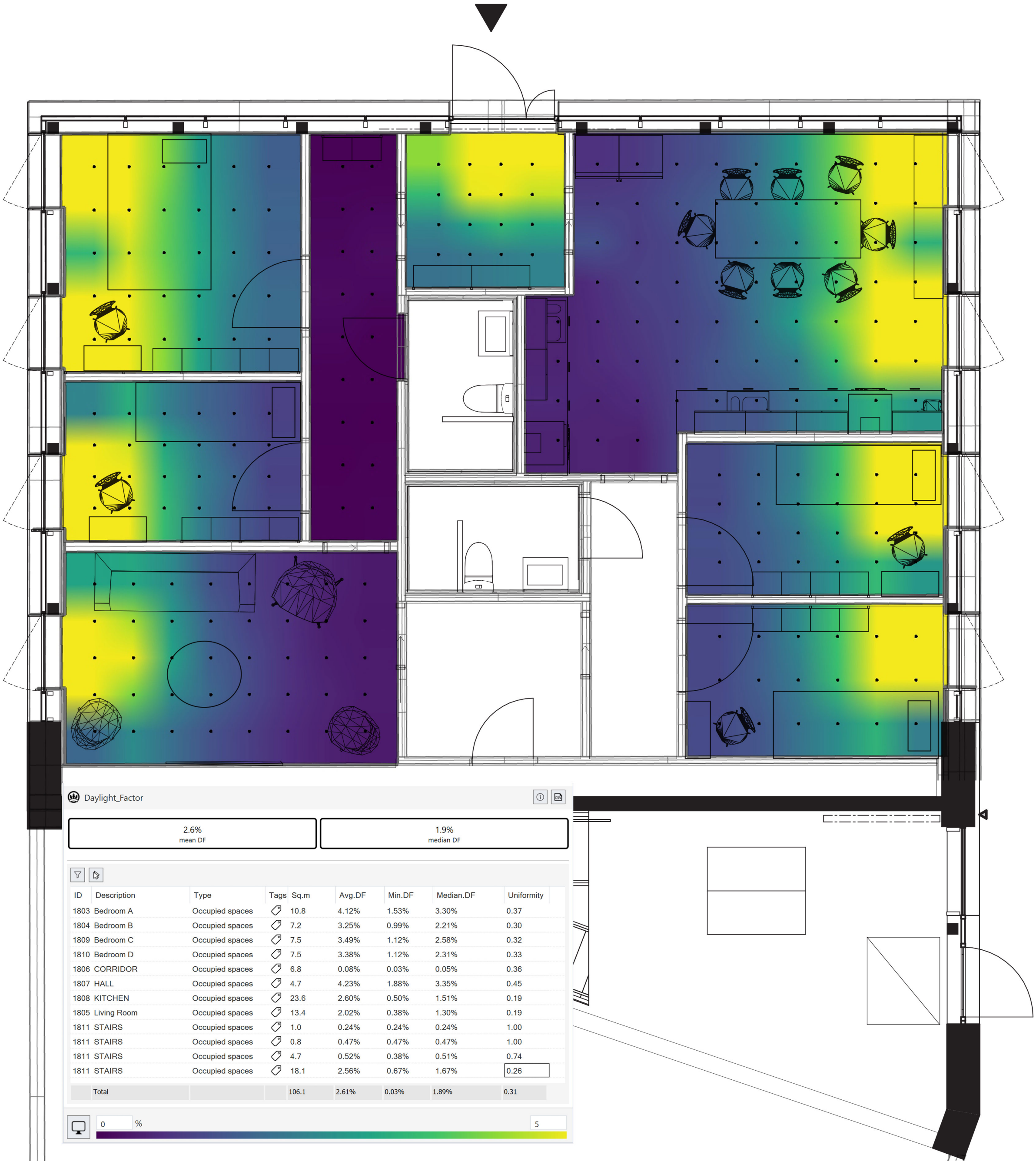


Figure 4.5.4: Average of 855 Lux at 8:30 on May 10th | LEED Daylight Analysis. Source: Gregor Ruta.

Figure 4.5.5: Daylight Glare Probability (DGP) analysis for the KTH Live-in Lab on May 10th at 8:30 AM. Areas marked in red indicate regions with high glare probability (intolerable glare), while areas in yellow and grey represent perceptible and imperceptible glare levels, respectively. The chart below the floor plan illustrates the percentage of time each glare level is experienced throughout the day. Additionally, the analysis shows that 12.0% of views have disturbing glare for more than 5% of the time (sDG). This analysis helps identify critical areas where glare reduction measures are necessary to improve occupant comfort. Source: Gregor Ruta.



ID	Description	Type	Tags	Sq.m	Avg.DF	Min.DF	Median.DF	Uniformity
1803	Bedroom A	Occupied spaces		10.8	4.12%	1.53%	3.30%	0.37
1804	Bedroom B	Occupied spaces		7.2	3.25%	0.99%	2.21%	0.30
1809	Bedroom C	Occupied spaces		7.5	3.49%	1.12%	2.58%	0.32
1810	Bedroom D	Occupied spaces		7.5	3.38%	1.12%	2.31%	0.33
1806	CORRIDOR	Occupied spaces		6.8	0.08%	0.03%	0.05%	0.36
1807	HALL	Occupied spaces		4.7	4.23%	1.88%	3.35%	0.45
1808	KITCHEN	Occupied spaces		23.6	2.60%	0.50%	1.51%	0.19
1805	Living Room	Occupied spaces		13.4	2.02%	0.38%	1.30%	0.19
1811	STAIRS	Occupied spaces		1.0	0.24%	0.24%	0.24%	1.00
1811	STAIRS	Occupied spaces		0.8	0.47%	0.47%	0.47%	1.00
1811	STAIRS	Occupied spaces		4.7	0.52%	0.38%	0.51%	0.74
1811	STAIRS	Occupied spaces		18.1	2.56%	0.67%	1.67%	0.26
	Total			106.1	2.61%	0.03%	1.89%	0.31

Figure 4.5.6: Daylight Factor (DF) distribution in the KTH Live-in Lab. The floor plan shows the spatial variation of DF, with color gradients indicating different levels of daylight penetration. Although the concept of DF is considered outdated, it remains useful for comparing results with other studies. The mean DF is 2.6%, and the median DF is 1.9%. The table below the floor plan provides detailed statistics for each room, including average, minimum, and maximum DF values. This analysis helps in understanding the daylight availability within the space and identifying areas that may need lighting improvements. Source: Gregor Ruta.

4.6 Curtain Designs on Daylight Exposure

At the KTH Live-in Lab, large daylight openings are intended to maximize natural light. However, resident feedback has indicated several issues, including excessive brightness in the morning and compromised privacy due to inadequate curtain coverage. These challenges underscore the need for a curtain design that more effectively manages daylight exposure and privacy concerns.

4.6.1 Daylight Management and Privacy Enhancement

Residents have reported early wake-ups from excessive morning brightness and privacy concerns due to large, inadequately covered windows. Additionally, excessive sunlight exposure has led to discomfort from heat and glare. To address these issues, a new dual-section curtain configuration was proposed to enhance natural light utilization and maintain privacy while mitigating glare and overheating. Figure 4.6.1 illustrates three configurations of the proposed design, showing varied levels of openness to balance light and privacy.

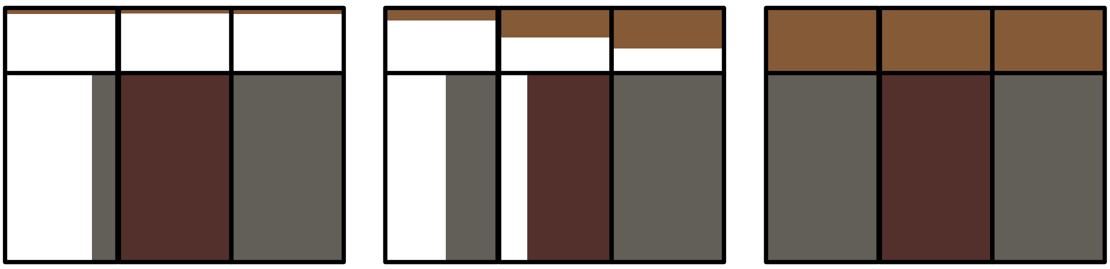


Figure 4.6.1: Three configurations of a dual-section curtain design in a residential setting, ranging from semi-closed to fully closed, offering varying degrees of light control and privacy.

4.6.2 Comparative Analysis of Curtain Designs

The simulation objectives focused on comparing the light distribution and daylight autonomy of the existing single-piece design against the proposed dual-section curtains. Analysis involved evaluating each design's effectiveness in managing daylight exposure and privacy within residential settings. Figure 4.6.2 visually compares both configurations.

Subsequent analyses compared the performance of single and dual-section curtain setups in terms of daylight autonomy and sunlight exposure. The dual-section design demonstrated better daylight distribution and relevantly improved daylight autonomy, indicating its potential to enhance both daylight utilization and indoor environmental quality without compromising privacy or comfort See Figures 4.6.3 and 4.6.4 for a detailed comparison of daylight performance metrics between the single and dual-section curtain setups.

