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Analyse Design und Prototypentwicklung eines smarten Aufwachlichtsystems zur Unterstützung morgendlicher Wachheit und Stimmung in Personen mit spätem Chronotyp

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Analysis, design and prototype development of a smart light wake-up system to support morning alertness and mood in subjects with late chronotype

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Erklärung zur Verfassung der Arbeit

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Kurzfassung

Ein verzögerter zirkadianer Rhythmus steht mit chronischer morgendlicher Müdigkeit und einem erhöhten Depressionsrisiko in Verbindung. Morgenlicht ist der wichtigste Faktor zur Synchronisierung der zirkadianen Uhr mit frühen Aufwachzeiten. Spezielle Anwendungen von Licht am Morgen zeigen in Studien großes Potenzial zur Verbesserung von Morgenmüdigkeit und Gemütsstörungen. Da diese Interventionen im Schlaf oder im Aufwachprozess angewandt werden, könnten sie sogar in ein angenehmes Aufwacherlebnis integriert werden. Für eine Praxisanwendung im Alltag fehlen jedoch bislang akkurate Reproduktionen oder gar eine Kombination dieser Lichtanwendungen.

Im Rahmen dieser Masterarbeit wurde untersucht, wie eine akkurate Reproduktion der erwähnten Lichtinterventionen als Smart-Light für den privaten Gebrauch realisiert werden könnte. Ein besonderer Fokus lag dabei auf der Interaktion zwischen Nutzer:innen und Gerät, sodass eine Anwendung nahtlos in den Alltag integriert werden kann. Ziel der Arbeit war die Konstruktion eines Prototyps, der diese Anforderungen erfüllt.

Die Entwicklung des Konzepts folgte einem nutzerzentrierten Designprozess. Die Systemanforderungen wurden auf Basis von 3 Experteninterviews, einer Analyse von 11 Nutzerinterviews sowie systematischer Literaturrecherche formuliert. Diese wurden in einen initialen Designentwurf für das System übergeführt. Es folgten zwei Iterationen der Implementierung des Geräts zu funktionalen Prototypen. Jede Iteration wurde mit je 3 Testpersonen (19-35 Jahre) über einen Zeitraum von je drei Wochen getestet und evaluiert.

Das resultierende Smart-Light schaffte es, die gewünschten Lichtinterventionen akkurat und in kombinierter Form zu reproduzieren. Alle Prototyp-Nutzer:innen gaben ein verbessertes Aufwacherlebnis an und zeigten eine hohe Akzeptanz des Geräts. Als größte Schwäche der Prototypen stellte sich die Verlässlichkeit der Softwaresteuerung heraus.

Das in dieser Arbeit entwickelte Smart-Light-Konzept repräsentiert die erste akkurate Reproduktion einer *natürlichen Dämmerungssimulation* für die Privatanwendung und ebenso die erste algorithmische Kombination mehrerer biologisch wirksamer Lichtinterventionen in ein angenehmes Aufwacherlebnis. Durch die passive Integration in den Alltag hat das Konzept Potenzial, die morgendliche Wachheit und Stimmung langfristig und auf einfache Weise zu unterstützen.

Abstract

A delayed circadian rhythm is associated with chronic morning tiredness and an increased risk of depression. Morning light is the most important factor in synchronizing the circadian clock with early wake times. Specific applications of morning light have shown great potential for improving morning tiredness and mood disorders in clinical trials. Since these light interventions are applied prior or upon awakening, it may be possible to couple their application with an inherently pleasant wake-up experience. However, accurate reproductions or even a combination of these light applications for practical use in everyday life are still lacking.

This thesis explored how an accurate reproduction of the mentioned light interventions could be realized as a smart light for personal use. Particular focus was put on the user-device interaction so that the smart light would integrate seamlessly into the users' lives. The goal of this thesis was the construction of a functional prototype that meets these requirements.

The concept was developed following a user-centered design process. Requirements were collected through 3 expert interviews, an analysis of 11 user interviews, and a systematic literature review. On this basis, an initial system design was specified. In two iterations, the design was implemented as functional prototypes of the smart wake-up light. Each prototype iteration was tested and evaluated by 3 test users (ages 19-35) for 3 weeks each.

The resulting smart light successfully reproduced the desired light interventions accurately and in a combined manner. All users of the final prototype reported improved wake-up experiences compared to baseline and showed high acceptance of the device. Operational reliability of the software controller emerged as the biggest shortcoming of the prototypes.

The smart light concept developed in this work represents the first accurate reproduction of *naturalistic dawn simulation* and the first algorithmic combination of multiple biologically effective light applications into a pleasant wake-up experience. With its passive integration into daily routines, the concept holds potential to support morning alertness and mood in the long term and in an effortless manner.

Contents

CHAPTER 1

Introduction

Our human physiology is influenced by an inner clock that cycles in a near-24-hour period [1]. Due to this roughly daily repetition, this inner clock is called the *circadian rhythm* (from Latin: circa - around, and dies - day) [2]. Circadian rhythms play a regulatory role in metabolic, thermoregulatory and functioning of human physiology [3, 4]. In particular, the circadian system plays a vital role in regulating the human sleep-wake cycle, i.e., when we naturally feel awake or tired [5].

The circadian clock does not run equally in all individuals. On a foundational level, it synchronizes to the daily light-dark cycle it is exposed to. However, influenced by genetic predisposition, timing of artificial light exposure, lifestyle and age, people exhibit different *chronotypes*, which describes a person's biological tendency toward an earlier or later daily rhythm. Approximately 3 in 10 people are considered late chronotypes, colloquially called "night owls," who naturally rise and stay up later than early or moderate types [6].

1.1 Problem Statement

In modern society, the natural tendencies of late chronotypes frequently conflict with early wake times required by rigid schedules in jobs, schools, or other circumstances [7]. This leads to a phenomenon called circadian misalignment, where the externally imposed schedule is out of sync with the individual's biological clock. Late chronotypes are often woken by alarm clocks at a time that corresponds to their biological night, resulting in pronounced sleep inertia, a state of grogginess and impaired cognitive function after waking [8]. Research has shown that waking during the biological night produces sleep inertia that is 5.5 times greater than waking during the biological day [9].

Beyond morning tiredness, chronic circadian misalignment has been associated with a range of health risks, including cardiovascular and metabolic diseases, a higher risk of diabetes, and an elevated body mass index (BMI) in overweight individuals [7].

Furthermore, late chronotypes display a significantly higher risk of depression compared to earlier chronotypes [10].

Getting the right light at the right time plays a decisive role in regulating the circadian rhythm, sleep and wakefulness [11]. Morning light of specific intensity and wavelength can advance the circadian phase, effectively shifting delayed internal clocks to align better with early schedules [12, 13]. Specific applications of light have been demonstrated to be an effective treatment for mood disorders, notably but not limited to *seasonal affective disorder* (SAD), which is a seasonal form of depression that recurs annually during fall and winter and affects approximately 2.4% of the Austrian population [14].

A relevant subset of these light applications can even be applied during sleep, without interrupting it [15], or be integrated into the process of awakening while making the same more pleasant [16].

The potential benefits of integrating light therapy into the wake-up process include:

- Direct reduction of subjective sleep inertia [16]
- Reduction of social jetlag by shifting circadian phase towards earlier waking hours
  - Indirect reduction of sleep inertia by better alignment of natural and actual time of awakening [9]
  - Decrease of health risks associated with circadian misalignment [17]
- Mood improvement, including a recognized form of SAD treatment [18]

Despite the compelling evidence supporting the use of light around awakening for circadian phase advancement, mood regulation, and the reduction of sleep inertia, these interventions have remained largely confined to controlled clinical or research settings. Current commercial wake-up lights fall short of achieving significant circadian phase shifts and are explicitly not recommended for the treatment of SAD [19, 16, 20]. To date, no wake-up system has been designed to fully exploit the potential of light for addressing the challenges faced by late chronotypes and individuals with SAD.

This thesis aimed to close the gap in morning lighting between scientific state of the art and practical application. With today's LED technology and smart light interfaces, there was no apparent technical reason why an accurate reproduction of these validated light applications should not have been possible in the private bedroom. A look at the individual applications even suggested that they could be used in combination, possibly stacking their benefits while being experienced daily as a single, pleasant wake-up experience.

The thesis investigated if and how a comprehensive, accurate reproduction of the state-of-the-art light applications around awakening was possible in a private setting. Beyond mere light specifications, it explored how this functionality could be embedded in an accessible, user-friendly smart wake-up light suitable for daily use.

1.2 Motivation

The widespread issue of circadian dysregulation and mal-illumination, i.e., biologically unhealthy lighting patterns, has significant health, social, and economic consequences [21]. SAD alone affects millions of Europeans annually [22]. Carpenter et al. [23] suspect that also many other mood disorders are underpinned by circadian dysregulation. In the case of depression and sleep inertia, late chronotypes represent a particularly vulnerable part of the population [10, 9].

Light therapy interventions such as 10,000 lux bright light therapy (BLT) or naturalistic dawn simulation are recognized first-line treatments for SAD by the American Psychiatric Association [18]. BLT is widely regarded as the current best light therapy practice [24], showing promise in the treatment of seasonal but also non-seasonal depression [20]. However, compliance with BLT is inconvenient [25] and often challenging, as it requires consistent early-morning use, a particular difficulty for late chronotypes who already struggle with waking early. For these individuals, SAD is frequently accompanied by hypersomnia, further compounding the challenge of adhering to early-morning treatments. [26]

A solution that passively integrates validated morning light interventions into the private bedroom, without requiring explicit user action, could address these barriers and provide meaningful benefits. A noteworthy example is represented by naturalistic dawn simulation (NDS), which replicates the natural gradual increase in light intensity during spring dawns [27]. NDS and has been shown to treat SAD with effect sizes similar to BLT and even shift the circadian phase without requiring active user participation [27, 12]. However, the scientific literature has repeatedly highlighted the lack of commercial availability of NDS throughout the years [20, 28, 11].

Working towards the availability of NDS, among other morning light applications, therefore, represented a significant translational contribution to the field of circadian health, paving the way for help that has the potential to impact the lives of millions of people for the better [24, 27].

1.3 Goals and Research Questions

Goal of this thesis was the conception and prototype implementation in hardware and software of a system that unites different applications of lighting before, during and after awakening to support ease of awakening and daytime mood in the target group of people with late chronotype. Design focus lay on the reproduction of functionality proven effective by scientific studies with readily available commercial hardware, while offering a user interface that integrates conveniently into people's evening and morning routines.

The question of how the scientifically described positive effects of light on awakening, circadian rhythm and mood could be implemented into a usable consumer product using off-the-shelf hardware broke down into **3 research questions**:

1. **Research question 1 (RQ1)**:
   What are the functional requirements of the wake-up system to alleviate problems in late chronotype subjects?

2. **Research question 2 (RQ2)**:
   How can the user interface and human-system interaction look like so that users appreciate the usability of the system?

3. **Research question 3 (RQ3)**:
   How or to what extent can the hardware requirements for the conceptualized wake-up system be met by an arrangement of off-the-shelf hardware?

Based on the theoretical answers to the research questions above, a prototype of the smart wake-up light in hardware and software should be constructed. Its performance should be evaluated with the feedback of subjective ratings of user experience by users from the target group. On the basis of the theoretical analysis and practical findings, a revised system specification represented the final deliverable.

Ultimately, the envisioned result of this thesis was a specification for a smart wake-up light that brings the state of the art in lighting for circadian health into the private bedroom. Ideally, the concept could be specified in a way that it can serve as a blueprint for do-it-yourself reconstructions in private settings.

1.4 Methodological Approach

The methodological approach of this thesis followed user-centric design principles. It was structured into four distinct phases: *Requirements Engineering*, *Initial Design*, *Prototyping & Evaluation*, and *Final Specification*. Each phase systematically contributed to answering the research questions and delivering a successful design and implementation of the system.

Phase 1: Requirements Engineering Phase 1 focused on gathering and analyzing theoretical and practical requirements for the wake-up system. A analysis of photobiological requirements based on scientific literature explored the scientific state of the art how morning light impacts circadian rhythms, sleep, and mood. The findings were discussed with researchers of the intersection of light and human physiology. After this process, an initial set of photobiological requirements - describing how a smart wake-up light could reproduce and combine the most effective morning light interventions - was formulated. Then, requirements for the user interaction and user experience (UI/UX) were derived through an analysis of semi-structured interviews, which had been conducted in a prior project with individuals struggling with morning awakening. These insights informed the system's functional and non-functional UI/UX requirements. Following an interview with a lighting expert, specific hardware requirements to satisfy the previously identified requirements were defined.

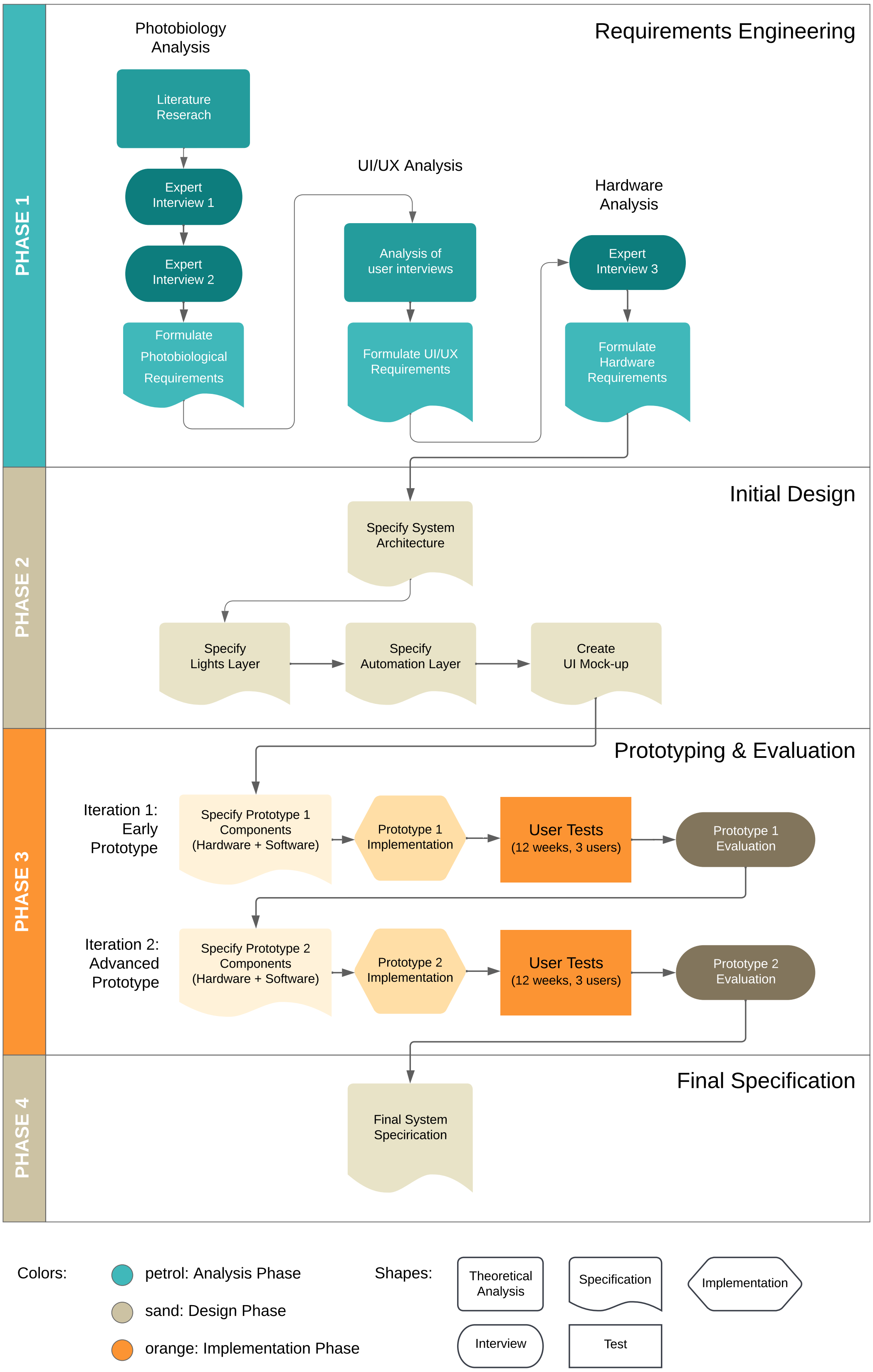

Figure 1.1: Process chart of the work conducted for this thesis.