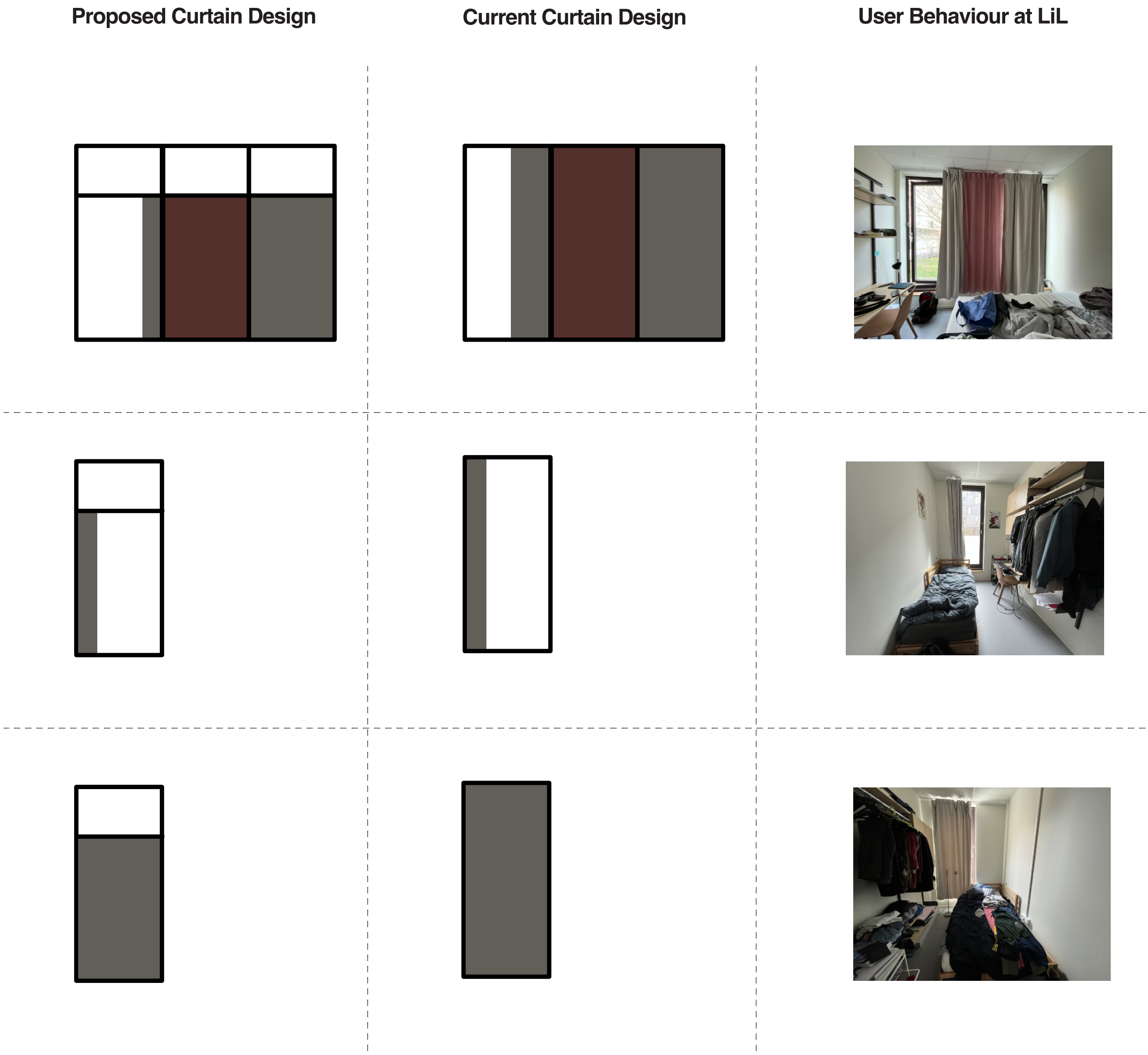
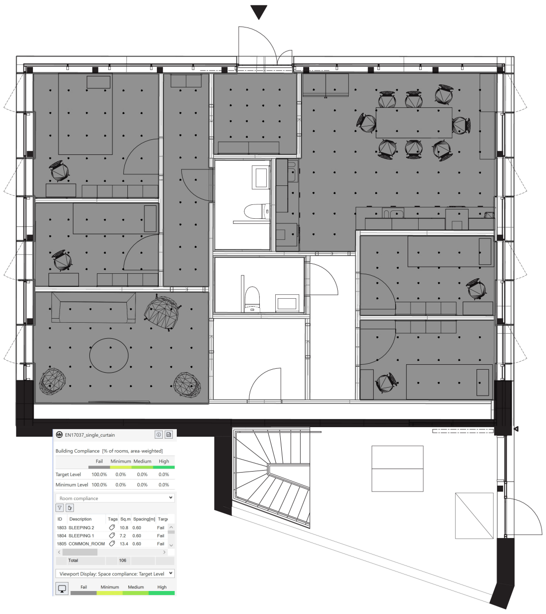
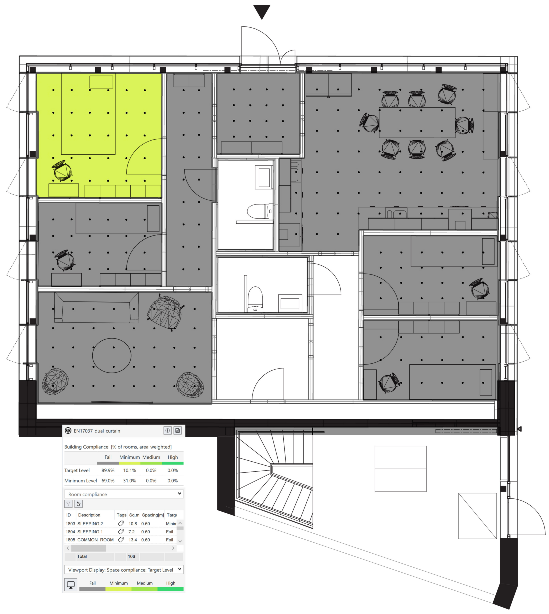


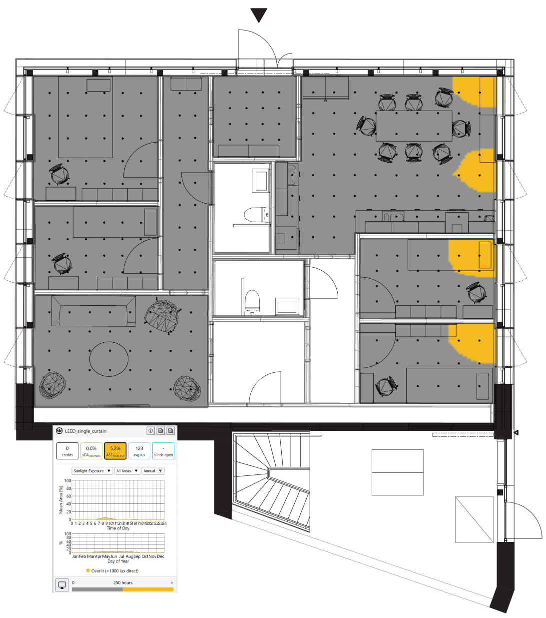
Figure 4.6.2: Comparison of the existing single-piece and proposed dual-section curtain designs at KTH Live-in Lab, highlighting improvements in light regulation and privacy.



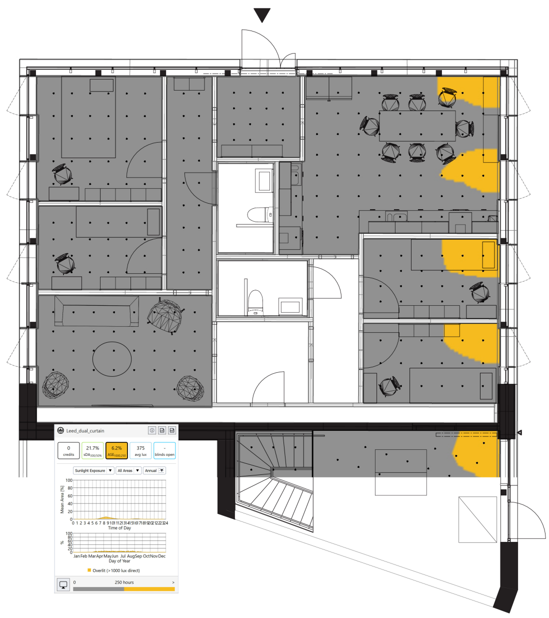
(a) Daylight analysis according to EN17037 for the single curtain setup.



(b) Daylight analysis according to EN17037 for the dual-section curtain setup.

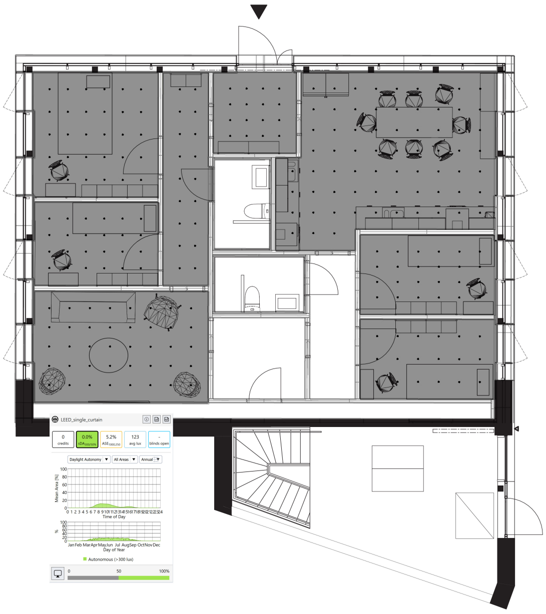


(c) LEED Annual Sunlight Exposure (ASE) analysis for the single curtain setup, showing 5.2% exposure.



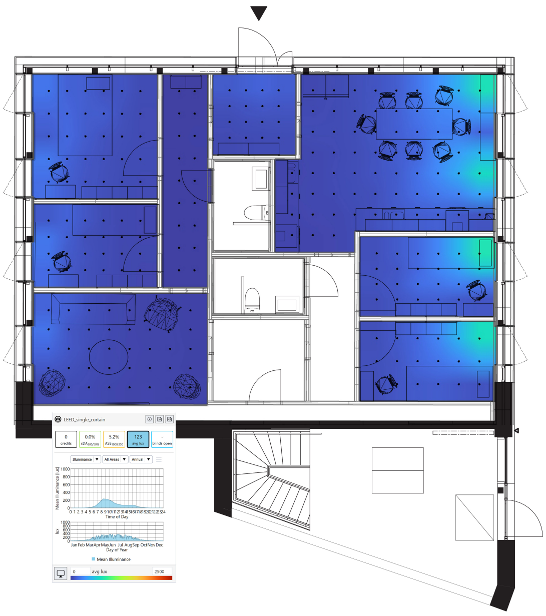
(d) LEED Annual Sunlight Exposure (ASE) analysis for the dual-section curtain setup, showing 6.2% exposure.

Figure 4.6.3: Comparison of EN17037 and LEED ASE metrics between single and dual-section curtain setups. These analyses help in understanding how each configuration affects daylight distribution and exposure. Source: Gregor Ruta.

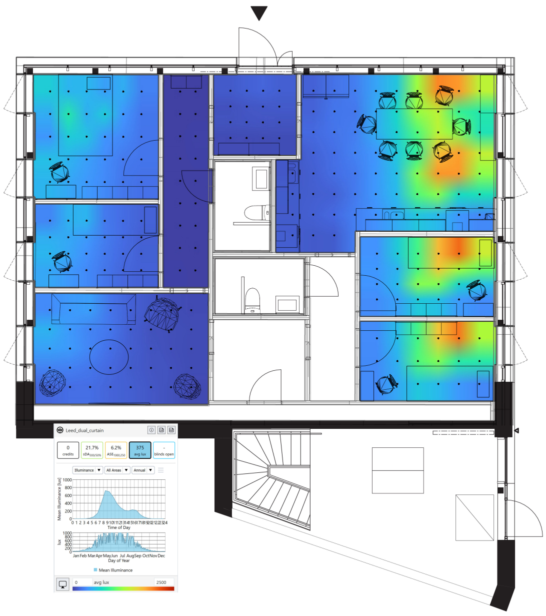


(a) LEED Spatial Daylight Autonomy (sDA) analysis for the single curtain setup.

(b) LEED Spatial Daylight Autonomy (sDA) analysis for the dual-section curtain setup, showing an increase to 21.7%. The dual-section design relevantly improves daylight penetration and autonomy.



(c) Average illuminance (Lux) analysis for the single curtain setup, showing an average of 123 lux.



(d) Average illuminance (Lux) analysis for the dual-section curtain setup, showing an increase to 375 lux. This setup enhances overall daylight availability in the space.

Figure 4.6.4: Comparison of LEED sDA and average illuminance between single and dual-section curtain setups. These analyses illustrate how the dual-section design improves daylight autonomy and overall light levels. Source: Gregor Ruta.

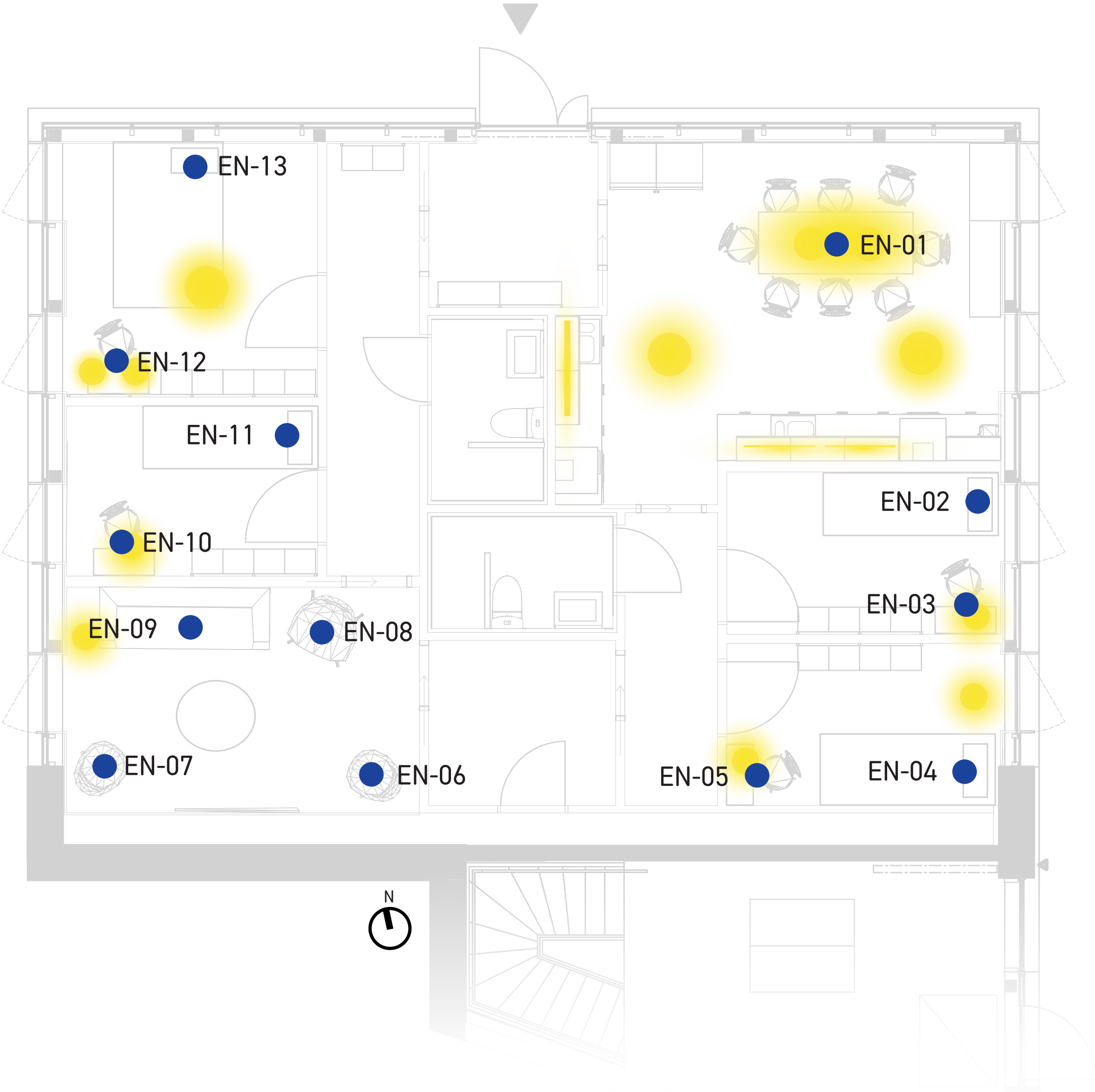
4.7 Spectrometer Measurements

Spectrometer measurements were performed using GL Spectis 1.0 touch on May 9, 2024, from 21:00 to 21:30 during the evening civil twilight to evaluate ambient light exposure at the KTH Live-in Lab. This timing was chosen (following the measurement strategy explained in Table 4.7.1) to avoid disturbing residents during the early morning civil twilight that occurred from 3:31 to 4:27. The observations took place under variable weather conditions, including light clouds and rain, which could have influenced the light levels recorded. The ambient temperature was approximately 10 degrees Celsius at the time of measurement.

Lighting Setup: The lighting was not artificially enhanced during the measurements; thus, the data reflects the lab's existing lighting setup as left by the residents. This method ensured the capture of a typical environmental lighting scenario within the facility. It is important to note which lights were on during the measurements, as this can impact the recorded values. For example, the high melanopic Equivalent Daylight Illuminance (mEDI) at point EN-05 is likely due to the desk lamp being on, as the window is on the opposite side of the room.

Table 4.7.1: Measurements Strategy

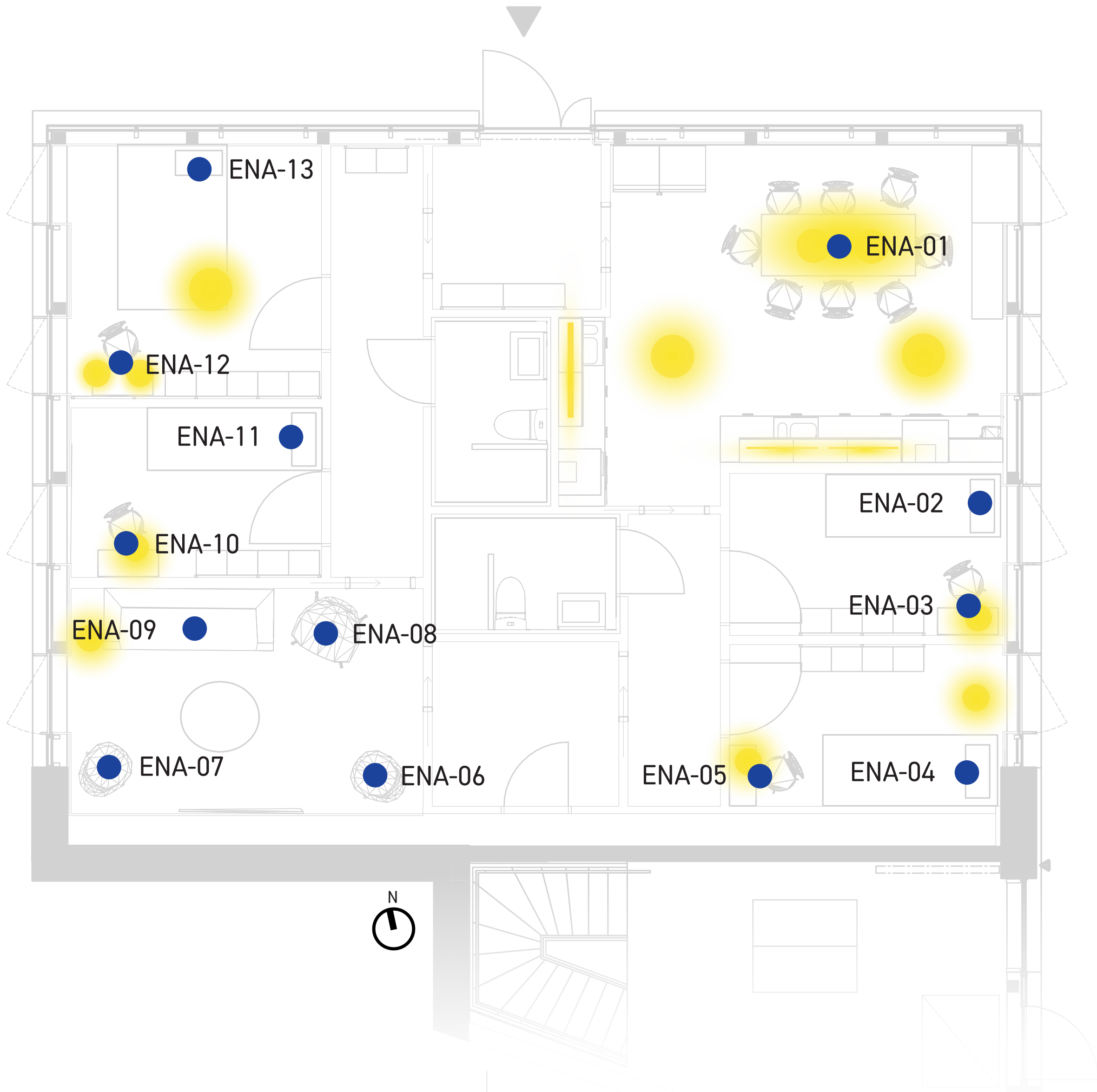
Measurement Plane	**Description**
Horizontal Plane	Measurements conducted at a height of 75cm from the floor, which corresponds to the typical height of work surfaces and tables, representing areas of frequent activity for residents (Figure 4.7.1).
Vertical Plane	Measurements at a height of 120cm from the floor were carried out to evaluate the lighting conditions at an approximate eye level when seated (Figure 4.7.2).
Above the Pillow Area	Measurements above the pillow area were taken to specifically analyze the light exposure levels where residents rest their heads, providing insights into potential impacts on sleep quality and circadian rhythms.



Orizontal Measurements

POINT	ID	Equivalent melanopic lux (lx)	Melanopic Ratio	M-EDI (lx)	Lux Levels
EN-01	205714	46,82	0,617	35,63	75,93
EN-02	211802	54,12	1,231	40,35	43,96
EN-03	211906	64,14	1,126	48,62	56,94
EN-04	212234	56,79	1,174	42,38	48,35
EN-05	212146	1053,73	0,537	793,65	1960,61
EN-06	211314	26,35	0,828	20,24	31,81
EN-07	211244	47,19	1,228	35,52	38,44
EN-08	211343	55,01	1,251	39,68	43,98
EN-09	211206	56,59	1,016	42,62	55,71
EN-10	211116	55,73	0,942	41,59	59,16
EN-11	210923	34,08	1,181	25,33	28,86
EN-12	211455	143,98	0,680	107,77	211,78
EN-13	211430	61,06	0,992	45,61	61,58

Figure 4.7.1: Spectrometer Measuraments, Horizontal Plane.



Vertical Measurements

POINT	ID	Equivalent melanopic lux (lx)	Melanopic Ratio	M-EDI (lx)	Lux Levels
ENA-01	205824	43,05	0,749	32,60	57,48
ENA-02	211725	53,54	1,312	39,60	40,82
ENA-03	212006	67,62	0,985	50,76	68,67
ENA-04	212309	60,66	1,150	44,64	52,72
ENA-05	212059	116,89	0,738	87,33	158,29
ENA-06	210740	31,61	1,045	23,64	30,26
ENA-07	210641	37,15	1,193	27,93	31,13
ENA-08	210709	36,10	1,163	27,12	31,03
ENA-09	210610	41,73	1,044	30,13	39,98
ENA-10	210946	92,11	0,709	68,81	129,90
ENA-11	211032	40,32	1,200	30,16	33,60
ENA-12	211618	119,20	0,567	90,11	210,24
ENA-13	211553	66,31	0,989	49,47	67,05

Figure 4.7.2: Spectrometer Measurements, Vertical Plane.