Phase 2: Initial Design Based on the identified requirements, phase 2 focused on creating an initial system design. Starting with a high-level specification of the system architecture, detailed descriptions of the layers of the system and their interfaces were formulated. A preliminary user interface (UI) concept was proposed, supported by UI mock-ups that aligned with the identified user interaction requirements.

Phase 3: Prototyping & Evaluation The system was implemented in two iterative cycles, beginning with the creation of an early prototype (Prototype 1). After selecting suitable hardware components and software frameworks, the prototype implemented the specified architecture and the proposed UI concept. User tests were conducted over a 12-week period with three participants from the target group, providing valuable feedback on the system's usability and overall the overall user experience. In addition, technical measurements assessed whether the system met the technical requirements. Based on the results of these evaluations, adjustments were made to the design and a second, advanced prototype (Prototype 2) was developed. This prototype underwent another round of testing to refine the system further and ensure it met the identified requirements. The results of this phase enabled a qualified answer to research question RQ3.

Phase 4: Final Specification In the final phase, the insights and feedback from the iterative prototyping and evaluation cycles were synthesized to formulate a final system specification. This specification included the revised list of system requirements, which represented this thesis' answer to RQ1. Furthermore, a final proposal for the UI implementation was created, which, in combination with the final UI/UX requirements, answered RQ2.

1.5 Structure

After introducing the topic, problem statement, and methodological approach in Chapter 1, the theoretical foundation upon which this thesis builds is presented in Chapter 2. Specifically, the concept of circadian rhythm, its connection to sleep inertia and mood, and the factors influencing circadian regulation are explained.

Chapter 3 examines the current state of the art regarding the use of light to improve ease of awakening and mood. Existing solutions for dawn simulation, light therapy and the shift of circadian phase are reviewed.

The methods used in this thesis are detailed in Chapter 4. The results of the conducted work are then presented in Chapter 5: First, the theoretical analysis results and the resulting requirements for the conceived wake-up system are outlined in Section 5.1. The software architecture for the prototype implementation is described in Section 5.2. For the iterative prototype implementation, the chosen hardware and software components, prototype construction, and evaluation results are detailed in the respective iteration sections (5.3, 5.4, 5.5).

Finally, the findings from Chapter 5 are discussed in Chapter 6. Directions for future work are identified before a summary of the conducted research concludes the thesis.

CHAPTER 2

Theoretical Background

To develop a smart light system that effectively enhances morning alertness and mood, it is essential to first understand the biological mechanisms that regulate these aspects. Morning alertness and mood are closely linked to circadian rhythms and sleep, both of which are significantly influenced by light exposure [11]. Therefore, this chapter begins by exploring the biological background, focusing on the circadian system, sleep inertia, and affective disorders, providing the necessary foundation for understanding how light can be used as an intervention.

Since the effects of light on human physiology depend on specific characteristics of light exposure, a vocabulary for the relevant light measures is needed. Section 2.2 introduces the key metrics and parameters used in lighting before examining the physiological effects of light on the human body.

Once the photobiological foundation has been established, the discussion shifts toward the technical background necessary for designing and implementing an effective yet usable smart light system. Therefore, Section 2.3 details the principles and methods of *user-centered design* (UCD), a development approach that ensures usability and effectiveness by involving end users throughout the development process.

Finally, to successfully implement a smart lighting system, it is critical to systematically capture all relevant system requirements. Section 2.4, *Requirements Engineering*, summarizes essential methodologies for eliciting and specifying requirements, providing a structured approach to defining the system's functional and non-functional needs.

2.1 Biological Background

This section examines fundamental aspects of the *circadian rhythm*, the endogenous biological clock that regulates physiological and behavioral processes within an approximately 24-hour cycle [1]. Following an introduction to this concept, it also sheds light on *sleep inertia*, which is the scientific term for the grogginess that people experience after awakening [8], along with its contributing factors. The final subsection, Section 2.1.3, explores affective disorders, with a particular focus on *seasonal affective disorder* (SAD). Notably, it will become apparent how and to which degree sleep and mood are underpinned by circadian biology.

2.1.1 Circadian Rhythm

Physiological processes in humans, as well as in animals and plants, change over the course of a day. Like the bloom of a flower is open during the day and closed overnight, humans are naturally active at daytime and sleep at night. One might assume that this is a direct response to external time cues such as daylight. In 1729, however, the French geophysicist De Mairan found that even in constant darkness, flowers open and close their blooms in a roughly daily pattern. In 1938, the American researchers Kleitman and Richardson confirmed this observation for humans, when they isolated themselves in a cave for 6 weeks. Today, we know that there is a cellular process in humans, animals and plants that works like an inner clock. It cycles in a near-24h pattern, therefore it is called *circadian rhythm*, from latin "circa" meaning "around" and "dies" meaning "day". The field of study of the inner clock is called *chronobiology*. [2]

The circadian clock works on a cellular level through the expression of certain genes during the day and their degradation during the night. The circadian rhythm in individual cells of our body is aligned by a "master clock" that sits in the *suprachiasmatic nucleus* (SCN) in the hypothalamus of the brain [11]. In 2017, the researchers Hall, Robash and Young were awarded the *Nobel Prize in Medicine* for their discovery of the molecular mechanics of circadian clocks [29].

Circadian regulation of arousal

Our daily levels of tiredness and alertness are regulated by two independent factors. The first one is *homeostatic sleep pressure*, governed by the neurotransmitter *adenosine*. It increases linearly with the amount of time spent awake and decreases during sleep. Circadian rhythm is the other one, regulating the drive for arousal via the hormones *cortisol* and *melatonin* (see figure 2.2). The "stress hormone" cortisol increases at biological morning time, activating body and mind, and is decreased at biological evening times. The opposite holds true for the "sleep hormone" melatonin, which induces tiredness in the evening. The interplay between these two processes is known as the *two-process model of sleep regulation* [30]. See figure 2.1 for a visualization.

Note that biological morning and evening are subjective times. They depend on circadian phase and do not occur at the same absolute clock time for all people. As chronotype distribution in society shows a large dispersion, some people naturally wake up before 6 a.m. while others sleep until 10 a.m. and later. The same holds true for the onset of tiredness in the evening.

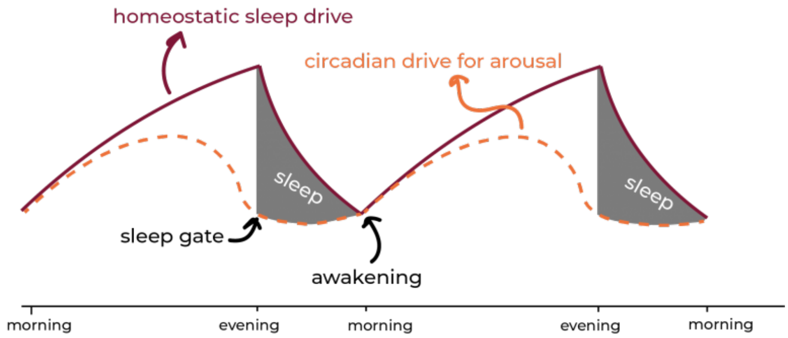

Figure 2.1: *Two-process model of sleep regulation*: Sleep is facilitated by a high homeostatic sleep drive as well as a low circadian drive for arousal [30].

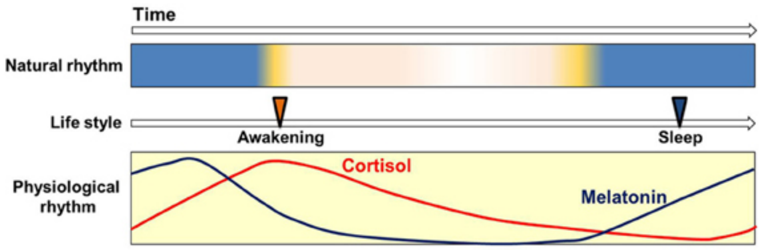

Figure 2.2: Habitual times of sleep and wake correlate with the oscillation of the hormones melatonin and cortisol. Cortisol peaks around awakening and is dominant during the subjective daytime, resulting in a high drive for arousal during the day. Melatonin rises in the evening and calms the body for the night. From [31]

Chronotype

The circadian rhythm differs from person to person in period and timing. The individual setting is referred to as *chronotype*. Its foundation is set by genetic predisposition. Circadian period was found to be 24:18h, with a standard deviation of only 12 minutes in healthy adults [1]. Regarding chronotype, the variance is much more pronounced. Around 40% of people ("larks") tend to naturally rise earlier in the morning, 30% ("owls") tend to rise late and stay awake longer while the rest lies in-between the two types (see figure 2.3 for a distribution) [6]. The human chronotype changes with age: Over the course of life, circadian phase experiences a peak delay of 1-3 hours during adolescence, before it slowly shifts towards morningness with increased adulthood (see figure 2.4) [32, 33]

Circadian Entrainment

To prevent the near-24h circadian rhythm to shift away from actual daytimes over time, it synchronizes to certain exogenous time cues. The synchronization of circadian rhythm

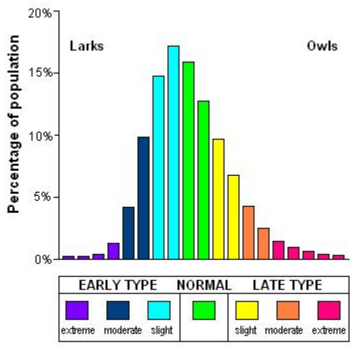

Figure 2.3: Chronotype among the population follows a near-Gaussian distribution with its mean between normal and slight morning type. The *late type* accounts for approximately 30% of people [6]

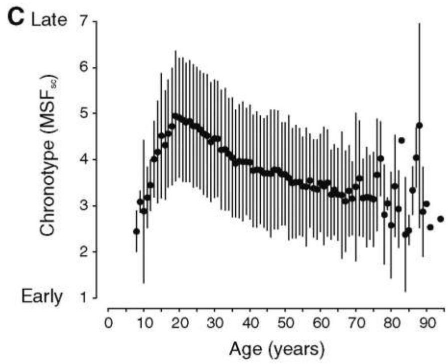

Figure 2.4: Depiction of chronotype distribution over age. Chronotype is represented by the midpoint of sleep on free days (MSF). It experiences a delay in adolescent years before it gradally advances with age. From [33]

to repeating exogenous time cues is called *entrainment* [6]. Entrainment allows humans and other living beings to adapt to changes in the environment, such as seasonality or a different time zone after trans-meridian travel. The time-cues that the circadian clock adapts to are called *zeitgebers* (from German "giving time"). The most dominant zeitgeber is light, but also factors like temperature, exercise, food intake or exogenous melatonin have been shown to impact circadian phase [2]. Environmental zeitgebers, such as light or temperature enable a passive synchronization of circadian rhythm. They do not require personal action for the phase amendment, while other zeitgebers, e.g. physical exercise or food intake, do.

Zeitgebers Zeitgebers phase-advance or phase-delay circadian rhythm, depending on the stimulus and the time of stimulation. How a certain stimulus affects circadian phase at different times of the biological day is represented by the *phase response curve* (PRC) of the stimulus. See figure 2.8 for the PRC of bright light.

Circadian Misalignment and Health

The circadian rhythm supports a consistent sleep-wake schedule that is in line with rhythmic exogenous time cues for day and night. Deviations from this instrinsic rhythm result can manifest in acute impairments such as increased sleep inertia (see section 2.1.2) or insomnia [34]. On a chronic basis, they have been shown to pose a significant risk to mental and physical health [21].

Circadian disruption *Circadian disruption* describes a severe misalignment between circadian rhythm and actual cycles of rest and activity or light exposure [35]. It can be observed as a consequence of trans-meridian air travel, which is then called jet lag. While jet lag has been connected to mood impairments in humans [36], chronic jet lag significantly increased mortality in aged mice [37]. In humans, an analysis by Windred et al. revealed sleep regularity as a stronger risk factor for mortality risk than sleep duration [38]. Night shift work, as a systematic form of chronic circadian disruption, has even been labeled "probably carcinogenic" by the *International Agency of Research on Cancer* (IARC) [39].

Social Jetlag Even without complete disruption, people with late chronotype oftentimes do not have the freedom to wake and sleep according to their circadian clock [7]. Driven by early working hours or other life demands, they may force their body out of sleep unnaturally early on work days and sleep significantly longer on free days. The difference between their early sleep schedule during the week and late natural schedule on weekends is referred to as *social jetlag*, as it corresponds to a change in time zones twice a week [**?**]. Strong social jetlag is linked to a higher risk for depression, cardiovascular diseases and type-2 diabetes [17].

2.1.2 Sleep Inertia

Sleep inertia describes the grogginess, cognitive impairments, and desire to fall back asleep that people experience directly after awakening. While the exact mechanisms are not yet clear, it appears the brain needs some time to transition from sleep to complete wakefulness. This process can take minutes to hours [40]. To understand influential factors behind sleep inertia, it is important to understand how the human body's natural sleep-wake-cycles are regulated.

Influential factors for sleep inertia

While a certain amount of sleep inertia is normal even under healthy sleeping conditions, different factors appear to negatively impact severity and duration:

- **sleep debt**: After prior sleep loss, sleep inertia is experienced stronger and longer [40]
- **circadian rhythm**: The circadian timing of awakening is a significant factor for the experienced sleep inertia [8, 40]. In a study by Scheer et al. [9], cognitive impairments after an awakening during the biological nighttime were shown to be 3.6 times greater than after an awakening during biological daytime. The circadian influence is independent of possible sleep debt: In settings with prior sleep loss, the level of sleep inertia after a nap still varied according to the circadian time of the nap [40].
  The underlying mechanics of this influence may have to do with thermoregulation and (de-)centralization of body temperature: A noteworthy study by Kräuchi et al. [41] has shown that the proximal skin temperature gradient (DPG, i.e. temperature at hands and feet minus core body temperature) positively correlates with subjective sleepiness. Biological midnight, called *nadir*, is defined as the point in time of lowest core body temperature. As this is also the point of highest DPG [42], this would explain how circadian nighttime worsens sleep inertia.
- **sleep stage**: Early studies on sleep inertia showed correlations between the stage (i.e. the depth) of sleep and the impairments on awakening. This established the belief that an awakening from slow wave sleep (SWS) results in greater sleep inertia than waking up from "lighter" sleep, such as dream sleep that is characterized by rapid eye movements (REM-sleep) [40]. However, recent studies with more differentiated settings did not find a significant impact of sleep stage on sleep inertia [40, 9, 41]. Thus, the relationship between sleep stage and ease of awakening might be more complex than previously anticipated [40].