4.7.1 Spectrometer Measurements Light Map

The light distribution at KTH Live-in Lab is based on spectrometer measurements, providing insights into the quality and intensity of light in various areas (Figure 4.7.3). The key findings from the measurements are summarized as follows:

- **Equivalent Melanopic Lux (lx):** The measurements revealed a relevantly higher equivalent melanopic lux at point EN-05 compared to other points. Interestingly, the corresponding vertical measurement at ENA-05 did not show such prominence, indicating a possible anomaly at EN-05.
- **Melanopic Ratio:** Points such as EN-02/ENA-02, EN-03, EN-04/ENA-04, ENA-06, EN-07/ENA-07, EN-08/ENA-08, EN-09/ENA-09 and EN-11/ENA-11 exhibited high melanopic ratios (above 1.0), suggesting a greater proportion of light potentially affecting the circadian system.
- **M-EDI (lx):** Similar to the equivalent melanopic lux, point EN-05 showed exceptionally high M-EDI. The Melanopic Equivalent Daylight Illuminance (M-EDI) values at this point are indicative of the spectral content's potential to influence circadian rhythms. High M-EDI levels during the evening can delay melatonin production, potentially disrupting sleep patterns [30].
- **Illuminance Levels:** Point EN-05 displayed an extremely high illuminance level, much higher than other points, suggesting intense light intensity that could lead to glare and discomfort. EN-12 also had a relatively high illuminance level but was less extreme.

The comparison between horizontal and vertical measurements further highlights variations in light quality and intensity at different heights, emphasizing the complexity of lighting environments in residential settings. The relevant discrepancy at point EN-05 between horizontal and vertical measurements might be attributed to measurement error, uneven light distribution, reflective surfaces, obstructions, or differences in instrument calibration.

These factors should be considered to accurately interpret the lighting conditions and their potential impact on resident well-being. Additionally, maintaining EDI levels at evening times within the recommended standards is crucial for not disrupting circadian rhythms, which underscores the need for careful management of light exposure in residential settings.

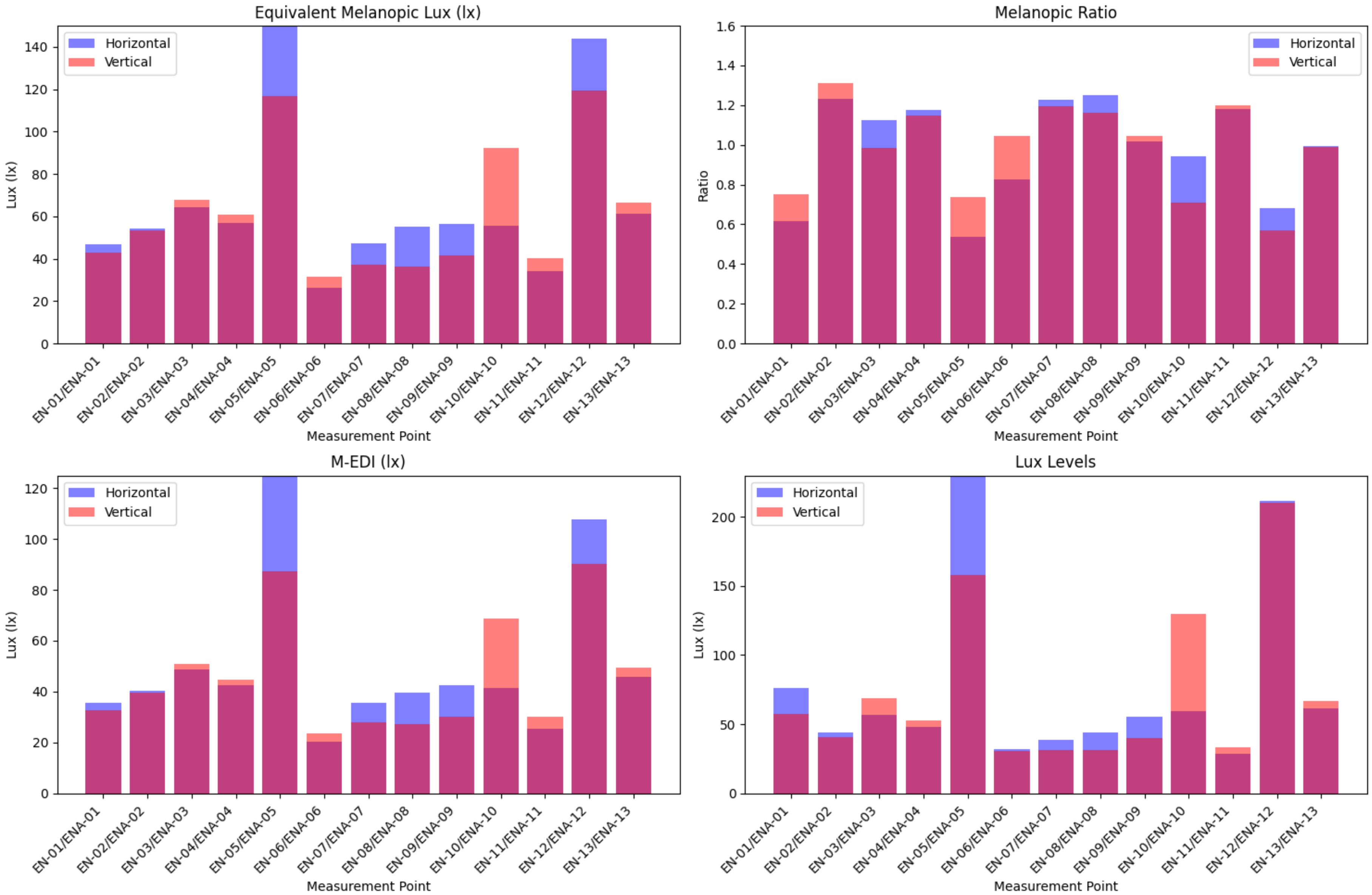


Figure 4.7.3: Comparison of Equivalent Melanopic Lux, Melanopic Ratio, M-EDI, and Illuminance Levels at Various Measurement Points. The plots illustrate the horizontal and vertical measurements for each parameter, highlighting variations across different locations. Note that the y-axis scales have been adjusted to better visualize the data distribution, excluding the outlier effects of extreme values.

4.8 Semi-Structured Interviews, Key Insights

4.8.1 Lighting and Mood

Common Theme: Respondents consistently reported that natural light relevantly effects their mood and productivity, noting better moods and increased productivity on sunny days.
Specific Insight: One participant experienced a relevant mood boost from sunlight, highlighting the psychological benefits of increased natural light exposure (see Transcription B).

4.8.2 Privacy Concerns Related to Ground Floor Living

Common Theme: Privacy emerges as a major concern for residents on the ground floor, where large windows and proximity to foot traffic compromise privacy.
Specific Insight: Multiple participants expressed discomfort due to the visibility into their apartments during private activities such as changing clothes after a shower (see Transcriptions A, C, D).

4.8.3 Impact of Light on Sleep

Common Theme: Exposure to early morning light disrupts sleep patterns, with several participants reporting waking earlier than desired due to inadequate curtain coverage.
Specific Insight: Despite existing curtains, light penetration in the mornings suggests a need for more effective light-blocking solutions (see Transcriptions A, C).

4.8.4 Curtain Use and Satisfaction

Common Theme: Current curtains fail to adequately meet the dual needs for privacy and light control.
Specific Insight: Participants showed interest in the proposed dual-section curtain design, which offers adjustable light control while maintaining privacy, signaling support for innovative solutions (see Transcriptions A, D).

4.8.5 Seasonal Changes and Lighting Needs

Common Theme: Residents face different challenges with artificial and natural light across seasons, affecting their comfort and daily routines.
Specific Insight: In winter, the lack of sufficient natural light leads to increased reliance on artificial lighting, which fails to meet ambient lighting needs (see Transcriptions A, D).

Chapter 5

Discussions and Conclusions

This chapter synthesizes the key findings, discusses their implications, and provides conclusive insights based on the observational study.

5.1 Discussion of Findings

The overall effect across all conditions suggests that low illuminance levels during Civil Twilight, combined with resident habits, generally do not alter sleep patterns relevantly enough to disrupt circadian rhythms. Despite the observed lack of a relevant correlation between twilight light exposure and sleep patterns, the implications for architectural design and urban planning are profound. The proposed dual-section curtain design demonstrates considerable promise by providing adjustable light control while maintaining privacy, addressing the substantial need for improved light-blocking solutions in residential environments [4]. These findings align with the United Nations' Sustainable Development Goals, particularly Goal 3 (Good Health and Well-being) by aiming to enhance individual well-being through improved sleep patterns, and Goal 7 (Affordable and Clean Energy) by promoting energy-efficient lighting solutions that contribute to sustainable architectural design.

Metrics such as Daylight Autonomy (sDA) and Annual Sunlight Exposure (ASE) have provided quantifiable insights into the efficacy of indoor lighting setups, corroborating residents' feedback concerning excessive brightness and underscoring the need for tailored lighting solutions that align more closely with human circadian biology [2]. The study's findings concerning the variability in illuminance levels before bedtime across different rooms, particularly those with higher average illuminance levels, highlight the critical need for environmental adjustments to mitigate excessive light exposure that can disrupt circadian rhythms and impair sleep quality [28].

Moreover, the variations in room temperature in response to different light exposures during twilight periods reflect the complex interplay between architectural design elements and their thermal and optical performance, suggesting the building's thermal mass plays a relevant role in influencing indoor environmental conditions [31].

5.1.1 Integration of Theoretical Insights

The circadian system's sensitivity to light, a crucial zeitgeber, as discussed in the theoretical background, is evident in the study's findings, which underscore the importance of managing light exposure to support the circadian health of urban residents [3]. The study aligns with historical and contemporary circadian rhythm research, illustrating the persistent influence of natural light on human physiological processes [19].

5.2 Limitations and Future Research

5.2.1 Limitations of the Study

The primary limitation of this study was its confined duration—spanning only 10 days from May 6th to May 16th—within a single season. This constraint substantially limits the generalizability of the results across different times of the year and under varied environmental conditions [22]. Furthermore, while the study utilized basic light sensors, the absence of biometric sensors to track physiological responses limited the depth of insight into the residents' circadian rhythms and overall health. An expanded sensor array, including advanced spectrometers, would enable a more detailed and comprehensive mapping of light quality and intensity.

5.2.2 Future Research

Future research should extend beyond the current study's scope and technological integration. A longitudinal, multi-site study across various latitudes and seasons would help generalize the findings and provide a more global perspective on the interplay between light exposure and human health. Integrating a broader array of biometric and environmental sensors would enhance the granularity and accuracy of the data collected, enabling researchers to draw more precise conclusions about the physiological and psychological effects of lighting environments.

5.2.3 Proposal for Future Study on Curtain Behavior

A proposed study on the dual-section curtain design could explore its efficacy in enhancing privacy and natural light management in residential settings, contributing to improved living conditions and well-being. Such a study could examine the behavioral aspects of curtain usage, correlating positional data of the curtains with illuminance data captured by internal sensors to gain valuable insights into resident behaviors and preferences.

5.3 Recommendations

During the evening, starting at least three hours before bedtime, it is recommended that the maximum melanopic Equivalent Daylight Illuminance (EDI) does not exceed 10 lux, measured at eye level in the vertical plane at approximately 1.2 meters height. To achieve this, it is advisable to use white light with a spectrum that is depleted in short wavelengths, particularly those near the peak of the melanopic action spectrum [30].

5.4 Conclusions

The findings of this study provide foundational insights into the impact of lighting on residential well-being, with implications for future research and practical applications in architectural lighting design. By integrating scientific insights into practical applications, particularly in building design, this research underscores the potential for creating environments that enhance human health and productivity.

Aligning architectural designs with circadian health research offers a promising pathway toward environments that naturally support human biological rhythms, enhancing overall well-being. Continued interdisciplinary research and collaborative efforts are crucial for realizing these goals, ensuring that our living spaces evolve to meet both our physiological needs and environmental challenges.

Future initiatives should focus on enhancing the integration of circadian health insights into practical applications, fostering environments that nurture rather than negate our inherent biological rhythms, and promoting sustainability and well-being in tandem.

Chapter A

Appendix A: Research Instruments

Important, but complementary material/results will be placed in appendices.

A.1 Plots

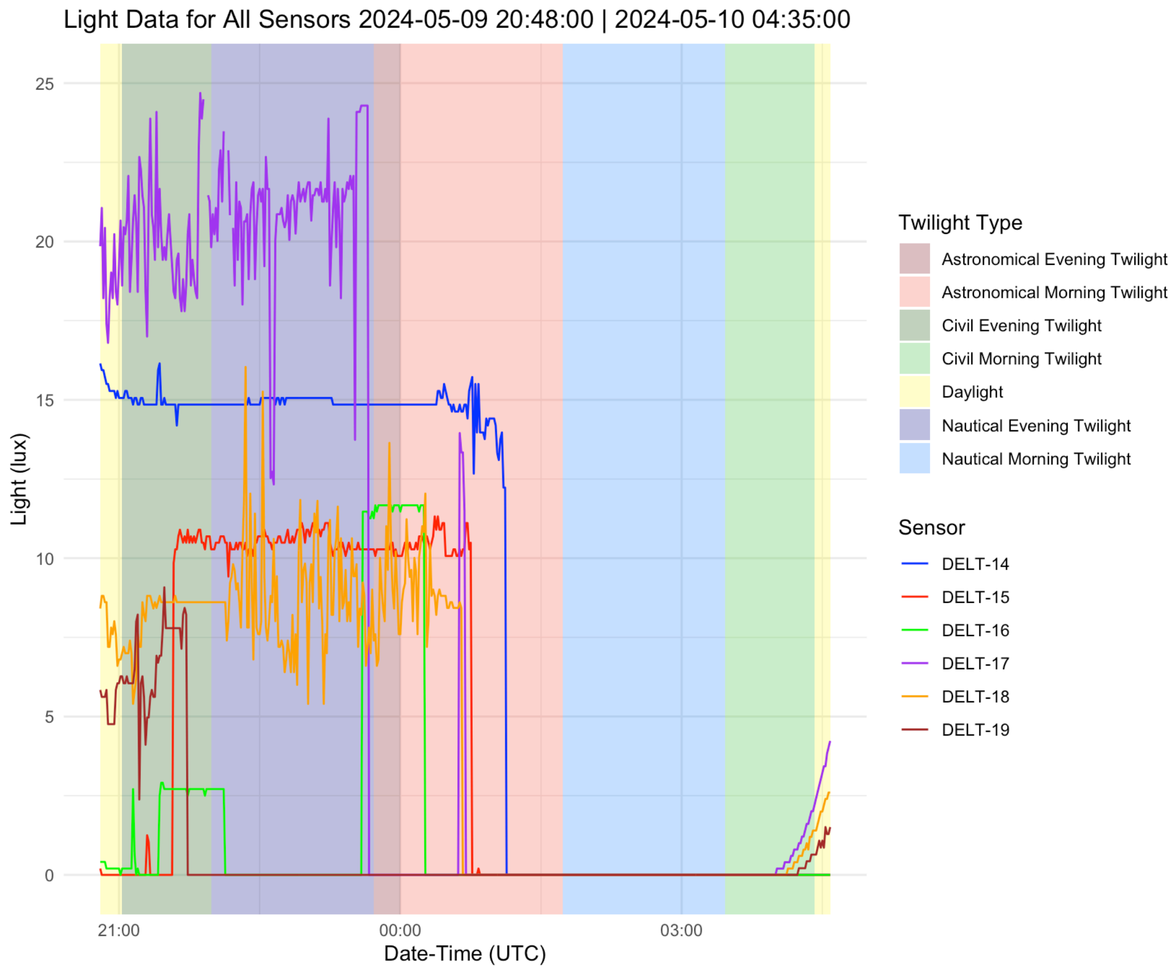


Figure A.1.1: Light Data for All Sensors from 2024-05-09 20:48:00 to 2024-05-10 04:35:00 (UTC). This plot displays the light intensity measurements captured by six different sensors (DELT-14 to DELT-19) over the course of the evening and early morning hours. The background colors correspond to different twilight types and daylight, illustrating how ambient light levels change across these periods. Notably, the graph shows how light intensity varies relevantly among sensors during twilight transitions and stabilizes as it approaches and enters the daylight phase. This visualization aids in understanding the differential response of each sensor to the natural light conditions, which can influence indoor lighting strategies and circadian rhythm synchronization.

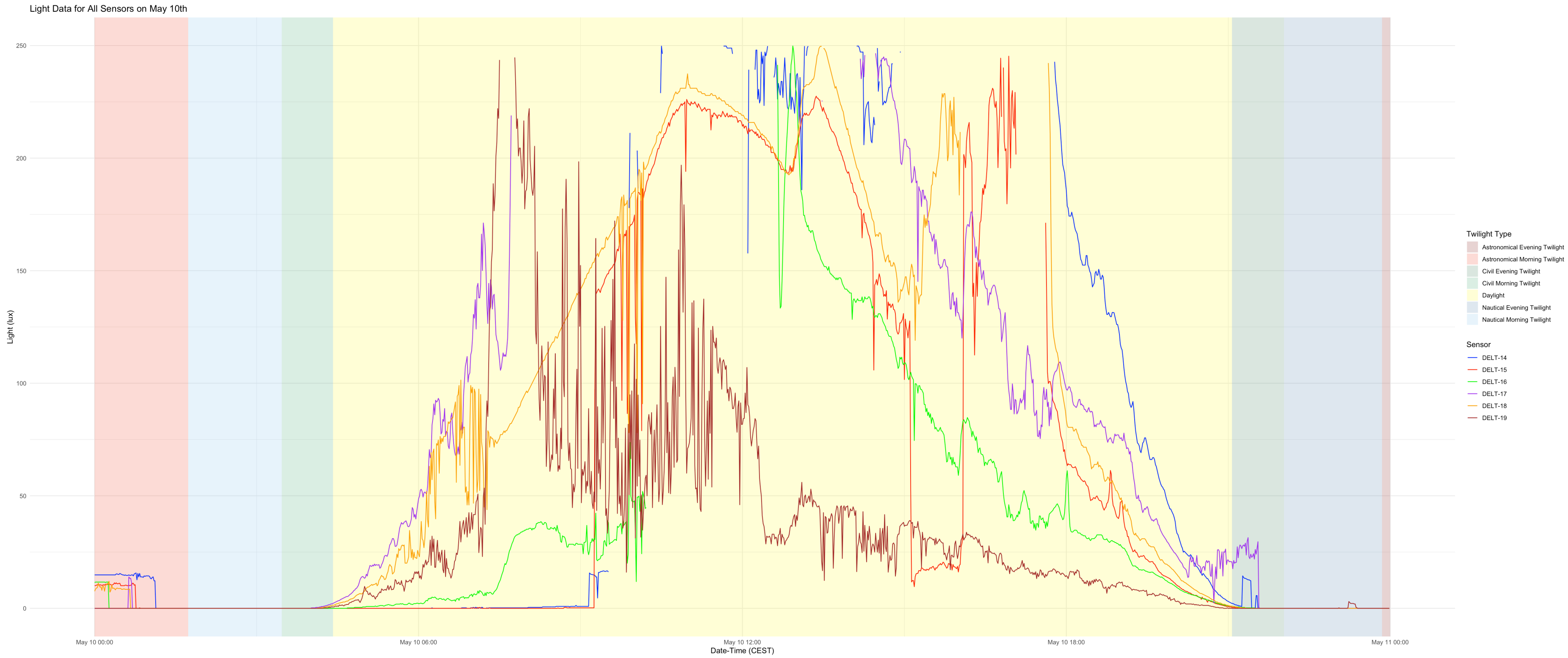


Figure A.1.2: Light Data for All Sensors on May 10th. This comprehensive plot tracks the changes in light intensity detected by sensors DELT-14 to DELT-19 throughout the day, overlaying these variations against the backdrop of different twilight phases and daylight. The colored background bands mark the periods of Astronomical, Civil, and Nautical Twilight in both morning and evening, alongside full daylight exposure. This visualization helps illustrate the dynamic nature of environmental light across different phases of the day and its potential impacts on indoor lighting conditions and human circadian rhythms.