2.1.3 Affective Disorders

Affective disorders, also known as mood disorders, describe psychiatric disorders that have a strong impact on the patient's mood. The currently prevalent classification system for mental health disorders, *Diagnostic and Statistical Manual of Mental Disorders 5* (DSM-5), broadly separates affective disorders into *bipolar disorders* and *depressive disorders* [43]. The categories have further subdivisions, such as major depressive or premenstrual depressive disorder [44].

Connection between affective disorders and circadian rhythm

The causes of affective disorders and their underlying pathophysiological mechanisms have yet to be fully understood [23]. As the DSM-5 classification focuses on symptoms, one and the same type of mood disorders could have multiple different causes, which can make a successful treatment difficult. One influential mechanism appears to be circadian: A review by Carpenter et al. [23] points to circadian dysregulation as one causal mechanism for affective disorders. They propose *circadian depression* as a clinical phenotype, which is characterized by sleep-wake cycle abnormalities, reduced physical

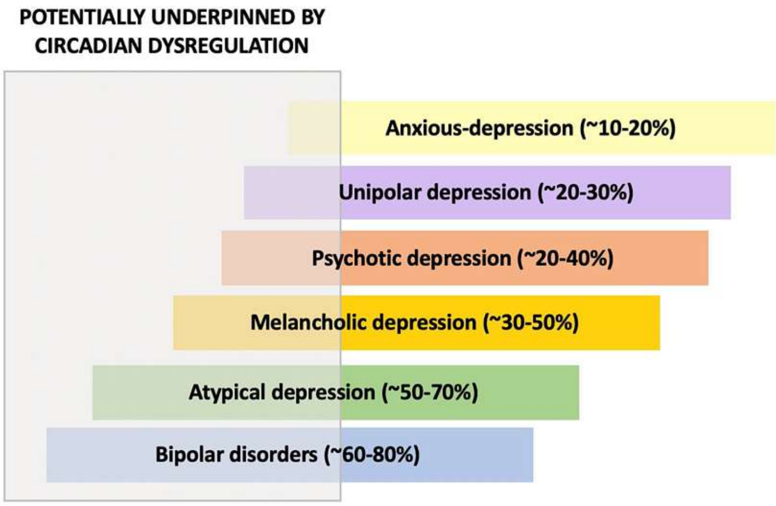

Figure 2.5: Estimated percentage of depression cases caused by circadian dysregulation, across different types of affective disorders. [23]

activity but increased appetite, among other factors, during a depressive episode. Figure 2.5 shows to what extent Carpenter et al. estimate different mood disorders to be underpinned by circadian dysregulation. Identifying the circadian phenotype could lead to improved treatment success using *circadian therapies*, such as light therapy (see Section 2.2.2) or timed melatonin supplementation [23].

Seasonal Affective Disorder (SAD)

A particularly relevant form of depression in association with light and circadian rhythms is seasonal affective disorder (SAD). SAD is defined as a recurring type of major depression with seasonal patterns. Typically, the depressive episodes span the fall and winter season and vanish completely in spring [45]. Therefore, SAD is also often referred to as "winter depression" [20]. In an analysis from the outpatient SAD clinic in the General Hospital in Vienna, 69% of the SAD patients showed atypical depression characteristics [26], such as hypersomnia (i.e., an abnormal increase in sleep duration) and increased appetite [46]. These symptoms fall into the characteristics of the circadian depression phenotype as proposed by Carpenter et al. [23].

In Austria, SAD is estimated to affect around 200,000 people (2.4% of the population) each year, while more than 800,000 Austrians experience a sub-syndromal form called "winter blues" [14]. The prevalence of SAD increases with geographic latitude, i.e., it is most prevalent in countries with few hours of daylight per day in winter [22]. Furthermore, pronounced evening chronotypes are more likely to develop SAD than other people [14]. These factors hint at a strong circadian component underlying SAD. In support of this assumption, SAD patients show the biggest response to light therapy, a circadian therapy approach detailed in Section 2.2.2 [20].

2.2 Light

Light, as an essential component of the natural environment, exhibits various measurable properties and characteristics that influence its impact on human perception and biology. This section introduces key concepts relevant to understanding the biological and psychological effects of light.

The interplay between light and biology represents interdisciplinary field of scientific research named *photobiology*, derived from the ancient Greek word "*photo*" meaning "light". [47]

2.2.1 Light: Measures and Characteristics

Technically, photobiology speaks of *light* as all non-ionizing electromagnetic radiation. [47] The relevant aspects of light in this thesis follow a narrower definition, focusing on the visible spectrum of light as a subsection of the non-ionizing electromagnetic spectrum.

Visible Spectrum

The visible spectrum refers to the range of wavelengths of electromagnetic radiation detectable by the human eye, spanning approximately 380–800 nanometers (nm). This range includes all colors of light that are perceptible, from violet at shorter wavelengths to red at longer wavelengths [48].

Photometric Measures

To quantify the characteristics of light in terms of its impact on human perception and biological systems, the following photometric measures are commonly used:

- **Luminous Flux (Lumen):** The number of lumens describes the total amount of visible light emitted by a source. It provides an objective metric for assessing the brightness of a light source. [49]
- **Illuminance (Lux):** Illuminance represents the intensity of light that falls on a surface. For the purposes of this thesis, that surface is usually the eye. The unit *lux* is defined as the luminous flux received per unit area, measured in lumens per square meter. By definition, 1 lux is the light intensity from one candle at one meter distance. As illuminance does not decrease linearly with increasing distance but is inversely proportional to the square of the distance, the light intensity at 2 meters distance would be 0.25 lux. [49]

The human eye can adjust to a vast range of light intensities. Humans can see their surroundings at illuminances well below 0.1 lux while they can also tolerate outdoor illumination of more than 10,000 lux [50]. Figure 2.6 illustrates the light intensities in different environments on a logarithmic scale. What is perceived as linear increases

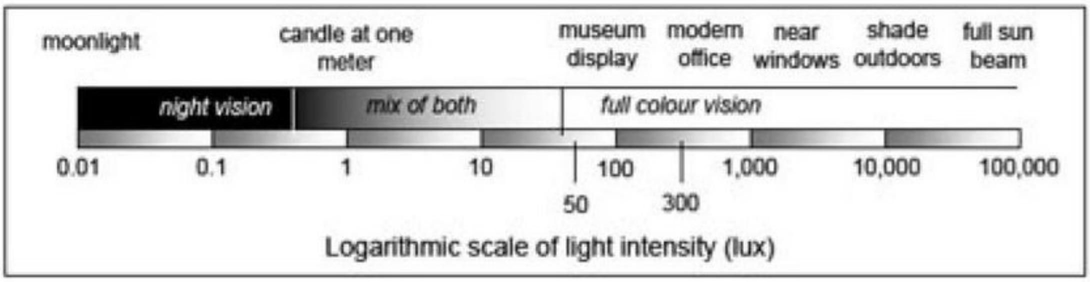

Figure 2.6: Typical light intensities (lux) by type of environment. From [50]

in light intensity, therefore, is actually an exponential increase in light intensity. This conversion is important to consider in lighting. To account for it, the dimming curve in smart lights or electronic displays is not a linear curve between 0.0 and 1.0 but an exponential curve: A parameter *gamma* specifies the size of exponent of the function $\exp^{\gamma}$. This is called *gamma correction* in lighting. A gamma of 0 leads back to a linear (identity) function, as $\exp^0 = 1$ [51].

2.2.2 Effects of light on human biology

Light affects human physiology and behavior beyond its role in enabling vision. The *non-image-forming effects of light* include the regulation of alertness, circadian rhythms and mood [11]. The non-image-forming effects of light are mediated by intrinsically photosensitive retinal ganglion cells (ipRGCs), which exist beside the rods and cones in the retina [?]. ipRGCs transmit light information via dedicated neural pathways to brain regions involved in regulating alertness, circadian rhythms and mood [11].

Measuring non-visual illuminance

ipRGCs are primarily activated by the photopigment *melanopsin*, which has a peak sensitivity at a wavelength of approximately 480 nm in the blue-ish part of the visible light spectrum. This spectral sensitivity is different than the image-forming (visual) sensitivity to light, which is highest in the green-ish part of of the visible light spectrum (see Figure 2.7) [52]. To capture the physiological impact of light specifically, a spectral efficiency function called *melanopic equivalent daylight illuminance (M-EDI)*, also referred to as *melanopic lux*, has been developed. Opposed to *photopic illuminance* (introduced in Section 2.2.1, melanopic illuminance weights the wavelengths according to their impact on melanopsin cells. Figure 2.7 illustrates a simplified model[1] of the melanopic illuminance function in comparison to the photopic illuminance function.

[1] https://balancedcare.axislighting.com/resources/circadian-metrics-spd/, accessed on 2022/08/12

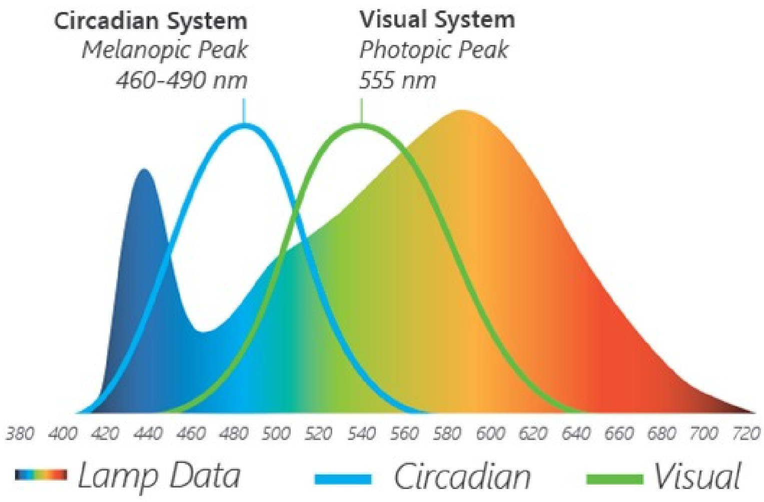

Figure 2.7: Distribution of melanopic sensitivity versus photopic sensitivity over the visible light spectrum (simplified model). The x-axis describes the light wavelengths in nanometers (nm). The "Lamp Data" spectrum is representative of conventional LED light. Web-based adaptation of the model from Brown et al. [53]

Light's acute effect on sleep inertia and alertness

Bright light has immediate effects on promoting alertness and reducing sleep inertia, primarily through its influence on melatonin secretion and thermoregulation:

- **Melatonin Suppression:** Light exposure, particularly during the evening or night, inhibits the release of melatonin, which leads to a strong increase of alertness during the biological night [54].
- **Thermoregulation:** Bright light exposure reduces subjective feelings of grogginess after waking [40]. This may be due to a decrease in the *distal-proximal skin temperature gradient (DPG)*, a thermoregulatory response to bright light [55], which is correlated to sleep inertia in the morning [41].

Furthermore, dawn simulation, which is a gradually increasing light signal that precedes awakening, has been shown to significantly reduce sleep inertia upon awakening [16].

Light's effect on circadian rhythm

As the dominant zeitgeber, light entrains the human circadian system to the natural 24-hour day-night cycle. This synchronization is mediated through a neural pathway leading from the ipRGCs to the suprachiasmatic nucleus (SCN), which functions as the body's "master clock" for circadian rhythm regulation. [11]. As established in Section 2.1.2, a better alignment between circadian and social clock is a potent lever to reduce

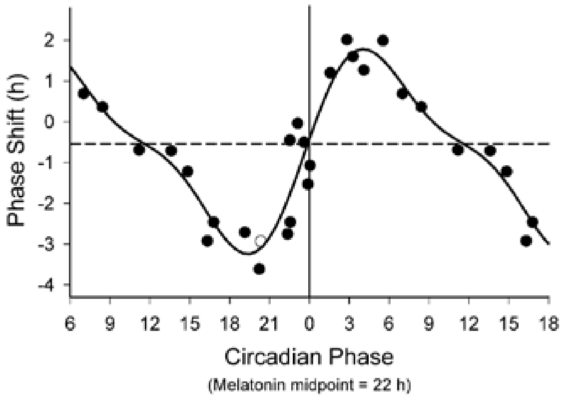

Figure 2.8: Phase response curve to a 6.7h bright light pulse at 9000 lux intensity. Early morning exposure (start of exposure between 3-6 a.m. biological time) led to an approximate 2h phase advance, while late evening exposure (between 6-9 p.m. biological time) resulted in around 3h of phase delay. The direction of phase shift changes over biological noon and midnight. From [56]

sleep inertia upon awakening [40]. For evening types, as the target population in this thesis, this means a phase advance of their circadian clock .

The direction and magnitude of light-induced circadian phase-shift depend on the time and duration of exposure, melanopic illuminance and light dynamics. [11].

Timing: Circadian Phase Response Curve (PRC) The effects of light on circadian timing vary with the time of day:

- **Morning Light:** Exposure in the early morning induces a *phase advance*, shifting the circadian rhythm earlier.
- **Evening Light:** Exposure in the late evening causes a *phase delay*, shifting the circadian clock to later biological bedtimes and wake times.

During the day, the circadian system appears to be less sensitive to light. The function the maps the time of light exposure to its impact on circadian phase is called *circadian phase response curve* (PRC). Figure 2.8 illustrates the circadian PRC for A 6.7h bright white light pulse of 9000 lux [56]. Next to timing, duration of the exposure is critical: St. Hilaire et al. [13] found that while 6.7 hours of bright light exposure led to more than 2 hours of phase shift in either direction, a 1-hour pulse of the same illuminance resulted in peak shifts of only 40% the magnitude.

Melanopic Illuminance: The brighter the light, the stronger is its impact on the circadian system. The dose-response curve for 3 consecutive days of morning light administration appears to be non-linear (or nearly linear over a cubic-root representation

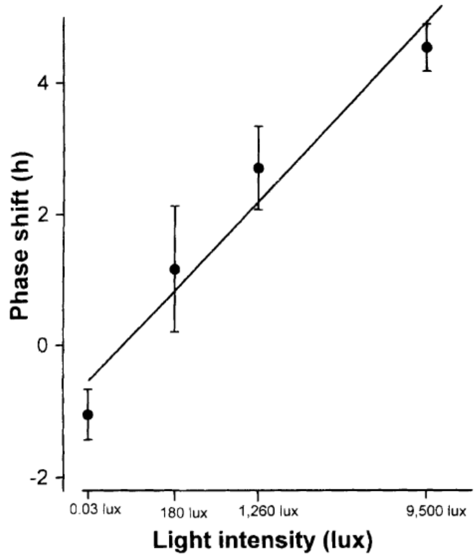

Figure 2.9: Dose-response relationship between light intensity and the magnitude of circadian phase advance for a 5-hour light pulse administered on 3 consecutive days in the early biological morning. From [57]

of light intensity from 0-10.000 lux) with significant effects already observable at 180 lux intensity of cool white fluorescent light (see figure 2.9) [57]. In a follow-up study by Zeitzer et al. [58], half of the maximal phase-delaying response to evening light was evoked by an intensity of only 100 lux, which is around 1% of the light intensity needed for the maximal response (9000 lux).

Light dynamics: Dynamic changes in light can have notable effects on circadian entrainment, even at low intensities. Two forms of dynamic lighting have proven relevant:

- **Dawn Simulation:** Artificial dawn light, which is a gradual increase of light intensity in the morning, can have notable effects on circadian entrainment, even through closed eyelids. [59]. In a field study, a 90-minute naturalistic dawn simulation prior to awakening could advance circadian phases by ∼30 minutes over weeks of consistent exposure. [12].
- **Millisecond flashes**: Beside dawn simulation, it was found that periodic ultra-brief flashes of light (e.g., 2 milliseconds every 10 seconds) induced even larger circadian phase shifts than continuous exposure to light of the same illuminance [60]. Interestingly, these millisecond flashes, administered when the study participants were asleep, potently shifted the participants circadian phase without waking them up or significantly disrupting sleep architecture [15]. This finding has opened up new possibilities to reset people's circadian clocks as a perfectly passive intervention during sleep.