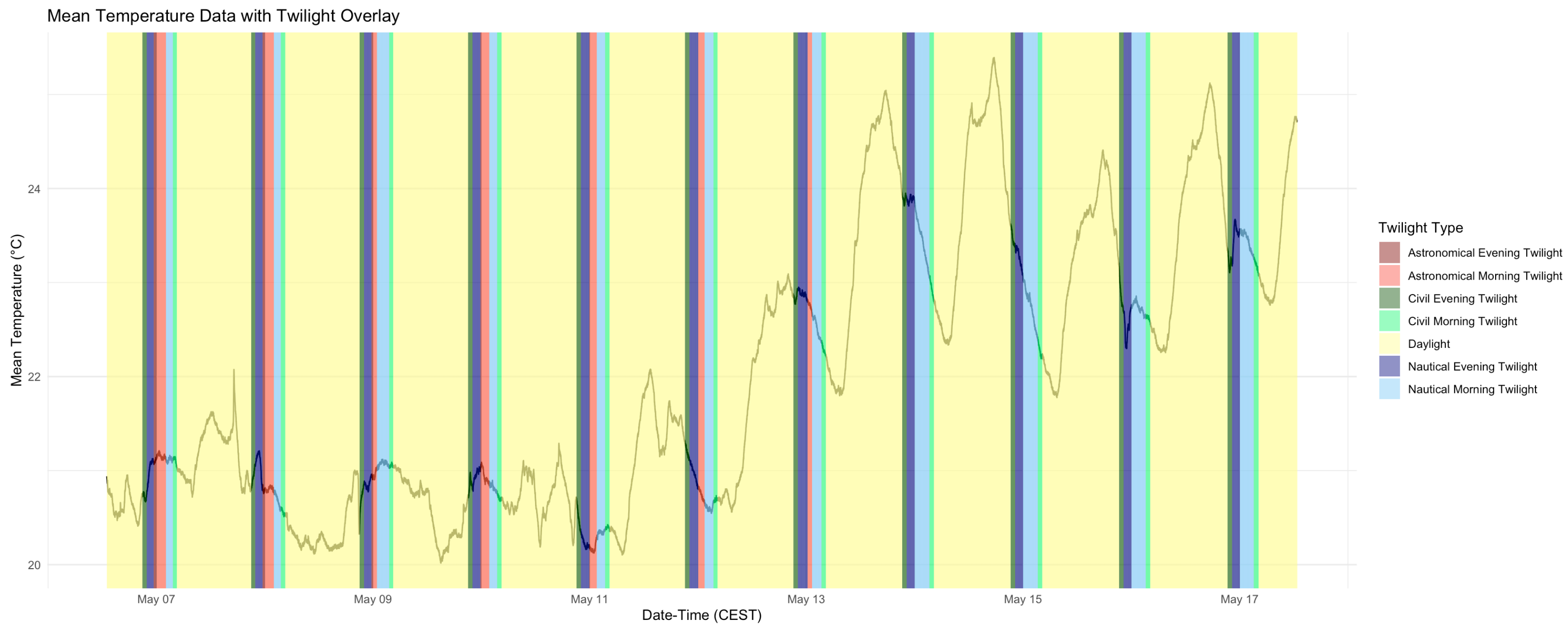


Figure A.1.3: Mean Temperature Data with Twilight Overlay. This plot illustrates the mean temperature trends over time at the KTH Live-in Lab, superimposed with twilight type indicators. The vertical colored bands represent different types of twilight—astronomical, nautical, and civil—both in the morning and evening, as well as full daylight periods. Notably, temperature fluctuations correlate with changes in twilight phases, suggesting potential impacts of natural light variations on indoor temperature dynamics.

Chapter B

Appendix B: Interview Transcripts

This section documents the semi-structured interviews conducted on May 9, 2024, from 16:00 to 18:00. These interviews were designed to gather qualitative data on participants' experiences and perceptions related to the lighting conditions within the KTH Live-in Lab. The interviews aimed to deepen our understanding of how the built environment affects residents' daily lives and well-being, particularly in relation to artificial and natural light exposure. The insights gathered are integral to interpreting the quantitative data collected through sensors and contribute to a holistic understanding of the impact of lighting design on human behavior and health.

B.1 Interview Framework

Twilight's Role in Enhancing Sleep Quality and Daytime Well-being Interview Questions:

General Experience with Lighting at KTH Live-in Lab:

1. How would you describe your overall experience with the lighting conditions in your residence?

2. What do you like most about the current lighting setup?

3. Are there any aspects of the lighting that you find unsatisfactory or that could be improved?

Perception of Lighting Effects on Daily Activities:

1. How do you feel the lighting affects your daily activities such as reading, cooking, or relaxing?

2. Do you notice any changes in your mood or productivity levels based on different lighting conditions throughout the day?

3. How often/how long are you normally exposed to daylight?

Suggestions for Improvement:

1. What changes or enhancements would you suggest to improve the lighting conditions based on your personal experience?

2. Are there specific times of day when you feel that adjustments to the lighting could enhance your well-being or comfort?

Environmental Optimization for Better Sleep

(scale from 1-8)

1. Do you find the temperature in your bedroom comfortable?

2. Do you find the noise level in your bedroom comfortable?

3. Do you find the lighting in your bedroom comfortable?

Discussion on Sleep Routines and Comfort Aids

1. Do you use any blackout curtains, or eye masks to help you sleep beler? Is it for privacy or for the light?

Morning Wake Up and Sleep inertia

1. Do you use an alarm to wake up? How often do you hit the snooze button?

2. Do you notice chances in your sleep quality throughout the seasons?

Feedback and Additional Support

1. Was the information we discussed today helpful for you? Is there anything else you would like to know about improving sleep?

2. What other types of support or resources do you think would help you sleep beler?

Conclusion and Thanks

Thank you for your participation! Your insights are crucial for our ongoing efforts to improve living conditions in the KTH Live-in Lab.

If you have any further comments or wish to discuss any specific points in more detail, please feel free to share.

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Figure B.1.1: Interview framework

B.2 Interview Transcripts

These interviews provide in-depth qualitative data on participants' perceptions and experiences with the lighting conditions and privacy aspects in their residences at the KTH Live-in Lab.

B.2.1 Interview Transcript A

Interviewer: LDC **Participant:** A **Date:** May 9, 2024 **Location:** KTH Live-in Lab

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LDC: How would you describe your overall experience with the
   lighting conditions in your residence?

A: I think it's fine but it could be improved. I mean, at least in
   the first months, like in the winter, it felt really dark. Yeah,
   and when you were studying, you felt sometimes that there wasn't
   enough light in your room, maybe. But I would say that it's quite
    cozy, the light, because it's like hot light. So, yeah, it's
   like orange and that stuff. So, it's fine.

LDC: Do you study in your room?

A: Yeah, I usually study in my room. So that's why in winter, I felt
    like sometimes there was not enough light. I felt like it was
   very cozy. But yeah, sometimes we missed a bit of light in the
   room.

LDC: How do you feel the lighting affects your daily activities such
    as reading, cooking, or relaxing?

A: I would say that the relaxing part, no, because as I said, it was
    cozy, so it was relaxing. But yeah, when I had to study, maybe
   it was, maybe too relaxing, so I felt like, I felt a bit tired.
   So I couldn't really study or have a good session of study. But
   yeah, overall, I think it was fine. The worst thing is like the
   curtains and everything, so when we asleep, that some light come
   through. Yeah, I think that's the main issue. I mean, in winter
   it's fine because not so much light pass through the window. So
   it's fine, but now in the mornings, you can wake up because of
   that. Because you are just sleeping and suddenly, you just turn
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around and just see all the light in your room and everything. So it can be a bit disturbing.

LDC: Do you use an alarm to wake up?

A: Yeah, I usually wake up with an alarm. But now I feel like I wake up earlier because of the sun. I think, and I feel a bit more tired, I would say.

LDC: How come you feel a bit more tired?

A: Yeah, because I wake up like that when the sun is rising. So I check, like there's light in my room, so I cannot go back to sleep. So I wake up, I struggle a bit to sleep back.

LDC: Do you use any blackout curtains, or eye masks to help you sleep better?

A: I don't use anything. Only like earplugs.

LDC: How so, is it noisy?

A: I think in my room there's like ventilation system. And that makes a little noise. But also we have different schedules like the four of us. So maybe I hear them maybe a bit in the morning. But yeah, it's not so bad. I think it's mainly because of the floor. Because as you know under the floor there's nothing. So it 's just air. So it's like if I stomp with my foot, it sounds a bit... But I think it's fine.

LDC: How often and how long are you normally exposed to daylight?

A: It really depends on what I'm doing on my day. But I will sit out every time there's a bit of sunlight. I go out. Yeah. As I'm from Spain, from Madrid. So yeah, in the center of the country. So yeah, whenever there's some light, with my housemate, we always go out. Just enjoy it with the sun or just to feel better.

LDC: It's your first year in Stockholm?

A: Yeah, in Sweden.

LDC: How do you find the changes in seasons here in Sweden?

A: I will say in winter is cold and dark. But yeah, we felt it was a bit dark for us. And we're more used to having more sunlight in the street and different schedule as well. So that could disturb us a bit. Now I feel it's very good because in the evenings it's not so bad because you have a lot of sun till like 8, 9 pm. So it 's fine. But we find it's starting the opposite. Like at 4, 5 am the sun's rising. So yeah, we don't like that. And because of the curtains, finally I will say. Yeah, they don't block so much.

LDC: Do you use an alarm to wake up? If so, how often do you hit the snooze button?

A: I usually use the alarm on my phone. Snooze at least a couple of times. That's why I have to put it like sooner than what I really want to go. Or when I really need to go and do all this stuff. So I had to put that 50 minutes earlier than what it should be.

LDC: Do you notice changes in your sleep quality throughout the seasons?

A: Yeah, I would say that in winter, I felt more tired. Yeah, and also I wanted to sleep like, do like napping. And that stuff. I felt like when I came back from university, I felt like it was okay to just go napping. But now I don't think I've set many naps . I don't have so much.

LDC: Are there any aspects of the lighting that you find unsatisfactory or that could be improved?

A: I would like... But I think it's more... Talking about my room. I would like a bit more ambient light. Like... Yeah, it felt like sometimes it was just a big light. Even though you can regulate it, it felt like too much light from top to the ceiling. And maybe I would like more to have like many other sources of light instead of just one. But... Yeah, I think I'm fine with the rest. I would say that there's always the same problem that in the winter there's lack of light. Maybe now we don't feel it so much. But yeah, back in the winter I can remember that 3pm it was very dark. And then we had to put like the big lights in order to have enough light just to study it, to be cool to whatever.

LDC: Do you have any concerns regarding privacy?

A: Yeah, I would say that at first, the first month it was quite weird to see so many people passing by while having breakfast in your pajamas. And you even know that everyone was watching you because I mean... So you can watch them and they can watch you. So that was a bit weird. But then you get used to it. I think... Or at least you don't pay much attention to. That's happening. But yeah, I would say that was a bit weird.

LDC: What about in your room?

A: Yeah, that's also weird because maybe I was taking a shower and I get out, I want to change. Then I have to close everything so I don't feel like I have that privacy. I have to close the curtains in order to change and everything. If you are like in another floor or whatever, you don't care as much. But here we're at the ground level, everyone goes here. And other people pass by also because it's the universities. Yeah, a lot of people pass by and it felt really awkward.

LDC: What do you think of this design suggestions for the curtains (LDC shows Figure 4.6.2) of the design proposal).

A: Yeah, I mean that looks like a big improvement. I think that's a great idea also if you can completely blackout the room. And with a dual mode you have your privacy, you don't have to open everything and you just have some light. Because it's true that when I came from the shower and I curtains I blocked the light and I need to turn on the artificial light.
So yeah, you're right. I think that will be nice.

LDC: Great! Thank you for your participation! Do you have any questions?

A: I was thinking like what do the sensors you installed actually measure?

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LDC: The Hobo I installed measure Illuminance and temperature.

A: Are you also using any other sensors that are already installed
   in the house?

LDC: Yes, CO2 and Pressure Sensors. Hopefully we will be able to use
    Occupancy and Luminous Intensity sensors.
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B.2.2 Interview Transcript B

Interviewer: LDC **Participant:** B **Date:** May 9, 2024 **Location:** KTH Live-in Lab

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LDC: How would you describe your overall experience with the
   lighting conditions in your residence?

B: I mean I would say it's been good, but I mean the problems I may
   have had with lighting is not so much with the house itself, but
   with the fact that here in Sweden in the summers we have light
   since very early in the morning. But the house itself I wouldn't
   say we've had, or at least I haven't had, many problems with it.

LDC:Are there any aspects of the lighting that you find
   unsatisfactory or that could be improved?

B: Maybe my room I could have slightly more artificial light or one
   closer to the bed at least.

LDC: How do you feel the lighting affects your daily activities such
    as reading, cooking, or relaxing?

B: I can do everything normal.

LDC: Do you notice any changes in your mood or productivity levels
   based on different lighting conditions throughout the day?