Light's effect on mood

Light is a potent modulator of mood and mental health. Light therapy is a first-line treatment for SAD and an increasing number of studies hold promise for the treatment of non-seasonal forms of depression [18, 20, 61, 62]. Light therapy is segmented into the two interventions *bright light therapy* and *naturalistic dawn simulation* [18].

Bright Light Therapy (BLT) Bright Light Therapy describes the exposure to artificial light of high intensity, typically delivered through a lightbox emitting light at an intensity of 10,000 lux for 30 minutes per day [63]. BLT is considered a first-line treatment for SAD and has demonstrated remission rates of up to 80% in clinical trials [18, 24]. Its effectiveness extends to non-seasonal depression, though with lower effect sizes than for SAD. Still, BLT outcomes are comparable to those of antidepressant medications [61]. BLT is most effective when performed in the early biological morning, coinciding with the time of highest circadian sensitivity for phase advance [24].

Naturalistic Dawn Simulation (NDS) Naturalistic Dawn Simulation mimics the gradual increase of light during dawn by using programmable lighting systems to provide low-intensity light that brightens over time, simulating a naturalistic dawn pattern over 90 minutes [27]. Unlike BLT, which involves exposure to bright light over a shorter duration, NDS operates at a light intensity one order of magnitude lower BLT and the patient is asleep most of the intervention period [27]. Dawn simulation has also been recognized as a first-line treatment for SAD by the American Psychiatric Association. The average effect size was found to be slightly smaller than that of BLT, [18] although there are comparative studies that show found the two interventions to be similarly effective [27] or NDS even superior to BLT [25]. The author did not find any trials investigating the effect of dawn simulation on non-seasonal mood disorders.

2.3 User-centered Design (UCD)

In product development, a successful solution is one that optimally serves the purpose it was made for. When developing interactive systems for humans, success becomes directly connected to the users' experience with the product. The best product is one that optimally serves the user's needs in their respective context [64]. Therefore, it is of critical importance to integration the user as a stakeholder into the design process [65].

User-centered design (UCD), also known as human-centered design, is an iterative design process that integrates the prospective user into the entire development process. The UCD process does not follow a rigid structure, but rather follows a set of design principles and offers a variety of methods that both put the user into the center of the development process [66]. This section presents the principles of UCD, outlines the development phases derived from these principles. Finally, an unexhaustive set of distinctive methods of the UCD process is listed, notably the methods relevant for this thesis.

While UCD puts the user into the center of development, users are not actively included in the design process, which makes UCD different from participatory design [66]. As is of particular relevance for this thesis, the people who use the product may lack relevant expertise in domains that are critical for the design of the system. In this thesis, this would be the biological background knowledge and the technical lighting expertise. As Abras et al. [66] have put forth, users cannot substitute for the integration of respective domain experts into the development process, too. In UCD, a qualified team develops the product while the user is integrated into the process for feedback and a profound understanding of the user's context and needs.

2.3.1 UCD Principles

In their foundational work for the field, Gould et al. [67] recommend three key principles that underlie the UCD process:

1. **Early Focus on Users and Tasks:** Understand who the users will by studying their characteristics. Furthermore, study the nature of the work to be accomplished

2. **Empirical Measurement:** Early on, seek to enable an interaction between the user and the product. This can be through prototypes of different growing fidelity. Measure and analyze user behavior and reactions.

3. **Iterative Design:** Employ and repeat a cycle of design, test and measure as often as necessary. After every iteration, revise the design to fix identified problems.

In 2010, the International Organization for Standardization (ISO) published a guideline *"ISO 9241-210: Human-centered design of interactive systems"* [68], specifying an official and standardized framework for UCD. In their guideline, the key principles of Gould et al. [67] are expanded into 6 guiding principles of the UCD process [68]:

a) The design is based upon an explicit understanding of users, tasks and environments.

b) Users are involved throughout design and development.

c) The design is driven and refined by user-centred evaluation.

d) The process is iterative.

e) The design addresses the whole user experience.

f) The design team includes multidisciplinary skills and perspectives.

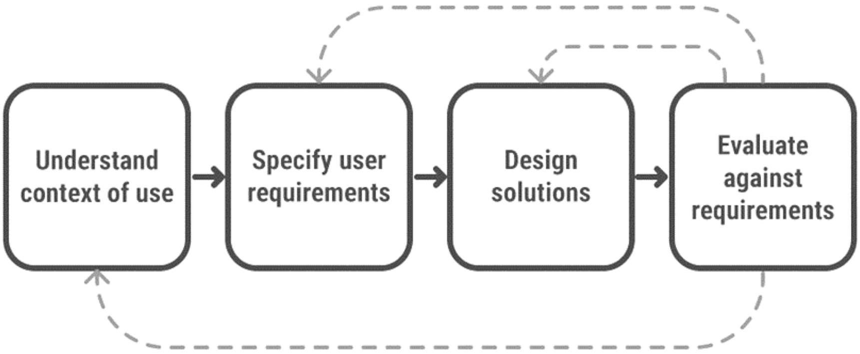

Figure 2.10: User-centric design phases: The four phases of user-centric design are repeated iteratively. Each stage focuses on the user and includes the same wherever suitable. From [69] based on the ISO 9241-210 guidelines [68]

2.3.2 UCD Process

In their work, Gould et al. [67] propose division of the UCD process into an *initial design* phase and an *iterative development phase*, although they stress that there is no clear cut between these two phases.

The initial design phase allows for preliminary system specifications but shall also include user research and the development of goals and measures based on which the success of the product shall be assessed. The iterative development phase, then, foresees a looping through specification, prototypical implementation, testing and evaluation phases. Based on the findings of the previous iteration, the specification is revised and the next implementation iteration is started. [67]

The ISO 9241-210 framework [68] provides a more structured framework for the UCD process. After an initial preparation stage, in which the process itself is planned, the UCD process is represented by a loop between 4 stages, visualized in Figure 2.10:

1. Understand and specify the context of use In this stage, relevant information on the users and other potential stakeholder groups is collected. Via research methods, such as interviews, questionnaires or observation, goals and tasks of users should be identified, as well as their environment and constraints. [68]

2. Specify user requirements In this stage, individual user needs within their context are formulated. The specified user needs should rather focus on what users aim to achieve rather than how they could achieve it. To guide the design and evaluation processes in the next stages, the user requirements should be testable. [68]

3. Design solutions Based on the specified requirements, concepts that align with the user's needs are created and refined. Generative methods such as brainstorming or prototyping can be employed. This output should be something that, in alignment with Gould et al.'s [67] UCD principle 2, can be empirically tested by users. [68]

4. Evaluate against requirements In the last stage of the loop, prototypes and design solutions are tested by users and feedback is gathered. The feedback is used to assess whether or to which extent requirements are being met, to identify issues and refine the design further. [68]

However suitable, this 4-stage loop may be re-iterated in its entirety or in parts throughout the UCD process. The results of stage 4 are used to inspire a revision of the solution. When the 4-stage cycle is looped until there are no more relevant issues, the result of the process can be expected to be a solution that meets the user requirements. [67, 68]

2.3.3 UCD Methods

UCD prioritizes direct interaction with users to guide the design process. It employs a diverse range of methods, each tailored to specific objectives: some are particularly suited to understand the user better, while others are effective in generating or evaluating system designs. Although not exhaustive, this section provides 3 exemplary methods that can be used for the UCD process which particularly relevant for the methodological approach pursued in this thesis.

Interviews

Interviews are an intuitive yet highly effective method in the UCD process. Widely endorsed in the literature, interviews are a foundational technique for gaining a deeper understanding of user needs and behavior. Conversely, in the evaluation phase of the UCD process, interviews can provide valuable insights into the users' experiences with the tested system. [70, 71]

Interviews can be conducted in various formats, depending on the level of preparation and guidance provided during the conversation. Structured interviews follow a formal approach, using a predefined set of questions to ensure consistency and comparability. Semi-structured interviews, on the other hand, combine a core set of planned questions with the flexibility to explore unanticipated topics as they arise. Both structured and semi-structured formats are well-suited for generating quantitative data due to their more focused scope. In contrast, unstructured interviews adopt an open and informal approach, allowing for a free-flowing discussion without predetermined questions. This format is particularly effective for gathering qualitative data, as it enables participants to share deeper insights and explore novel ideas. However, the richness of the data obtained through unstructured interviews often comes at the cost of increased time and effort compared to the more structured formats. [72]

Prototyping

Prototyping is a fundamental method in UCD, enabling the visualization of design concepts and early user feedback. Prototypes can vary in fidelity, ranging from low-fidelity sketches and wireframes to high-fidelity, fully interactive models. Low-fidelity prototypes, such as paper sketches or basic mockups, provide a quick and cost-effective way to explore ideas and identify major usability issues early on. In contrast, high-fidelity prototypes, such as clickable digital interfaces or near-complete models, offer a more realistic representation of the final product, allowing for detailed feedback on functionality and aesthetics. Regardless of fidelity, prototypes serve as a vital communication tool between designers and users, ensuring that design choices are informed by real user needs and preferences. This iterative process of creating, testing, and refining prototypes helps to align the design with both functional requirements and user expectations. [65]

Logging

Logging is a method for collecting data about user interactions with prototypes. The prototype may automatically record user actions, times of interaction, feature usage or error occurrences, providing insights into user behavior over time with minimal effort. Logging is particularly useful for reconstructing user behavior patterns and identifying usability issues. Complementing logging with interviews can help gain deeper insights into why certain features were used or avoided, making it an effective supplementary method for refining prototypes. [70]

2.4 Requirements Engineering

For a development project to achieve success, it is essential to establish a clear definition of what constitutes 'success' within its specific context. Requirements Engineering represents the process that leads to this definition. Requirements engineering comprises the elicitation, documentation, validation and management of system requirements [73]. The goal of the process is the specification of high quality requirements, which are complete and consistently documented. Each requirement has to fulfill certain quality requirements in itself: They should be unambiguously understandable, identifiable, verifiable, complete in its description of the functionality yet atomic, i.e., each requirement ID should only describe a single functionality, among other criteria [74].

Depending on the development process as a whole, the requirements engineering process can represent an initial stage of the development process, but it can also be iteratively or continuously interwoven with other stages of development [74]. In user-centric development, which is an iterative development process, an initial set of requirements is iteratively revised based on the learnings from each development iteration [75].

Typically, requirements are classified into functional and non-functional requirements, as two disjoint types [74]:

Functional Requirements Functional requirements describe *what* a system should be able to do. They comprise requirements towards the *statics* (i.e., the structure of functionality and data), *dynamics* (e.g., how a system behaves in relation to the time or its interaction history), and *logic* (e.g., certain rules regarding how decisions are made) of a system. [74]

Non-functional Requirements Non-functional requirements describe expectations towards the system that concern the *how* things are done, rather than *what* things are done. Within non-functional requirements, Pohl et al. [73] further distinguish between *quality requirements* and *constraints*. Examples for quality requirements of software systems are the expected availability, accessibility or maintainability of a system. Constraints put limits to the temporal, legal or contextual frame within a project is developed [73]. For example, a system may be required to be finished within 6 months and comply with national or international privacy guidelines.

2.4.1 Requirement Elicitation

The requirement elicitation phase is a fundamental step in identifying the underlying requirements that align with the overall project vision. According to Pohl et al. [73], a well-defined vision serves as the foundation for the development process. While the system requirements may evolve throughout the course of development, the overarching vision should remain stable. [73]

A comprehensive requirements elicitation process necessitates the involvement of all relevant stakeholders. Whereas in user-centered design (UCD), particular emphasis is placed on the users as a stakeholder group, other stakeholders may also play a critical role in the requirements elicitation process. For instance, if the system's envisioned functionality includes the accurate reproduction of specific light applications, it is essential to determine the precise criteria that domain experts would consider an "accurate reproduction". Additionally, technical and legal requirements, which may not directly impact the user's interaction with the system, must also be taken into account. Consequently, while user requirements elicitation from the UCD process is a vital part of the process, it represents only a subset of the broader requirements elicitation. [75]

There are various established methods for eliciting system requirements, three of which are outlined below. Since the users represent a key stakeholder group, the respective methods exhibit significant overlap with the UCD techniques presented in Section 2.3.3. Generally, though, the focus of the requirement elicitation methods lies on the integration of all relevant stakeholders.

Workshops In workshops, as a requirements elicitation method, multiple stakeholders to gather input and refine system specifications. Beyond the inclusion of multiple perspectives, workshops foster stakeholder buy-in, and support the formation of an effective project team. Moreover, the collaborative process can help identify and resolve challenges to the project's success that might otherwise remain latent. The outcome of the workshop can represent an initial version of functional and non-functional system requirements. [76]

Interviews Interviews are a requirements elicitation method in which the analyst talks to a representative stakeholder, such as an opinion leader, technical expert or key user, to gather their needs and inputs. Interviews only require one stakeholder at a time and can, therefore, be more easily arranged a workshop, which requires synchronous availability of multiple stakeholders. On the other hand, it lacks the advantages of that very synchronous exchange. As already discussed in Section 2.3.3, different levels of structure (open, semi-structured, or structured) serve different purposes of the interview. [72]

Document Analysis Document analysis is a technique for gathering requirements by examining existing documents to extract relevant insights. It represents an inexpensive method that is particularly useful to establish an initial set of requirements before engaging with stakeholders to refine them. When employed alone, however, document analysis poses the risk of missing important requirements that could easily be identified through an interaction with stakeholders. [72]

2.4.2 Requirement Specification

Once the requirements have been elicited, they need to be documented in a way that can be used for the further development process. The specification of requirements can be performed in different formats which vary in their level of structure and formalization.

1. **Unstructured Methods (Natural Language Specification)**: This unstructured way of specifying requirements relies primarily on natural language to describe requirements. The natural language approach is flexible and widely used. It has the advantage that the requirements can be understood without technical knowledge, which may not be the case for structured requirement formalization methods. As a disadvantage, specifications in natural language may be more vulnerable to ambiguities and inconsistencies. [73]

2. **Semi-Structured Methods (Template-based Specification)**: These methods still use natural language as a foundation but introduce constraints such as predefined templates, controlled vocabulary, or structured properties. This approach helps reduce ambiguity while maintaining some level of flexibility. Templates can be employed on a form level (e.g., for use cases), on a document level (e.g., requirement specification document) or for the structure of sentences (e.g., for user stories). [73]

3. **Structured Methods (Model-based Specification)**: Structured methods follow a strictly defined syntax, notation, or formal specification language. This structure ensures precision and consistency, making this approach particularly

useful for complex systems with rigorous requirements. Model-based requirement specification formats typically include one or more diagrams. Diagram Examples include use case diagrams, process model diagrams and class diagrams of the unified modeling language (UML). However, models can also represent a combination of diagram representation and written specification (e.g., use case diagram plus detailed description of each use case). [73]

CHAPTER 3

State of the Art

This section explores the state-of-the-art (SOTA) for alleviating sleep inertia upon awakening, applying light therapy to improve mood, and shifting circadian phase. The first three subsections investigate SOTA for each of these three categories. On this basis, the final section of the chapter summarizes the current gaps between the academic SOTA and its application in practice, revealing how a novel smart light concept closing these gaps would advance the SOTA of applied light interventions regarding sleep inertia, light therapy and the influence on circadian phase.

3.1 Alarm clocks addressing sleep inertia

As introduced in Section 2.1.2, sleep inertia describes the tiredness and cognitive impairment experienced among and after awakening. The mitigation of sleep inertia, therefore, is a significant added value for alarm clocks, beyond the core value of reliably awakening people at a set time. Two branches of specialized alarm clock types have emerged that address sleep inertia in different ways: Light alarm clocks and sleep cycle alarm clocks. This section gives an overview of the state of the art in both device categories. Furthermore, it explains the strengths and weaknesses of both approaches.

Sleep Cycle Alarm Clocks

Sleep cycle alarm clocks aim to mitigate sleep inertia by waking users during a light sleep stage. Sleep inertia is particularly pronounced when awakening occurs during slow wave sleep (SWS) episode. By contrast, waking during lighter sleep stages (N1, N2, or REM) facilitates a smoother transition to wakefulness, improving both mood and cognitive function upon awakening [77, 8].

To achieve the goal of waking users during light sleep, various technological approaches have been developed. Wearable devices such as smartwatches and fitness trackers have become a popular solution for monitoring sleep stages. These devices typically employ a combination of accelerometry (to measure body movement) and photoplethysmography (PPG) sensors (to measure heart rate variability) [78]. Algorithms analyze these physiological signals to estimate sleep stages in real-time, enabling the device to trigger an alarm during a user's light sleep stage within a predefined wake-up window.

Non-contact approaches, such as those employed by smartphone applications like *Sleep Cycle App*[1] and *Sleep as Android*[2], use the phone's inbuilt microphone as an ultra-sound sensor to infer sleep stages without requiring wearable hardware. Apart from smartphone-based approaches, radar-based solutions represent the state of the art for non-contact sleep detection [79].

The most notable drawback of sleep-stage-based alarms is the unpredictability of wake timing. To awaken the user from a suitably light sleep stage, the user must provide a time window in which they are flexible to be woken up. This can result in a significant reduction in sleep duration and represents a potential nuisance if the user's sleep opportunity allowed for a longer sleep duration and the level of alertness upon awakening is still not optimal.

Finally, although the commercial application of sleep cycle alarms is widespread, the review on sleep inertia by Trotti et al. [8] reports mixed results on the impact of sleep stage on sleep inertia at all, even when sleep stage is assessed with polysomnography, the gold standard in sleep stage grading.

Wake-up Lights

Wake-up lights aim to facilitate a gentle awakening by simulating dawn before and upon scheduled awakening. They present a light signal that gradually increases its brightness from zero to roughly 250 Lux in the last 30-90 minutes before the scheduled wake time [11]. Wake-up lights have been shown to reduce sleep inertia [16]. Their behavior is more predictable, which is an advantage over sleep cycle alarms. Young adults typically manage to sleep through the dawn signal but experience a more gentle awakening when they are finally awoken by an audio signal [80]. However, the reduction of sleep inertia seems to be an acute effect of the dawn signal and not a result of a circadian phase advance, as studies have shown non-significant effects of dawn simulation from wake-up lights on circadian phase. [16, 19].

Typically, wake-up lights are alarm clocks with a small lamp, placed on the bedside table (see Figure 3.1 for a photo of a representative model by Philips). With the advent of smart home lighting such as by *Philips Hue*[3] or *IKEA Tradfri*[4], light bulbs or smart ceiling lamps have become an alternative to bedside wake-up lights, offering scheduled dawn simulation support. Smart light setups can provide a more diffuse illuminance than

[1] https://www.sleepcycle.com/, accessed on 2024/12/10
[2] https://sleep.urbandroid.org/, accessed on 2024/12/10
[3] https://www.philips-hue.com
[4] https://www.ikea.com/at/de/customer-service/product-support/smart-lighting/licht-individuell-anpassen-leicht-gemacht-pub61503271

Figure 3.1: A representative commercial wake-up light: Philips Smart Sleep HF3531/01 in its packaging

wake-up lights, eliminating the small luminous field for which available wake-up lights have been criticized in the scientific literature [20, 11]. However, online research has not revealed any studies investigating the effects of dawn simulation with consumer smart ceiling lights on human physiology.

A notable special case in the alarm clock landscape was the *Amazon Halo Rise* wake-up light, which combined dawn simulation with non-contact sleep detection and sleep-stage-based smart alarm timing. However, due to undisclosed reasons, the product was discontinued by Amazon in late 2023[5].

3.2 Light Therapy

As established in Section 2.2.2, light therapy is a validated therapeutic approach for seasonal affective disorder and shows promise for other forms of depression, likely those underpinned by circadian dysregulation [20, 23]. This section explores the availability of devices to perform light therapy in the form of either *bright light therapy* or *naturalistic dawn simulation*.

Bright Light Therapy

The recommended protocol for bright light therapy (BLT) is a daily 30-minute exposure to 10,000 lux light intensity in the early morning. The recommended illumination angle is 15-45° from above [28].

The typical deice to produce this bright light are *daylight lamps*, which are light boxes dedicated to the purpose of producing bright light. There is a vast number of alleged

[5]https://www.aboutamazon.com/news/company-news/amazon-halo-discontinued

"10,000 lux" daylight lamps on the market. However, since lux is a measure that depends on the distance to the light source (see Section 2.2.1), 10,000 lux without a reference distance is a worthless information. For a suitable BLT setup, the lamp should provide 10,000 lux from at least 30cm, ideally 45cm or even 60cm distance. These devices are significantly larger and more expensive than typical consumer daylight lamps.

The *CET - Center for Environmental Therapeutics*[6], a non-profit organization that is a key opinion leader in the field of light therapy, lists the Northern Light BoxElite OS[7] as their recommended daylight lamp. It is depicted in Figure 3.2a.

A frequent complaint from patients who apply BLT is the inconvenience caused by the therapy: Firstly, patients have to rise early in the morning for the therapy every day. Secondly, the therapy requires patients to sit in front of a light box for 30 minutes [25, 26]. To provide a solution for the latter, the Belgian startup Lucimed offers a portable bright light therapy device *Luminette*[8], a light visor worn like glasses (see Figure 3.2b) that emits lights into the eyes from a short distance. However, light from the Luminette delivers only 1500 lux, which falls short of the recommended 10,000 lux. While the device is a certified medical product, the company does not list any studies addressing SAD treatment successes on its website.

(a) Daylight lamp: NLT BOXelite OS (image from the Luminette website)

(b) Light visor: Luminette 3 (image from the CET website)

Figure 3.2: Established devices for the application of bright light therapy

[6]https://www.cet.org
[7]https://cet.org/shop/lighting/bright-light-therapy-lamp-2/
[8]https://myluminette.com/en-eu

Naturalistic Dawn Simulation

In a large controlled study by Terman et al. [27], naturalistic dawn simulation (NDS) was shown to decrease symptoms of seasonal affective disorder (SAD) by 49.5%, which was comparable to the efficacy of BLT in the same trial. The dawn signal lastet 90 minutes and mimicked the natural illuminance curve from 0.001 to 250 lux, as it would occur in the morning on May 5 at 45 degrees north latitude.

Given the convenience of dawn simulation compared to 30 minutes of bright light therapy early in the morning, the study's author Michael Terman stated in a follow-up publication that *"it [NDS] may become the next-generation light therapy"* [81]. However, Despite its theoretical potential, there is no available device that accurately reproduces the lighting conditions used in Terman et al.'s study [27]. Dawn simulation with currently available devices is not a recommended treatment for SAD: Due to their small luminous fields, current wake-up lights fail to produce the diffuse illuminance that would be needed to reach the patients' closed eyes independent of their sleeping position. [11].

3.3 Applications to Advance Circadian Phase

As much as they are the SOTA treatmens for mood improvement, BLT and NDS represent the two applications that have been validated to advance circadian phase, even in a field application by roughly 30 minutes each [12]. Conversely, as much as they are not recommended for SAD treatment, wake-up lights have so far also failed to induce significant circadian phase advances, both in the lab and in the field [19, 16].

Blue Light Application

As the human circadian system is most sensitive to light with wavelengths around 480nm [82], there are devices on the market that produce only narrow-band blue light. Indeed, with only a fraction of the illuminance of bright light therapy, *blue light lamps* were shown to successfully induce circadian phase advances in humans [16]. Blue light therapy was even shown to improve SAD under controlled conditions [83]. Narrow-band light visors such as the *Re-Timer*[9] represent consumer devices to advance circadian phase.

Periodic Millisecond Flashes

In Section 2.2.2, it was established that periodic flashes of just a few milliseconds duration have a powerful impact on circadian phase. In a study by Kaplan et al. [84] from 2019, the exposure to millisecond flashes of bright light during the last hours of sleep appears to have effectively advanced circadian phase in adolescents, leading to an earlier intrinsic wake time and reduced sleep onset latency. In cominbation with cognitive behavioral therapy, this novel application of light led to an increase of the average participant's sleep

[9]https://www.re-timer.com/retimer-3/

duration by 43 minutes. In the study, custom hardware was used to create the flashes. [84]

For a real-life application, an anti-jetlag sleep mask from *Lumos Tech*[10] appears to be the only available device making use of this technology. The sleep mask has LEDs integrated into the mask, which produce the flashes. There are currently no bedside devices or other ambient light sources available that would offer such a functionality.

3.4 Summary of academic SOTA versus its practical availability

When comparing the theoretical potentials of ambient morning light against their availability for a day-to-day application, clear but closable gaps between the academic and practical SOTA becomes visible. Table 3.1 visualizes this juxtaposition of theory and practice.

In summary of the above sections in this chapter, the three domains *"facilitation of a gentle awakening"*, *"light therapy"*, and *"shift of circadian phase"* reveal a total of four different light interventions that represent the SOTA for one or more categories:

1. **Bright Light Therapy (BLT): applicable**.
   BLT represents the current SOTA intervention for light therapy, i.e., the treatment of affective disorders with light [20]. Furthermore, BLT in the early biological morning represents a SOTA approach to advance circadian phase [56]. Its practical application is widespread and accessible via *daylight lamps*, a type of luminaire that is optimized for the application of bright light.

2. **Naturalistic Dawn Simulation (NDS): currently no application**
   NDS, like BLT, is recognized as a SOTA treatment for SAD [18]. While showing similar efficacy as BLT in both SAD remission rate and magnitude of circadian phase shift [27, 12], NDS bears the great advantage that its application happens during sleep and upon awakening. Therefore, its application does not require any effort or dedicated time. Unlike BLT, there is currently no practical application for NDS available [11].

3. **Millisecond Flashes (MSF): currently no ambient application**
   MSF represent a third SOTA light application to shift circadian phase [60] and is also applicable during sleep [85]. Its application in the field is currently limited to a smart sleeping mask. While the mask-based approach may appear intriguing, it currently lacks scientific data about its viability. Anecdotal reports[11] reveal that sleeping masks often do not stay in place throughout the night. A displaced mask,

[10] https://lumos.tech/

[11] https://www.irishtimes.com/technology/consumer-tech/review/2024/10/10/aura-sleep-mask-review-a-comfortable-high-tech-sleep-aid-for-insomniacs-with-a-few-quirks/

however, leads to no light exposure in the morning. Conversely, the applicability of ambient flashes is well established [84] but lacks available implementations.

4. **Wake-up Lighting: applicable**
   The SOTA for the facilitation of a gentle awakening with light is found in a gradual increase of light intensity from zero to around 250 lux that starts 30 minute before the user's scheduled wake time [80]. The practical application is possible with wake-up lights, which represent an established category of specialized alarm clocks.

The lack of availability of NDS and ambient MSF means that people who fail to bring up the required time or effort for BLT are currently deprived of SOTA options for mood improvement or the treatment of social jetlag. This is important, since Avery et al. [25] and Winkler-Pjrek et al. [26] report that the inconvenience connected with post-awakening BLT is an obstacle to a successful application for many people. Considering the estimates that 22 million people in European Union suffer from SAD each year [22] and an astounding 70% of the population have a social jetlag of 1 hour or more [7], this lack of SOTA applicability has significant health consequences for millions of people. Consequently, making ambient applications of NDS and MSF accessible would represent a significant translational contribution to the field of circadian health. NDS and MSF would provide people with the opportunity to conveniently integrate light therapy and means to shift their circadian phase into their daily wake-up process. From a technical point of view, there is no reason why an at-home application of these interventions should not be possible. Furthermore, there is no technical or logical reason that would prevent even a combination of all four aforementioned SOTA morning light interventions. A successful combination could couple and possibly even stack their individual effects in every illustrated domain. The attempt to reproduce a proper NDS and MSF and couple it with BLT and wake-up lighting, therefore, is worth exploring.

Device Category	**Bright Light Therapy**^{ts}	**Naturalistic Dawn Simulation**^{ts}	**Millisecond Flashes**^{s}	**Wake-up Lighting**^{a}
Wake-up Light	No	No	No	✓
Daylight Lamps	✓	No	No	No
Light Visors	✓	No	No	No
Our concept*	✓	✓	✓	✓

*to be developed in this thesis

Table 3.1: Juxtaposition of the four SOTA light interventions for the domains *"facilitation of a gentle awakening"* (superscript "a"), *"light therapy"* (superscript "t"), and *"shift of circadian phase"* (superscript "s") with currently available ambient applications of them.

Given a suitable lighting setup, NDS and MSF are characterized more by their lighting dynamics than their hardware specification. Given the right hardware and modern smart light protocols, the reproduction of the mentioned SOTA light interventions in the private home is mainly a challenge of algorithmic light control and UX engineering. Therefore, this challenge falls into the field of Medical Informatics.

CHAPTER 4

Methods

The work for this thesis was split into four phases that are based on the principles of user centered design. In phase 1, *requirements engineering*, the necessary knowledge to define system requirements was acquired. It ends with the formulation of these requirements. After this analysis, phase 2 comprises the specification of an *initial system design* that promises to satisfy the system requirements. Then, in phase 3, *prototyping & implementation*, an iterative implementation process was followed to create two prototypes of the specified system concept. Each prototype built on the insights gained from the previous implementation iteration. Eventually, in phase 4, all the findings from the previous three phases were put together to formulate a *final system specification*.

4.1 List of people involved in the development process

A total of 9 people, other than the author of the thesis, were directly involved in the work conducted in this thesis. These are 3 domain experts who were interviewed, 2 people who assisted the author with the construction of the prototype hardware and 6 test users for the prototypes. This section lists all 9 people in their respective subsections as well as the identifiers by which they are referenced in this thesis.

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Domain Experts In the requirements engineering phase of this thesis, 3 interviews were conducted with experts in their respective domains. Two of them, Exp01 and Exp01, were researchers in the fields of sleep and light therapy, who authored relevant studies for this thesis. The third expert interviewee Exp03 held the academic title *Master of Light and Lighting* (MLL) and was an expert on lighting. Table 4.1 gives a formal overview of their professions and field of expertise.

Table 4.1: Domain Experts

Expert ID	Profession	Field of Expertise
Exp01	Psychologist (retired) at Columbia University, USA	Light Therapy
Exp02	Sleep Researcher at Stanford University, USA	Light and Sleep
Exp03	Lighting Designer in Vienna, Austria	Lighting

Hardware Assistants As the implementation of the prototype in hardware lay neither in the scope of Medical Informatics nor in the author's field of skill, hardware implementation for the prototype iterations was assisted by two people. These were Simon Bellink, BSc, wood technologist, and Saeed Helali, electrical engineer from TU Wien. Table 4.2 lists the two assistants and their backgrounds.

Table 4.2: Hardware Assistants

Name	Academic Background
Simon Bellink, BSc	Wood Technology
Saeed Helali, BSc	Electrical Engineering

Prototype Users A total of six users (ages 19-35, 2 women and 4 men) participated in prototype tests. 3 users tested the early prototype (iteration 1) and 3 users tested the advanced prototype (iteration 2) for 3 weeks each. Table 4.3 lists the demographic information for the users, as well as which prototype iteration they tested.