B: I would say if the sun is out and we have a lot of light coming
   in, I would say my mood is better and  that there's a huge
   difference in the winter. I mean I just feel a bit happier with
   the light.

LDC: How often and how long are you normally exposed to daylight?

B: I don't say every day and for how long it really depends. If it's
    sunny, way more. Yeah, every day at least one hour, and indoors
   I always have my curtains open, so more light coming in.

LDC: Do you always leave the curtain open?

B: Yes, except at night or if I'm taking a nap or something.
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LDC: Do you have any concerns regarding privacy?

B: I did it at the beginning, but then I just got used to. If someone looks and see something that they didn't want to see, it's their problem. They shouldn't be looking at in the first place.

LDC: Do you find the temperature in your bedroom comfortable?

B: Yeah, I do. We have the heating, I think it's like central, so it depends on the building. And in some days it's super high and others is super low, but in general I would say I'm happy here.

LDC: Do you find the noise level in your bedroom comfortable?

B: Yeah, I'm so far. The only issue with the noise is when the trash truck comes in the morning, so it's 7 a.m. But that's because they park in front of my window. I think it's just bad luck.

LDC: Do you use any blackout curtains, or eye masks to help you sleep better?

B: No.

LDC: Do you use an alarm to wake up? If so, how often do you hit the snooze button?

B: I use the one on my phone. Wonderful. Snooze button maybe one time, but not every day. I usually do very good with that. And I just wake up that won't happen.

LDC: Do you notice changes in your sleep quality throughout the seasons?

B: I wouldn't say so, at least not super, not so. Well now I'm waking up a bit more in the mornings, like earlier, because of the early sunrise. But I could just go back to sleep. I usually don't have a lot of problems with that. Overall throughout the whole night, I would say it's more or less the same.

LDC: Do you have any questions you would like to ask me?

B: No, I wouldn't say. Maybe. I don't know if this is a thing, also in other countries. ("B" shows a picture of a window shutter on the phone), but in Spain we have these kind of things. I think they would be great here in Sweden.

LDC: What do you think of this design suggestions for the curtains (LDC shows Figure 4.6.2) of the design proposal).

B: It's interesting, very interesting.

LDC: Great! Thank you for your participation!

B.2.3 Interview Transcript C

Interviewer: LDC **Participant:** C **Date:** May 9, 2024 **Location:** KTH Live-in Lab

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LDC: How would you describe your overall experience with the lighting conditions in your residence?

C: I think of it in my room. It's like the light in the morning. It gets very bright, which I think makes sleeping a bit harder. And, um, I mean, otherwise I like that we have like so many windows, so many big windows. And, um, I mean, I'm not sure if it's like also, I mean, do you also want me to talk about like how the lighting was in the winter?

LDC: Yes, anything you want to talk about.

Yeah, yeah, because of the winter it was like very dark, but I mean, I'm not sure if it's like specifically about the living situation here, but more just in Sweden, basically, but it's like a little bit. I think the artificial light is just normal. I don't know, it's not specifically worse or specifically better than what I'm used to.

LDC: You were saying about the lighting in your room gets very bright, Do you use any blackout curtains, or eye masks to help you sleep better?

C: I do have curtains and I also close them, but still in the morning it gets very bright, and I usually wake up in the morning because of it and then try to go back to sleep again.

LDC: Do you use an alarm to wake up? If so, how often do you hit the snooze button?

C: Well, if I have lectures or something I use the alarm clock, but if I don't have things to do, I just wake up naturally. As for now I would like to sleep longer but because it gets very bright very early. Don't use the snooze button.

LDC: What do you like most about the current lighting setup?

C: I like that we have such big windows, especially in the kitchen, like in the morning, when the sun shines, it's like very nice to have like the sun just completely shining into the kitchen.

LDC: Are there any aspects of the lighting that you find unsatisfactory or that could be improved?

C: I think, but I mean in my room maybe the curtains could be made better somehow, or like, like have like a different system for it , so that it stays darker. And also I think like what I haven't mentioned yet, but like also there's like some light that goes through the ceiling, basically. And yeah. So like I think the thing that I would most want to be improved is that the rooms are really dark if you want them to be dark.

LDC: What do you mean that some light goes through the ceiling, does it spill in from the outside?

C: No, no, no, no. Like I don't know like two tiles in my room, like the light shines through them. From above. Yeah. I don't know. I mean it's just shining like from outside on it. Because it's like glass above the ceiling, right? Like the walls were made of glass.

LDC: How do you feel the lighting effects your daily activities such as reading, cooking, or relaxing?

C: Not really

LDC: Do you notice any changes in your mood or productivity levels based on a different lighting condition through the day?

C: Ah through the day. I mean through the day not really I would say , but I mean it's definitely nice to have sun again, basically, like compared to not having much sun, winter. I mean that's just general for Sweden I guess.

LDC: How often and how long are you normally exposed to daylight?

C: I mean I usually go outside once a day at least. Once a day. I would say. I mean not that much outside maybe like 30 minutes, something. That's an average day.

LDC: Do you find the temperature in your bedroom comfortable?

I did notice that like now, like when the sun is shining, my room heats up quite a lot. Maybe because like the sun directly shines into my window into my room. And yeah, so I think I checked with temperature once and it was like 24.5 or something. So yeah. And I also felt like that in the winter this apartment in general was like a bit cold maybe.

LDC: Do you find the noise level in your bedroom comfortable?

C: I mean, I think in general it's fine, the noise level. Sometimes when I'm trying to sleep and like when people is on vacation and like they're here listening to music like you can hear it a little bit but it's fine for sleeping. But it's kind of on the edge what I feel.

LDC: I'm going back to the curtain topic. Do you use any blackout curtains, or eye masks to help you sleep better?

C: No, I don't use any. I mean, I just use the normal curtains.

LDC: Do you have any concerns regarding privacy?

C: Yeah, I mean, I think in the like in the beginning in the kitchen I felt a bit weird about it because there were like a lot of people just walking by and looking inside but I'm kind of used to it by now. So I don't really mind it that much. And then in my room I don't think so. Like I also have like a little like a little view blocker on my window.

LDC: Did you install it yourself?

C: No, no, it was there. It was just like so you can't see that well through it.

LDC: Do you notice changes in your sleep quality throughout the seasons?

```
I mean, I think that I slept better in winter and I think the main
   reason for that is because now I'm waking up in the morning early
    when the sun shines and I'm not used to having that much light
   in my room in the morning.

LDC: What do you think of this solution for the curtains? (LDC shows
    Figure 4.6.2)

C: I think personally it wouldn't really matter to me. I think it's
   not important to me because like I feel like in my room I don't
   mind it like having a little bit of people like outside and I
   think in the kitchen it's also fine. Like I would rather have
   more daylight and stuff than closing the curtains like,
   especially during the day. Yeah, so yeah. But it would be maybe
   nice to have like different curtains.

LDC: Thank you for your participation! Do you have any questions?

C: I don't really have any questions.
```

B.2.4 Interview Transcript D

Interviewer: LDC **Participant:** D **Date:** May 9, 2024 **Location:** KTH Live-in Lab

LDC: How long have you been living in Sweden for?

D: Since August. Almost a year.

LDC: The project research focus on light, and the questions will be focusing mainly on the light. How would you describe your overall experience with the lighting conditions in your residence?

D: I think it's really good like you get a lot of daylight in here. So for me the only point was that since we're living in the ground floor, and you have to like large windows, you don't always really want to open the curtains. And then it's pretty easy to look into the apartment. But as soon as you open them, it 's really nice. And since you get a lot of normal daylight, yeah, and like just otherwise in general, I'm not always the biggest fan of those normal headlights, I prefer like a little bit of a warmer light if you know what I mean. But yeah, in general, pretty happy.

LDC: What is the downside of opening the curtains to let the light in?

D: For me personally, it's mainly the privacy issue. Otherwise, I would probably have them open pretty much all the time, I guess. But especially when you're sleeping or maybe sitting on your bed or something, there are quite a lot of people walking by.

LDC: How do you feel the lighting affects your daily activities such as reading, cooking, or relaxing?

D: You mean like the natural light or the artificial light?

LDC: More about the lighting conditions like... can you accomplish the tasks you need to do? If not how would you improve it?

D: I can do pretty much anything I want. What I did personally was to buy myself a small lamp near the bed. It's easier to read because otherwise, don't think there's specific light design for that, especially in the evenings. Like, when you want to read something, I'm not the biggest fan of the big headlights. And when you've been up all night, it's kind of nice at work to have more concentrated warmer light from the side. Otherwise, in the kitchen, it's really good, I'd say, also since we have the lights under the shelf, and then you have the normal headlights so that makes a good combination, I'd say. And then here (LDC and Participant D are sitting in the living room), it's also pretty good. Like, also with this kind of lamp (Participant D point at a furniture lamp), it's really nice to watch a movie and you don't always have to have that light (Participant D refers to the ceiling light).

LDC: Did you notice any change in mood or productivity based on the different lighting conditions during the day?

Not really, I'm completely honest, I'm also not super often here during the day. Since then, I try to go to university in the library or something as I prefer having, like, kind of trying to separate a little bit workspace and getting home. I mean, it's just a general that you notice when it's winter yet. Overall darker, then you really notice a difference in productivity, otherwise, I didn't have a big issue, or don't see a big difference with concerning the lighting in the day.

LDC: You were mentioning the dark winter and the difference in productivity. What do you mean, can you elaborate more on, like, if you were to compare it with other seasons?

D: I would say I'm usually getting up fairly early, like, around seven-ish. By the soon as it got dark, I realized that I just slept longer without significantly changing... I was harder to get up at seven, so I just felt different. That's the issue. So then, you know, I kind of just adapted my day a little bit to that day. Maybe studied a little bit longer in the end, which is then fine, but for me, it was a little bit unusual and also a little bit annoying since I kind of like to get up early and start early in the morning. And then I always felt a little bit weird than getting up at nine or ten, just... Now I feel like it' s actually also because of the seasons, because now it's comfortable again for me to get up quite early.

LDC: How often and how long are you normally exposed to daylight?

D: Hmm... It's a good question. I would say every... Of course, every day, since you're kind of always going out to different lectures, going grocery shopping for the standard stuff. Especially when it was a little bit darker, we always tried to at least go during lunch, or after lunch for like half an hour, when you had some sunlight, tried to go out to catch some of the sun. Then we went maybe for a walk for like 45 minutes before we continued studying. So, yeah. It's hard to give an average of...

LDC: What changes or enhancements would you suggest to improve the lighting conditions based on your personal experience? You already mentioned that you bought yourself a small lamp to read, right?

D: Yeah, I think that could be really helpful, something like this. We also all have desk lamps, I think, so that's good there. Yeah, I mean, the question is maybe, especially for the winters, could be helpful to have a couple of... Especially then in the kitchen , or here to have those... ...daylight lamps that give a little bit more of a daylight to give you a feeling that it's a little bit brighter than it actually is.

LDC: What do you mean by having more daylight in the winter?