Table 4.3: Prototype Users

User ID	Sex	Age Group	Iteration
P01	Male	26–35	1
P02	Male	19–25	1
P03	Male	26–35	1
P04	Male	26–35	2
P05	Female	19–25	2
P06	Female	26–35	2

4.2 Phase 1: Requirements Engineering

In addition to the biologically motivated features, the concept requires system features related to user interaction, as well as functional and non-functional hardware requirements. To gather these requirements, scientific research and online market research was conducted.

Expert interviews with scientists and a lighting expert were conducted to refine and advance the findings from the individual research.

An interview with the target group of people with late chronotype, which had been conducted in a graduate course preceding this thesis, was evaluated with regards to the users' expectations towards the user interaction with the system. Consequently, user interaction requirements were derived from it and formulated in this thesis.

Overall, this process led to the formulation of photobiological requirements (see section 5.1.1), user interaction requirements (see section 5.4) and hardware requirements (see section 5.1.3). Furthermore, the market research laid the foundation for the technology stack and product selection in hardware and software that was made in the implementation stage of the practical phase.

4.2.1 Photobiological Research

The first part of the research phase regarded the biological effects of morning light on human physiology. From this research, photobiological requirements towards the smart morning light (see section 5.1.1) were derived. This requirement definition corresponds to this thesis' research question RQ1 (see Section 1.3).

The photobiological research phase consisted of scientific literature research and scientific expert interviews.

Scientific Literature Review

The literature research included a systematic search on popular research platforms for various keyword combinations, as defined by table 4.4. All interventions have been searched in combination with all effect domains, resulting in keyword combinations such as *"dawn simulation mood"*, *"dawn simulation alertness" "artificial dawn mood"*, *"artificial dawn alertness"*, etc.

Table 4.4: Intervention and effect candidates for the keyword search

Intervention	**Effect Domain**
Dawn Simulation	Mood
Artificial Dawn	Alertness
Morning Light	Sleep Inertia
	Circadian Phase

The entries for each search result have been filtered by relevance for the topic. The resulting publications were then analyzed as the literature base for the photobiological requirements.

Scientific Expert Interviews

After an initial scientific requirement concept had been formulated, the concept was discussed with expert Exp01, a psychologist and pioneering researcher in the field of light therapy (see Table 4.1). Today, he is the president of the *"Center for Environmental Therapeutics"*, a non-profit organization based in the United States for the endorsement of light therapy. The interview guideline used for this conversation is provided as Appendix A of this thesis.

Furthermore, the initial concept was discussed with expert Exp02, who is a sleep researcher and co-director of the *"Center for Sleep and Circadian Sciences"* at Stanford University. Exp02 is an internationally renowned expert on light's effects on sleep and human physiology. The interview guideline is provided as Appendix B.

Both inteviews were conducted following a semi-structured interview process. Based on the feedback of these two experts in the field, the initial photobiological requirements were revised and the concept as presented in Section 5.1.1 was formulated.

4.2.2 User Interaction Research

While scientific efficacy is a vital prerequisite for the overall benefit of the conceptualized smart light, the device's usability may be the key value proposition for why people would prefer it over existing bright lighting solutions to address their issues. Bright light therapy, as used to treat mood disorders today [26], requires time in the morning and is not something people would do if it were not for therapeutic purposes. Wake-up lighting, in contrast, integrates seamlessly into people's schedules while providing acute benefits and an inherently pleasurable experience. To keep this advantage upright, the users' interaction with the smart light device must be integrated conveniently into people's routines, too. How this can be achieved represents research question RQ2 of this thesis.

To assess user interaction requirements for the smart light system beyond necessary configuration features, interviews with prospective users from the target group were analyzed.

Interview Analysis

Interviews with 11 prospective users from the target group, that is, "night owls" struggling with morning tiredness, have been analyzed. These interviews were of semi-structured nature and had been conducted prior to this Master's thesis, in the context of my university course "Projekt in Medizinische Informatik" at TU Wien. This course served as the precursor for this thesis. Participants were interviewed with regard to their current wake-up experiences, their ideal scenarios, and hopes and fears towards a smart light wake-up aid. The semi-structured interviews were exploratory in nature. The interview guideline was as follows:

1. How would you describe your sleeping life?

  - sleeping habits
  - quality of sleep
  - sleep onset/wake up
  - sleeping environment

2. What do you consider the biggest pain points?
   - What possible causes do you see?
3. What have you already tried to solve these issues?
   - What have been your experiences with that?
4. What else would you like to try but have not tried yet?
   - Why have you not yet tried that?
5. What would you like to know about your sleep or sleeping environment?
6. Under which conditions do you sleep best?
7. How would you picture your ideal wake-up scenario?
8. (After a short concept briefing) How would you preferably interact with a smart wake-up lighting device?
9. To what extent should the device automatically adapt to your preferences?
10. What connectivity would you wish for?
11. What would be important for you regarding such a system?
12. How great is your desire to be able to positively influence your sleep or wake-up experience?
13. Assuming the system is able to create your optimal wake-up scenario, what value would you attribute to it?

For the question of optimal usability, particular focus has been put on the analysis of the interview questions 3 and 7 to 11. Still, the entire set of answers was taken into account, to better understand the daily circumstances of the target group.

Based on the analysis results (see section 5.1.2), functional and non-functional system requirements were identified that correspond to the target group's hopes towards their interaction with the proposed smart wake-up light. The interaction-related requirements add to the photobiological requirements of the concept. They are defined in section 5.4.

4.2.3 Hardware and Technology Research

Research question RQ 3 addresses the feasibility of satisfying the system requirements in practice with readily available hardware. To answer this question in theory, research on the state of the art in hardware was conducted, preceded by an interview with an industry expert.

Interview with a Lighting Expert

Before looking for solutions, it was important to identify the right problems. To identify the state of the art in lighting technology, a semi-structured interview with lighting expert Exp03 was conducted. Exp03 is a certified lighting designer with an extensive lighting project portfolio.

After a presentation of the thesis' goals and the system requirements identified so far, the interview comprised a discussion of the following topics:

1. Lighting Requirements
2. Smart Light Control & Automation
3. Construction of the Luminary

The complete interview guideline is provided as Appendix C.

The interview with lighting expert Exp03 led to a set of specific hardware requirements formulated in section 5.1.3. Individual hardware requirements may originate in photobiological requirements. Their formulation serves as an emphasis that the satisfaction of some functional requirement is a non-trivial challenge with off-the-shelf hardware.

Online Research

To find how the hardware requirements formulated in Section 5.1.3 could be satisfied, research was conducted on the state of the art in hardware. Further research on the explicit challenges mentioned by Exp03 aimed at understanding the problem context and identifying suitable technologies as well as concrete products to solve the challenges.

The online research resulted in a set of technologies and products that were used to implement the abstract system architecture. They are found in the design section of each prototype iteration (see Sections 5.3, 5.4 and 5.5).

4.3 Phase 2: Initial Design

Once all requirements were identified, a system architecture was defined that promised to satisfy all requirements if implemented properly.

The architecture defines the separation of functionality and logic into the different parts of the system. In order to leave enough implementation freedom, the architecture specified in section 5.2 was made on an abstract level, leaving out specific technologies or hardware products to implement the architectural entities such as "smart light" or "UI". As the choice of technologies and products was anticipated to vary from one prototype implementation iteration to another, it is specified in the design section of each respective implementation iteration (see sections 5.3, 5.4 and 5.5).

4.4 Phase 3: Prototyping & Evaluation

The prototype implementation process was conducted in two iterations. Following user-centric design cycles as proposed by the ISO 9241-210 guidelines [68] (see Figure 2.10), the prototyping process was coupled with user tests, feedback interviews and a revision of the system requirements in each iteration.

The phases of each implementation iteration (see Sections 5.3, 5.4) are documented with the following structure:

1. **Preparation (Specification)**: Each iteration consisted of a design phase, where choices for technologies and products were made. These choices were made based on the anticipated suitability for the context, market availability, ease of implementation and, lastly, affordability of the hardware.

2. **Implementation**: Based on the specified technology and product choices, the prototype was constructed in hardware and software. While the software implementation represents my work, the hardware construction was largely out of the scope of my personal skillset or the scope of a thesis in Medical Computer Science. Therefore, the hardware construction was assisted by the electrical engineer Saeed Helali and the DIY-enthusiast Simon Bellink. The software development included the development of a digital user interface and the core control logic that operated the peripherals (lights). Every implementation phase resulted in a working prototype in hardware and software.

3. **Evaluation Results**: Following the construction of the device, the prototype was tested for the satisfaction of function and non-functional requirements.

    a) Technical evaluation: The technical evaluation criteria corresponded to the objectively measurable system requirements that are defined in section 5.1.3.

    b) User evaluation: In each iteration, 3 users from the target group tested the finished prototype. To find the users, a public application form was disseminated through the author's social media channels. Then, purposive sampling [86] was employed to identify the applicants that best matched the target group specification. The specification was 18-35 years of age, no apparent sleep problems but a significant struggle with morning tiredness, a self-assessed chronotype of "rather night owl" or "definite night owl", and Vienna as the place of residence. The test duration was 3 weeks per user. Satisfaction with the product in terms of perceived effectiveness and user experience were elicited quantitatively and qualitatively with the following questions after the test phase:

i. *How did you experience your mornings with the prototype compared to your usual mornings?*
1 (much worse) - 5 (much better)
ii. *How did the interaction with the device work for you?*
1 (very badly) - 5 (very well)
iii. *What thoughts or remarks do you have regarding the interaction with the device?*
iv. *How do you feel about giving back the prototype?*
  1. I will miss it very much.
  2. I will somewhat miss it.
  3. I will not miss it.

As user feedback was collected throughout the iterations of prototypical implementation, the set of system requirements was subject to according updates. After every iteration, the requirement updates were noted. The final set of user-interaction-related requirements, together with the final design draft for a user interface, was taken as the basis to answer the usability research question RQ2 (*How can the user interface and human-system interaction look like so that users appreciate the usability of the system?*).

4.5 Phase 4: Final specification

The final phase of the methodology of this thesis comprised the formulation of a final system specification. After the initial system requirements were tested and updated in two prototype iterations, a comprehensive final list of system requirements was formulated in phase 4.

Furthermore, the initial system specification from phase 2 was reviewed. The final system specification includes a summary of the updated design, with a focus on the points that had been updated based based on findings in phase 3.

Finally, the final version of the user interface (UI) was described and supported with screenshots of its implementation.

CHAPTER 5

Results

This chapter contains the results of this thesis, produced through the execution of the user-centered design process defined in Chapter 4. The first two sections are structured according to their phases in the methodology, *Requirements Engineering* and *Initial System Design* of the smart wake-up light. Phase 3, *Prototyping & Evaluation*, is expanded into one section for each iteration of implementation. Finally, the last section covers the results of phase 4, the *Final Specification* of the smart wake-up light concept.

5.1 Requirements Engineering

The requirements for the smart light concept were elicited through an in-depth analysis of the intersection between light and biology, the user's needs and constraints, and current hardware constraints. The analysis of each of these three aspects resulted in their own requirements towards the system. The structure of this section reflects the separation of the analysis into these three aspects: *Photobiological Requirements* (Section 5.1.1, *User Interaction Requirements* (Section 5.4), and *Hardware Requirements* (Section 5.1.3). Each subsection contains the results throughout the respective requirements engineering process and ends with the formalized formulation of the aspect-specific system requirements.

5.1.1 Photobiological Requirements

Research question RQ1 of this thesis addresses the requirements that a smart wake-up light shall satisfy to maximize the odds of a biological benefit for the user (see Section 1.3). The pursued benefits, as mentioned by the thesis title, are increased alertness upon awakening, which corresponds to a decrease of sleep inertia, as well as an improvement of overall mood. To answer this question, a systematic literature research was conducted, which is described in more detail in Section 4.2.1. The findings were discussed with two domain experts in the fields of light, circadian rhythm and mental health.

Based on the reviewed literature and the expert feedback, a set of three lighting interventions was identified that the conceptualized smart wake-up light should have as features. These biologically motivated functional requirements represent an initial theoretical answer to research question RQ1. They are listed in this section.

To provide the maximum expected benefit, the smart wake-up light shall include the following features:

1. Naturalistic Dawn Simulation (NDS)
2. Bright wake-up light (BWL)
3. Millisecond flashes (MSF)

The combination of these three features has been, to the best knowledge of the author, neither used in a commercial device nor investigated scientifically. The investigation of the combination of features is of scientific interest, as each of these interventions alone resulted in complementary, significant benefits in the domains of circadian rhythm, sleep inertia, sleep and mood. It may appear surprising that two different kinds of dawn simulation were selected: Naturalistic Dawn (NDS) and Bright Wake-up light (BWL). Indeed, the two share the concept of a gradual increase in light. However, different specifications of simulated dawn have led to different results: 90-minute NDS has been shown to advance the circadian phase by 30 minutes on average [12] while a phase advance could not be observed in studies with a shorter dawn duration. [19, 16] On the other hand, acute beneficial effects of wake-up lights have been documented, e.g. on sleep inertia [19], regarding which no data for longer dawn durations were found.

In the following paragraphs, the respective feature specifications of NDS, BWL and MSF are presented and discussed in detail.

Naturalistic Dawn Simulation

- **Duration:** 90 minutes
- **Start time:** 7.5 hours after estimated DLMO or 90 min before the set wake time, respectively
- **Maximum Intensity:** 250 lux
- **Light dynamics:** naturalistic dawn transition from 0.001 - 250 lux
- **Light directionality:** diffuse light
- **Light spectrum**: 3000K CCT (warm-white) LED light

Naturalistic dawn simulation (NDS) describes a gradual dawn light signal that mimics the light intensity curve experienced in nature. The concept has been introduced and studied by Michael Terman et al. [27] The feature specifications presented above are mainly derived from the specifications used for Terman's 2006 publication [27], the largest clinical trial of dawn simulation to date. The trial found NDS similarly effective to bright light therapy (BLT) as a treatment for seasonal affective disorder (SAD) [27]. Terman et al. made use of a diffuse dawn light signal from 0.001 to 250 lux over a 90-minute duration. The dawn curve followed the curve of natural dawn in the pattern of May 5 at 45° north latitude. The luminant was a halogen light bulb, which is technically obsolete by today's power efficiency standards. According to our expert interviewee Exp01, warm-white LED light source should be used instead, as a replacement for the warm-white halogen light. In the trial, the dawn signal was timed to finish at the participants' habitual wake times. However, this may not have been the most effective setting. As Khalsa et al. have shown [56], light's phase-advancing effect on the circadian system is maximally effective when presented in the early morning. Likewise, Terman himself found an earlier morning timing to improve light therapy's efficacy for the treatment of seasonal affective disorder [20]. The exact timing of "early morning" differs between people, depending on their circadian phase as measured by *dim-light melatonin onset* (DLMO). Wirz-Justice et al. [24] recommend that early morning therapy start for BLT be 8.5h after DLMO. As people need to be awake for BLT, this corresponds to a wake time of 8.5 hours after DLMO. An inteview with expert Exp01 revealed that there are no a priori data on what the biologically optimal timing for NDS should be. However, as the expected awakening from NDS lies 60 minutes after dawn onset [27], a wake time analogous to Wirz-Justice et al's recommendation for BLT, i.e. 8.5h after DLMO [24], leads to a recommended start of the dawn signal 7.5 hours after DLMO. For the average chronotype [7], this start time corresponds to a clock time of 5:30 a.m, but it may be later for late chronotypes. Due to the lack of data, it was also not clear to which extent the NDS start time should vary with the user's intended wake time or be fixed based on their biological timing.