D: It's just like sometimes... Not maybe not daylight, but... ...I'm just like those, if you have some where those warm light, not those headlights, but the warm lights that just give a nice ambient atmosphere. Which is just for me a nicer to the eye, which just doesn't change anything about what you can accomplish or not, but it just... ...like once you enter a room, it just gives me an eyesight atmosphere, then having those brighter, colder colors that you sometimes have.

LDC: Oh, I see what you mean. Do you use candles?

D: Not really. At home sometimes, we used sometimes candles, and then we dimmed off all the lights. Also, we kind of had dimmers, which then where you can just pretty much reduce the light, and it just gives... ...have a nice atmosphere, actually.

LDC: In terms of tasks, does the lighting support the tasks visibility for example?

D: Yeah, I can accomplish everything with that. I have no struggles.

LDC: Would you prefer to have a smart lighting controls and fixtures ?

D: Like the dimmers, or where you can reduce the light...?

LDC: Perhaps controls operated with a phone or other devices?

D: Not the biggest fan of having it then controlling everything with your phones, and then you're like... ...with that you always increase your phone time even more. So, it's kind of nice to have some... ...like also the classic lights switch, which are for me no problems. So, that would be... ...for me it's not necessary to have any phone control or something like that.

LDC: How do you find the light controls in this residence?

D: The controls are really good.

LDC: Let's talk about temperature. Do you find the temperature in your bedroom comfortable?

D: Yeah, that's really good here.

LDC: Do you find the noise level in your bedroom comfortable?

D: Yeah, I'm also... I'd say especially when you... ...of course when you open the window you kind of have to expect that it's a little bit louder, but especially as soon as you close it... ... it's actually really good isolated.

LDC: Do you use any blackout curtains, or eye masks to help you sleep better?

D: No. I also don't really have sleeping issues I would say. I had barely like... ...once I fall asleep or sleep through the night. That's not a big issue for me in general.

LDC: Does it bother you the light in the morning coming through the windows ?

D: No, it doesn't bother me also. When you... ...will be interesting to see how it is when it actually... ...when we go to June where the days are actually really long but so far... ...if I wake up naturally by the light I'm also kind of happy that I don't have to wake up. Because it gives you some... ...nice not to wake up by an alarm but somewhat by yourself. I always feel a little bit better during the day.

LDC: Do you use an alarm to wake up?
D: Yeah. But even if I don't set an alarm right now my rhythm is back to that... ...I would probably wake up 15-20 minutes later anyway. So once you're kind of in one bio rhythm... ...then you feel you used to it and... ...just the alarm helps but it's not 100% necessary.

LDC: Do you notice chances in your sleep quality throughout the seasons?

D: No, not actually not now. Always felt very similar. Just that as I said that I just felt that I slept a little bit longer... ... but the quality of the sleep seemed to be very similar.

LDC: I wanted to show you an idea for the curtains. So the current curtains are like this one, just one piece (LDC shows Figure 4.6.2). Yeah. And one suggestion would have been to have two pieces... ...and one which you can open up for daylight... ...and one to keep maybe more privacy in these things. And then when you have only one... ...then you can still close but still have the daylight coming in.

D: Yeah, that would be really good actually. Especially like this split would be very good. Like a vertical one. I mean this is almost open. And you can have all open it or just close it all. I would like that.

LDC: Thank you for your participation! Do you have any questions?

D: No, nothing. In particular what is exactly your background?

LDC: My background is in Art and Light Design. I'm currently studying the Architectural Lighting Design MA course here at KTH .

LDC shows diagrams of the Daylight (Figure 2.4.1a)

So for example, the observation takes place in the period between from the 6th to 16th of May. And this diagram shows the astronomical, nautical and civil Twilight. Twilight is when the Sun is below the horizon, depending on it's position the type of twilight, between 18 and 8 degrees below the horizon is called astronomical, between 12 and 8 degree is called nautical, and between 8 and 0 degree is called civil.

We are currently without night time (LDC shows Figure 2.4.1a), the darkest we get is astronomical twilight but it's decreasing. By the 16th May the duration of the Astronomical Twilight will be 0 minutes , like you were saying, the days are going to be brighter .

And if you are interested here you can see the daylight duration in Stockholm during the all year (LDC shows Figure 2.4.1a). The yellow part is the daylight. The x axis shows the durations in hours, the y axis the period of the year. So in Stockholm in January the minimum amount of daylight during the Winter Solstice is around 6-7 hours, and then in June for the Summer Solstice it becomes, I think, 18-19 hours of daylight or something like that . But check out the differences between Quito, New York, Stockholm and Tromso for example (LDC shows Figure 2.4.1c). Places situated at different latitude.

D: Quito during the year doesn't change much. While New York is more organic in a sense.

LDC: True! We are observing this period now (LDC highlight on the plot the period). Thanks a lot for your time!

Chapter C

Appendix C: Participant Consent Form

The consent form used for participant agreement to partake in the study is included here to document the ethical procedures adhered to during research.

Twilight's Role in Enhancing Sleep Quality and Daytime Well-being

Information for participants

Dear Live-in Lab Residents,

We invite you to participate in a pioneering pilot study, "Twilight's Role in Enhancing Sleep Quality and Daytime Well-being," led by Lucio Domenico Cavallari. In this document you will receive information about the project and what it means to participate.

What kind of project is it and why do we want you to participate?

Our research investigates the effects of twilight on sleep quality and well-being. As part of this study, we're conducting a pilot test in the Live-in Lab, offering a unique opportunity to contribute to innovative research that combines architectural lighting design with circadian health insights. Your participation will contribute significantly to understanding how environmental conditions, specifically lighting, impact sleep and well-being. This research could lead to improved architectural lighting designs that support circadian health, offering personal insights into sleep habits and the potential benefits of lighting optimization.

The principal researcher for the project is Lucio Domenico Cavallari. Research principal means the organization responsible for the project.

Thesis coordinator: Federico Favero, ABE School of Architecture and Built Environment, KTH Royal Institute of Technology

Tutor: Professor Myriam Aries at Jönköping University.

Contact Information: Lucio Domenico Cavallari Tel: [redacted] Email: ldca@kth.se

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Figure C.0.1: Consent Form page 1.

Twilight's Role in Enhancing Sleep Quality and Daytime Well-being

Project Duration and Schedule:

Starting Date: May 6th 2024

End Date: May 16th 2024

Sensors installation: May 6th 2024 **Time required:** 1h

Light measurements: May 8th 2024 **Time required:** 1h

Twilight Observation: 6th May - May 16th
Observing current light scenarios and collecting environmental data using existing and planned enhancements in sensor technology.

Participant Engagement:

Daily Diary Entries: Participants are encouraged to log their sleep and well-being daily throughout the observation period. This continuous input will provide valuable insights into the residents' experiences and the impact of the current lighting setup.
Time required: ≤2min each day

Interview: May 6th - May 10th, 2024
One session per resident aiming to collect information on participants' sleep, well-being, and environmental influences. **Time required:** 1h per resident

Data Collection and Sensors:

For the ongoing study, KTH Live-in-Lab facility is equipped with a range of sensors to monitor environmental and usage parameters comprehensively. The currently installed sensors we will analyze include:

- Air Temperature Sensor: Measures ambient temperature to assess comfort levels.
- CO2 Sensor: Monitors carbon dioxide levels, indicative of air quality and occupancy.
- Occupancy Sensor: Detects presence to analyse space utilisation.
- Luminous Intensity Sensor: Measures light levels to ensure optimal lighting conditions.
- Relative Humidity Sensor: Assesses moisture in the air for comfort considerations.
- Electricity Usage Sensors: Records electricity consumption for specific circuits/groups such as stove, fridge, lights, and sockets to understand energy distribution.
- Water measurement: Records of water consumption.

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Figure C.0.2: Consent Form page 2.

Twilight's Role in Enhancing Sleep Quality and Daytime Well-being

Planned Enhancements Sensors:

To further our research and provide a more detailed analysis, additional sensors will be installed and analyzed:

- Temperature/Illuminance Data Logger: This dual-purpose sensor will record temperature fluctuations alongside light exposure over time.

Possible consequences and risks of participating in the project

There is no right or wrong way to perform the tasks. You may discontinue participation in this study at any time. Your name will not be disclosed at any time, and the information will be reported in such a way as to make direct association with yourself impossible.

What happens to your data?

The data will be encrypted and kept on a private computer, and any further use of the data will maintain the participants' confidentiality. The findings of this research will be published in a master thesis dissertation and a journal publication. If you would like to learn about the results of the study, please contact Lucio Domenico Cavallari Tel: [redacted] Email: ldca@kth.se.

Your answers and your results will be processed so that unauthorized persons cannot access them.

Responsible for your personal data is Lucio Domenico Cavallari. According to the EU's data protection regulation, you have the right to access the information about you that is handled in the project free of charge, and if necessary to have any errors corrected. You can also request that information about you be deleted and that the processing of your personal data be restricted. However, the right to erasure and to limit the processing of personal data does not apply when the data is necessary for the current research. If you want to share the data, please contact Lucio Domenico Cavallari Tel: [redacted] Email: ldca@kth.se. The Data Protection Officer can be reached at Email: dataskyddsombud@kth.se Telephone: 08-790 790 60 00. If you are dissatisfied with the way your personal data is processed, you have the right to file a complaint with the Swedish Data Protection Authority, which is the supervisory authority.

How do you get information about the results of the project?

If you would like to learn about the results of the study, please contact Lucio Domenico Cavallari Tel: [redacted] Email: ldca@kth.se

Compensation

There is no compensation for participating in the study.

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Figure C.0.3: Consent Form page 3.

Twilight's Role in Enhancing Sleep Quality and Daytime Well-being

Participation is voluntary

Your participation is voluntary and you can choose to cancel your participation at any time. If you choose not to participate or wish to discontinue your participation, you do not need to state why, and it will not affect your future care or treatment.

If you wish to cancel your participation, please contact the person responsible for the project (see below).

Responsible for the project

Project's Responsible: Lucio Domenico Cavallari Tel: [redacted] Email: ldca@kth.se

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Figure C.0.4: Consent Form page 4.

Twilight's Role in Enhancing Sleep Quality and Daytime Well-being

Consent to participate in the project

I have received oral and/or written information about the study and have had the opportunity to ask questions. I get to keep the written information.

- I agree to participate in the project *"Twilight's Role in Enhancing Sleep Quality and Daytime Well-being"*.

Place and date	Signature
	Name clarification

Figure C.0.5: Consent Form page 5.

Chapter D

Tools and Software Used

This thesis utilized a diverse array of tools and software, categorized as follows:

Audio and Video Editing:
Adobe Audition

Graphic Design and Image Editing:
Adobe Photoshop, Adobe Illustrator, Affinity Publisher

Artificial Intelligence:
ChatGPT, Whisper AI

Document and Text Management:
Pages, LaTeX (Overleaf)

Programming and Data Analysis:
Python (Visual Studio Code), R (R Studio)

Spreadsheet and Data Management:
Microsoft Excel, Apple Numbers

Architectural and Environmental Design:
Rhino 7, Climate Studio, Autodesk Revit

Sensors and Measurement Tools:
Zoom H6, Temperature/Illuminance Data Loggers (MX2202)

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List of Figures

Note: All images, unless otherwise stated, are proprietary.

List of Tables

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