Bright Wake-up Light

- **Duration:** 30 minutes
- **Start time:** 20 minutes before set wake time
- **Maximum Intensity:** 2500 lux
- **Light dynamics:** quadratic curve
- **Light directionality:** broad-field direct light
- **Light spectrum**: 3000K - 5000K CCT (neutral-white) broad-spectrum LED light

The 30-minute dawn signal of the bright wake-up light corresponds to the default dawn duration of commercial wake-up lights, which has been investigated in multiple studies

[19, 16, 80, 87, 88, 89]. Unlike commercial wake-up lights, however, the bright wake-up light increases up to a light intensity of 2500 lux. This high maximum light intensity upon awakening leads to a reliable suppression of melatonin if stared at with open eyes, regardless of individual melatonin sensitivity to light [90, 53]. The light spectrum starts with a warm-white hue that is typical of commercial wake-up lights. Over time, it transitions to a cool-white hue to increase the melanopic illuminance for the same photopic lux level, as the blue-sensitive melanopic illuminance modulates the alerting effects of light [53, 91]. A broad-field light source is advantageous to avoid glare and reach the user in different positions [63]. Overall, the bright wake-up light aims at leveraging the acute effects of light on human alertness and mood [19, 16].

Millisecond flashes

- **Duration:** 15 minutes
- **Start time:** 8.00 hours after estimated DLMO or 2 hours before wake time, respectively
- **Maximum Intensity:** 1000 lux
- **Light dynamics:** intermittent flashes of 2 ms duration every 20 s
- **Light directionality:** diffuse light
- **Light spectrum**: (6000K CCT (cool-white)) broad-spectrum LED light

In the most recent trial that investigated millisecond light flashes during sleep, a flash duration of 2 milliseconds every 20 seconds, presented in the morning hours, was found to leave the participants' sleep largely undisturbed. [84] In awake participants, a maximum efficacy was found in a flash interval of 8 instead of 20 seconds [60]. However, the risk of sleep interruption outweighs the potential benefit of increased efficacy, as discussed with one of the study's authors Exp02 in our expert interview. Therefore, a flash interval of 20 seconds was selected for this thesis. Xenon light, as used in the trial by Kaplan et al. [84], and LED lights [15] both appear suitable to elicit biological responses while leaving participants asleep. For the sake of availability and energy efficiency, 6000K cool-white broad-spectrum LEDs were selected for our concept. Although Kaplan et al. [84] presented their light signal to participants during the last two hours of their sleep, Joyce et al. [92] found diminishing returns for durations greater than 15 minutes. As a shorter intervention duration reduces the risk of sleep interruption, this shorter duration was adopted. Furthermore, the risk of an interference between the MSF and the other two light interventions of the concept can be reduced with a shorter MSF duration. The timing of the light signal was derived from Kaplan et al.'s study [84] as well, where the light presentation started 2 hours before wake time. On average, this corresponds to 8.00h after DLMO [93], but may be adjusted for habitual wake time. Like the naturalistic

Feature	Effect on Circadian Rhythm	Effect on Total Sleep Time	Effect on Sleep Inertia	Effect on Mood
NDS	30 min phase advance [12]	–	–	49% SAD remission rate [27]
BWL	–	–	Reduced subjective sleep inertia [16]	Improved morning mood [16]
MSF	phase-shift potential [60]	+43 min sleep/night [84]	–	–

Table 5.1: Overview of the three morning light interventions *Naturalistic Dawn Simulation* (NDS), *Bright Wake-up Light* (BWL) and *Millisecond Flashes* (MSF) and their documented effects on circadian rhythm, total sleep time, sleep inertia and mood.

dawn, the flashes are a mean to anchor and stabilize the circadian system. Consequently, their start should ideally remain the same over the course of a user test.

As far as light intensity is regarded, an astoundingly low intensity of 3.9 lux has been found to already induce 50% of the maximum circadian effect [94]. Given that adolescents could sleep through flash intensities of 4000 lux [84], it is fair to aim for considerably higher intensities than the 3.9 lux half-point of the dose-response curve. In our expert interview, Exp02 pointed out that one has to account for the attenuation of light through closed eyelids when the flashes are presented during sleep: Circadian effective light is estimated to be reduced through closed eyelids roughly by two orders of magnitude [95]. If this is the case, 1000 lux on the eyelids would still end up as 10 lux on the retina, more than double the 50% effect half-point. This illuminance was considered sufficient for our purpose and selected as the target illuminance. It is worth mentioning that the retinal cells responsible for flash-induced circadian effects are not yet clear and suspected to differ from the melanopsin cells that cause the blue-light response [94]. If the responsible cells are more sensitive to red wavelengths than blue wavelengths, about an order of magnitude more light may be transmitted through the eyelids, which would result in a substantial effective illuminance of the flashes [96]. Finally, to make the illuminance less dependent on the sleeping position, Exp02 recommended that the light stimulus shall be diffuse.

Table 5.1 provides an overview of the respective benefits of each morning light application.

It is worth noting that stacking multiple interventions is not guaranteed to add their isolated effects on top of one another. However, based on the current data and the feedback from the interviewed experts, a combined approach was regarded as most likely to be maximally beneficial for the user, at least until new evidence provides more nuance.

Formalization of Photobiological Requirements

The features presented are summarized and formalized in Table 5.2. Requirement ID prefixes "S-NDS", "S-BWL" and "S-MSF" were chosen to represent the features *naturalistic dawn simulation* (NDS), *bright wake-up light* (BWL) and *millisecond flashes* (MSF), from which the respective requirements were derived. The *Application* column of the table lists the components of the system to which the respective scientific requirement can be attributed.

5.1.2 User Interaction Requirements

Regarding the interaction with the device, the requirements are two-fold: On the one hand, the configuration of necessary parameters regarding the morning light simulation requires manual setting. The initial functional configuration requirements were derived from the scientific system requirements, wherever the parameters are not deterministic. On the other hand, the users' specific demands or preferences towards the interaction with the device were elicited via semi-structured intervews with prospective users.

Basic configuration parameters

The basic configuration parameters are represented by the photobiological requirements, listed in Table 5.1.1, which display a *configuration* tag in the *Application* column. This means that the optimal value for the respective parameter can vary from person to person and must be specified explicitly for each user.

Moreover, the conceptualized smart wake-up light as a whole represents a special case of an alarm clock. There are the following trivial interaction requirements that come with every alarm clock:

1. Setting the alarm time
2. Dismissing an active alarm
3. Activating/Deactivating an alarm

The resulting user interaction requirements are listed with in Table 5.4 with the *Requirement ID* prefix "UI-CONF".

UX Interview Results

11 people were interviewed with regards to their hopes and fears toward the interaction and user experience with a smart light wake-up aid. The interviews were exploratory in nature and were conducted according to a semi-structured interview guideline (see Section 4.2.2). The relevant findings for the user interaction are summarized in the following paragraphs.

Requirement ID	Description	Application
S-NDS-01	The Naturalistic Dawn Simulation shall have a duration of 90 minutes.	automation, algorithm
S-NDS-02	The Naturalistic Dawn Simulation shall start around 7.5 hours after the estimated DLMO or 90 minutes before habitual awakening.	automation, configuration
S-NDS-03	The Naturalistic Dawn Simulation shall have a maximum intensity of 250 lux.	lights
S-NDS-04	The Naturalistic Dawn Simulation shall transition from 0.001 to 250 lux.	algorithm, lights
S-NDS-05	The Naturalistic Dawn Simulation shall use diffuse light.	lights
S-NDS-06	The Naturalistic Dawn Simulation shall use a warm-white 3000K CCT LED light.	lights
S-BWL-01	The Bright Wake-up Light shall have a duration of 30 minutes.	automation
S-BWL-02	The Bright Wake-up Light shall start 20 minutes before the set wake time.	automation, configuration
S-BWL-03	The Bright Wake-up Light shall have a maximum intensity of 2500 lux.	lights
S-BWL-04	The Bright Wake-up Light shall follow a quadratic curve for brightness change.	algorithm, lights
S-BWL-05	The Bright Wake-up Light shall use broad-field direct light.	lights
S-BWL-06	The Bright Wake-up Light shall use a neutral-white 3000K - 5000K CCT broad-spectrum LED light.	lights
S-MSF-01	The Millisecond Flashes shall have a duration of 15 minutes.	automation
S-MSF-02	The Millisecond Flashes shall start around 8 hours after the estimated DLMO or 90 minutes before the habitual awakening.	automation, configuration
S-MSF-03	The Millisecond Flashes shall have a maximum intensity of 1000 lux.	lights
S-MSF-04	The Millisecond Flashes shall occur as intermittent 2 ms flashes every 20 seconds.	algorithm, lights
S-MSF-05	The Millisecond Flashes shall use diffuse light.	lights
S-MSF-06	The Millisecond Flashes shall use a cool-white 6000K CCT broad-spectrum LED light.	lights

Table 5.2: Scientific system Requirements for Naturalistic Dawn Simulation, Bright Wake-up Light, and Millisecond Flashes.

Ease of use: 7 interviewees emphasized that the interaction with the smart wake-up device should be simple. 4 of them did not want to do more on a daily basis than setting the alarm time. Optional advanced settings were explicitly appreciated by 2 interviewees. An initial configuration, which would take up more time, was found to be okay.

Reliability: Apart from a simple interaction, the reliability of the system as a whole (4 people) and the alarms in particular (2 people) were of critical importance for the interviewees.

Interaction modality: The biggest discrepancy in answers was represented by the controlling device, which was expected to be a smartphone (app) by 4 people and a remote control by different 4 people.

Automation: Automation, notably recurring alarm schedules on a weekly basis, was appreciated by 5 interviewees, as long as it reduced the need for interaction with the system and was reliable. On the other hand, 2 people stated that they do not see the need for any automation

The findings were summarized into formal system requirements that are found as requirements with the prefix "UI-UX" in TABLE 5.4.

Note: For the purpose of not exceeding the scope of this work, only software-based user interaction is addressed in this thesis. This does not negate potential additional benefits attained by hardware-based control approaches.

Formalization of User Interaction Requirements

Table 5.4 lists the requirements for user interaction derived from the system's photobiological requirements as well as user-specified demands toward the system. The list comprises functional as well as non-function requirements.

5.1.3 Hardware Requirements

To identify hardware-specific system requirements, an interview with lighting expert Exp03 was conducted. The interview results are summarized in Section 5.1.3. The formal hardware requirements derived from the interview are listed in Section 5.1.3

Hardware: Expert Interview Results

Lighting expert Exp03 was confronted with the thesis' goals and the requirements identified so far. Then he was asked for his thoughts on the concept, recommendations for architectural or technological choices as well as particular challenges that he would like to point out. The conversation was structured in the three sections *Lighting Characteristics*, *Smart Light Control & Automation* and *Construction of the Luminary*. The findings on each of the sections are summarized in the paragraphs below.

Requirement ID	Description	Application
UI-CONF-01	The user shall be able to set the start time of the naturalistic dawn simulation.	configuration, user interface
UI-CONF-02	The user shall be able to set the start time of the millisecond flashes.	configuration, user interface
UI-CONF-03	The user shall be able to set the alarm time manually.	configuration, user interface
UI-CONF-04	The user shall be able to dismiss an active alarm manually.	configuration, user interface
UI-CONF-05	The user shall be able to activate or deactivate an alarm.	configuration, user interface
UI-UX-01	The user interaction with the device shall be simple and intuitive. After the initial configuration, the daily use should be similarly easy as the setting of a smartphone alarm	user interface, non-functional
UI-UX-02	The system as a whole shall be reliable for consistent operation.	non-functional
UI-UX-03	The system shall be able to reliably wake people up at their desired wake times.	non-functional
UI-UX-04	The device shall offer a digital user interface that can be accessed wirelessly via common smartphones or tablets.	user interface, connectivity
UI-UX-05	The device shall provide optional advanced settings for power users.	user interface
UI-UX-06	The device shall support recurring alarm schedules with minimal user interaction.	automation, user interface

Table 5.3: User Interaction Requirements for the Smart Wake-up Light System. Requirements with the prefix "UI-CONF" represent configuration parameters while the "UI-UX" represents requirements that were derived from exploratory user interviews.

Lighting Characteristics As specified in Table 5.2, the simulated dawn and the millisecond flashes require a dynamic and diffuse lighting setup. According to Exp03, really diffuse lighting that is mostly independent of the user's sleeping position can only be attained with an indirect light source. This means that the light is directed to the room ceiling or walls, rather than to the user. This specification of having at least one indirect light source to produce the diffuse lighting, therefore, was adopted as as hardware requirement. Exp03 regards light emitting diods (LEDs) as the most suitable light source, as they rank among the most efficient light sources and can be used for dynamic lighting. There is a variety of LED *smart lights* available with which the light is dimmable and dynamic in color temperature. Using such a setting, the corrected color temperatures (CCT) for both the naturalistic dawn (3000K) and the millisecond flashes (6000K) could be created using a single off-the-shelf light source.

It might be challenging to find an off-the-shelf smart light with a dimming resolution as specified for the naturalistic dawn simulation, Exp03 suspected. As the requirement *S-NDS-03* states in Table 5.2, the naturalistic dawn transition shall span an illuminance range between 0.001 lux and 250 lux. This represents a dimming ratio of 1:250,000, which lies beyond commercial standards of around 1:4000. To make this particular challenge explicit, the desired dimming ratio for the indirect light was adopted as its own hardware requirement.

What Exp03 also regarded as important for users' acceptance of the device was visual comfort. This includes a low level of glare, as well as a good color rendering index (CRI). According to Exp03, cheap LEDs provide a CRI, which means that some colors, particularly skin tones, do not look appealing in that light. CRIs of at least 90 out of 100 are the current industry standard and is the baseline that one should go for in human-centric lighting. Industrial lighting with a CRI of 80 is visibly inferior in indoor lighting.

The other factor for visual comfort, glare, is of particular importance when dealing with high illuminances. The bright wake-up light, specified to reach a maximum light intensity of 2500 lux at eye level, is clearly at risk to induce glare. Glare is inversely proportional to the light-emitting area of the light source. Consequently, Exp03 identified the need for a broad enough light emitting area as a hardware requirement. The ultimate reduction of glare would again be diffuse ambient illumination with an indirect light source. However, the level of illuminance decreases inversely proportional to the square of the distance to the light-emitting area. It is not realistic to reach illuminance levels of 2500 lux using indirect illumination with reasonable levels of electric power. For 2500 lux, a direct light source is required that is positioned near the user's head. To reduce the glare induced by this direct light source to a minimum, its light-emitting area must be generously sized.

As far as the luminant for the direct light is concerned, Exp03 advised to go with dimmable, color-dynamic LED light products again, as they provide the flexibility required by the bright wake-up light dynamics.

Smart Light Control & Automation Exp03 regarded the smart light protocol *DALI DT-8* as the industry standard for office and public interior lighting. In the consumer market, the wireless protocol *Zigbee* is smart light protocol that most consumer smart lights support. Exp03 suspects both of these protocols to work for the purposes of the smart wake-up light device. While *DMX*, as the industry standard in stage lighting, supports highly dynamic lighting as well, the protocol targets RGB-LEDs (i.e., red-blue-green color channels rather than hues of white), which Exp03 said offers a bad CRI. Furthermore, the dimming resolution in DMX typically offers only 256 steps, which produces uncanny discrete changes of brightness upon dimming over longer periods of time. The typical dimming resolution of home lighting is 4000 steps, which results in much smoother dimming transitions.

When asked about time-based light automations, Exp03 pointed out that the availability of time is a non-trivial challenge in current smart light controllers. When the controllers are governed by a hub that is connected to the Internet, time can be requested from there. Otherwise, a special electronic unit that is called a *real-time clock* has to be added to the controller to keep track of time over longer periods. Like wristwatches, real-time clocks accumulate a certain error over time. Thus, ideally, they are synchronized with a ground truth clock time every once in a while. To keep this challenge in mind, the availability of the clock time was added to the hardware requirements.

Construction of the Luminary When it comes to the construction of the device, Exp03 agreed with initial concepts that showed the device as an overhead light installation. He does not regard the wall mount as an obstacle for self-installation for future users. However, for people who do not like to mount the device to their wall, an optional additional freestanding fixture would come in handy. The device itself must be robust enough to be touched and moved without the risk of breaking. In case of a wall-mounted installation, there must be no danger of the device falling down on the user.

Exp03 pointed out that for the required brightness levels, heat dissipation is a critical issue that has to be taken into account. No part of the device that can be touched by the user must be so hot that it inflicts pain upon touch. Ideally, the temperature of the diods themselves should stay below 100 ° C to warrant the durability of the diods.

Finally, Exp03 thought that the aesthetic appeal of the device would also play a role when it comes to user acceptance. Since the device is to be placed in people's private bedrooms, Exp03 suspects that an elegant design makes people much more inclined to associate their smart wake-up light as a welcome addition to their interior.

Formalization of Hardware Requirements

Using the information obtained from the lighting expert interview, additional formal requirements were added to the system specification. The prefix "HW-" in the requirement IDs indicates that the requirements are hardware specific.

5.2 System Architecture

The creation of a smart light system as specified by the requirements from section 5.1 poses challenges on multiple levels. Firstly, there has to be light technology offering the dynamics and interface to be controlled according to the photobiological requirements. This part of the system is referred to as **lights**. Secondly, there has to be a core control unit which stores all relevant parameters and operates the light in an automated fashion according to the specifications. This part is termed the **core automation**. Thirdly and lastly, the user interaction (see Section 5.4) will be conducted via a digital user interface. The corresponding part of the system architecture is referred to as the **user interface**.

Requirement ID	Description	Application
HW-01	The device shall produce the diffuse light for the naturalistic dawn simulation and millisecond flashes using an indirect light source.	lights
HW-02	The indirect light shall have a dimming ratio of at least 1:250,000	lights
HW-03	All lights shall provide a color rendering index (CRI) of 90 or higher	lights
HW-04	The device should produce the peak intensities of the bright wake-up light using a user-facing direct light source.	lights
HW-05	The direct light source shall use a large enough light emitting area to prevent glare at peak illuminance	lights
HW-06	The device shall have access to an accurate clock time at any time.	automation
HW-07	The device shall be robust enough to be touched and moved without the risk of breaking.	construction
HW-08	The device shall withstand incidental bumps with no danger of the device falling down on the user.	construction
HW-09	No part of the device that can be touched by the user must be so hot that it inflicts pain upon touch.	construction, lights
HW-10	The device should be visually pleasing and integrate well into users' bedroom interior.	construction

Table 5.4: Hardware-specific requirements for the Smart Wake-up Light System.

5.2.1 Architecture: Lights

The lighting architecture comprises the system components responsible for the actual light output. On a high level, they are split into the different light sources as well as the interface via which these lights are controlled by the core automation controller. On a lower level, each light source comprises the drivers, luminants, enclosure, and power supply and may even be subdivided into multiple light sources that work together and can be controlled as one light source.

Based on all light-related system requirements, the general light architecture was chosen to be a bidirectional overhead lighting design (see Figure 5.2. This means that the lights are mounted above the headboard of the bed. A ceiling-facing light source illuminates the room without being directly visible to the user in the bed, while a downward-facing light panel directly illuminates the bed and the person lying in the bed. This design was chosen over nightstand-based architectures because it promised the best combination of position-independent illumination, high peak illumination levels, and glare reduction. Any light source from the side would require the user to lie in a position where their head faces the light source, to achieve high levels of illuminance. In a personal experiment with

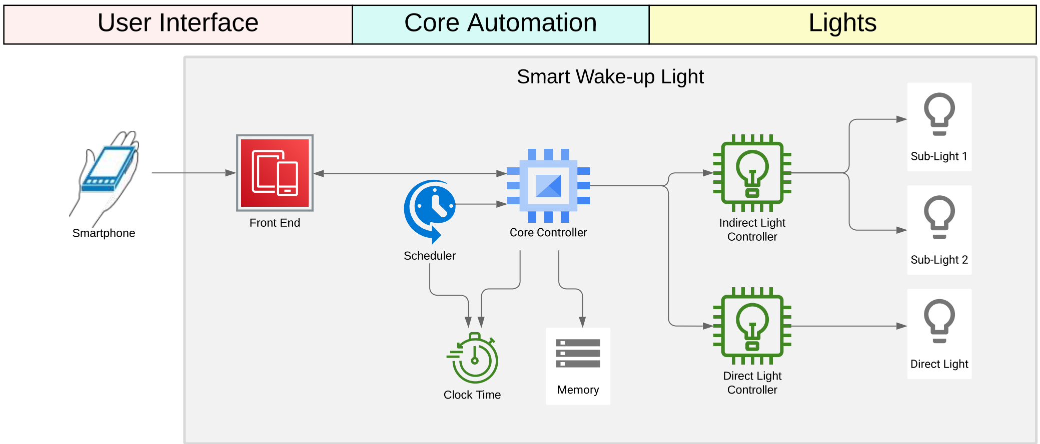


Figure 5.1: Visual model of the system architecture. The architecture is divided into the three layers *user interface*, *core automation* and *lights*. The core controller, implementing the main automation logic, is in a bi-directional communication with the front end, which implements the use interface, as well as in uni-directional communication with peripheral controllers that set the lights.

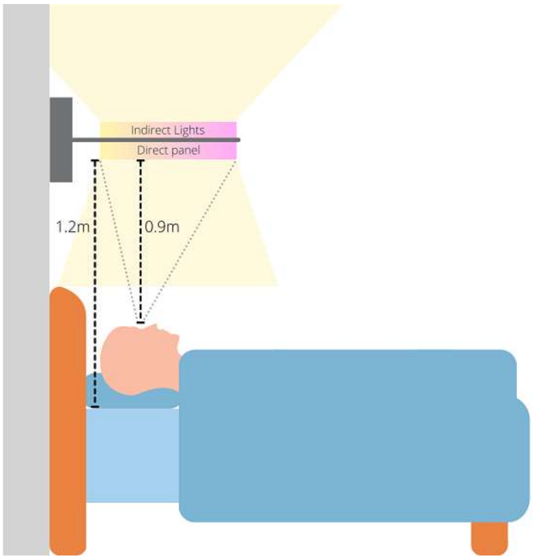


Figure 5.2: Sketch of the device hardware as a bi-directional lighting installation. The device is mounted to the wall above the bed headboard, at a height that results in roughly 0.9 metres distance between the user's eyes and the direct light. A large, evenly lit LED panel for the direct light covers much of the user's visual field, so that glare is minimized despite high illuminance levels.

a commercial wake-up light, the illuminance on the eyes dropped from 300 lux facing the light to only 14 lux when turned away from the light. This position-dependence poses a great risk to the device's effectiveness in practice. In contrast, an overhead light source, while brightest when looking directly into it, illuminates the pillow and bed sheets, too, providing a lot of light to the eyes even in a side position. Furthermore, lying on the back in the morning upon awakening was deemed a more natural posture than lying on the side when already awake. A ceiling-mounted light source, as a third option, could provide the mentioned benefits with regard to sleep position independence. However, the increased distance between the user and the light source would render the required peak illuminances of 2500 lux unattainable without extremely high power usage or extreme glare. The overhead mount allows the device to be located near the user's eyes, overcoming that problem. At the same time, indirect ceiling illumination from the overhead device creates a bright background for the downward-facing LED panel, which reduces the contrast between the bright direct panel and the background and, thus, reduces glare. This background illumination is a further advantage over the nightstand design, where a background illumination is not possible if the bed stands at a wall or would not result in a diffuse room illumination if it was directed sideward. Therefore, a bi-directional overhead mount was considered the option to best satisfy the system requirements.

Indirect Lights

The indirect light source serves the purpose of providing a diffuse room illumination for the naturalistic dawn simulation and the millisecond flashes. The required range in color temperatures from 3000K to 6000K and color rendering index of 90 or more were found to be easily be met by modern CCT-LED products. The CCT stands for *corrected color temperature* and indicates that the luminants can switch dynamically between color temperatures, usually in the range from 2700K to 6500K.

Further requirements address the maximum illuminance received from the natural dawn simulation and millisecond flashes, which are 250 Lux and 1000 Lux, respectively. Since light sources cannot be specified in the light received (Lux) but light emitted (Lumens), a conversion between those two units was required. Generally speaking, the conversion from illuminance to brightness is well defined as $1lx = 1lm/m^2$. However, the room architecture and ceiling and wall reflections make the calculation of the illuminated surface area a complex task. Instead, a number of experiments in different rooms led to an estimate of $20m^2$ for a typical bedroom. Therefore, the required brightness for 250 Lux 5000 Lumens.
Using the same estimate, 1000 Lux for the millisecond flashes would require an indrect light source with 20,000 Lumens. This was considered an unreasonable amount of additional brightness for this limited use case. Instead, the specified brightness was kept at 5000 Lumens and the addition illuminance chosen to be added by the direct light, which can easily provide the required light levels. The solution comes at the cost of lowered diffuseness of the millisecond flash light but the expected level of diffuseness

using this solution was considered suitable.

A final major challenge that posed by the requirements is the dimmability beyond industry standard to only 0.001 Lux for the dawn simulation. As specified in the hardware requirements, this results in a required dimming ratio of 1:250,000. As this dimming ratio, if attainable at all, require special driver hardware, a different approach was chosen: The indirect light source was split into two sublight sources, where the first should provide a maximal brightness of 5000 Lumens and the second should provide only 80 Lumens at maximal brightness. If each of these lights offers a dimming ratio of 1:4000, a combined usage would result in a total dimming ratio of 1:250,000. This is because the dim light, at minimum dimming, provides 0.02 Lumens, which corresponds to $1/250,000$ of 5000 Lumens. Using an intermediary controller, the indirect lights should be controlled like a singular light source from the core automation controller. The intermediary controller then translates the lighting command to two separate commands for the actual light sources. The resulting architecture is depicted in the system component diagram in figure 5.2.

In summary, the following specifications for the indirect lights were determined:

- **Color Temperature:** dynamic, 3000K to 6000K
- **Color rendering index (CRI):** 90 or higher
- **Maximum Brightness:**
  - Large Sublight: 5000 Lumens
  - Small Sublight: 80 Lumens
- **Dimming ratio:**
  - Large Sublight: 1:4000
  - Small Sublight: 1:4000

The concrete products that implement these requirements were left unspecified at this point, as no a-priori preference for any single product could be derived from the requirements. In the implementation sections (Sections 5.3, 5.4, 5.5), concrete products were chosen to implement the specifications listed here.

Direct lights

The direct lights are mainly responsible for the light output of the bright wake-up light. It is also used for the millisecond flashes, together with the indirect lights. When matched against the requirements for these features, the direct light should span a color temperature range between 3000 and 6000 Kelvin. Its light should be dimmable and have a color rendering index of 90 or higher. These requirements can satisfied with typical smart LED panels.

A non-trivial challenge was posed by the requirement that the bright wake-up light should be able to reach a peak illuminance level of 2500 lux on eye level. One the one hand, a large visible light-emitting surface area is required to produce the required light without unbearable glare. On the other hand, since the illuminance (Lux) decreases inverse proportionally to the square of the distance to the light, the light source must be near the user's eyes to possibly get to the desired illuminance level. However, if the device is mounted very low, i.e., too close to the user, the user can be expected to feel cramped. This would lead to a uncomfortable user experience and should be avoided. The identified architecture, therefore, places the direct light source, in the form of a diffusely lit LED panel, 1.2 metres above the mattress surface, which would translate to roughly 0.9 metres distance between the user's eyes and the light in back position on a small pillow. Still, 1.2 metres distance to the bed would leave enough space for the user to sit comfortably under the device, for example to read. Empirical experiments showed that a light source with a luminous flux of 4600 Lumens was needed to achieve the desired illuminance.

Summarizing the identified speicifications, the desired direct light panel should implement the following specifications:

- **Color Temperature:** dynamic, 3000K to 6000K
- **Color rendering index (CRI):** 90 or higher
- **Maximum Brightness:** 4600 lumens
- **Dimmable**: yes
- **Panel Area**: $0.25m^2$

The concrete products to implement these specifications were chosen in the respective implementation section (Sections 5.3, 5.4, 5.5).

Lights Interface

Via the lights interface, the concrete lighting commands are transmitted from the core controller to the light drivers. The drivers then electronically operate the luminants to produce the desired result. The concrete connection type and protocol were left to be decided for each iteration of implementation. A priori, both wired and wireless communication protocols were deemed viable.

Based on a typical smart lighting protocol, the interface provides the following minimum functionality:

- **Set lights**
  - Light ID: the identifier of the light to be addressed

- Brightness: the brightness level to reach. 1.0 corresponds to maximum brightness, while 0.0 means turning the lights off.
- Transition time: The transition duration requested to change the light from the previous state to the new one. The transition between two different brightness states will be smooth dimming. The transition time is given in milliseconds.
- Color temperature (optional) : If the light supports different color temperatures, a change in color temperature is passed via this parameter. The color temperature is given in Kelvin, where 2700 represent a warm white and 6500 a cold white hue.

While this minimum specification satisfies the requirements, the actual smart light interface could support further commands and should not need to be limited to this specification.

The lights were chosen to use a gamma correction factor of 1.0, which corresponds to an identity function, (see THEORETICAL BACKGROUND GAMMA CORRECTION), so that the set brightness levels correlate linearly with the lumen output. This facilitates the calculation for the reproduction of specific illuminance values.

5.2.2 Core Automation

The conceptualized smart wake-up light is required to produce the three different lighting programs *naturalistic dawn simulation* (NDS), *bright wake-up light* (BWL) and *millisecond flashes* (MSF). The timing and light output for each program are parametrized by various parameters. Since the start times of the programs are critical parameters, the device must know the current local clock time. The "alarm", which comprises the three different light programs, shall be dismissable by the user with a respective device interaction. Finally, the user shall be able to activate or deactivate the entire device. The device should not trigger any light program when deactivated. To address these requirements, a *core automation* layer was defined for the system architecture. This section gives an overview of the components within the core automation layer. Following the above mentioned order of the requirements, the section is divided into the paragraphs *parameters*, *light programs*, *schedule*, *interaction interface*. After these paragraphs, a UML class diagram visualizes the structure of the entire core automation layer.

Parameters

The actitivty of the device as a whole but also the individual light programs are parametrized by user-specific settings. The following list names the necessary parameters, together with with the requirements they originate from:

1. **alarmIsEnabled**
   a) type: boolean

   b) derived from: UI-CONF-05
   c) description: Indicate whether the device will produce its light programs at the set time. If *false*, no further light program will be triggered.

2. **alarmIsDismissed**
   a) type: boolean
   b) derived from: UI-CONF-04
   c) description: Indicate whether the light programs are dismissed. If *true*, currently running light programs will be dismissed and no further light program will be triggered and until the next wake time.

3. **wakeTime**
   a) type: TimeOfDay
   b) derived from: S-BWL-02, UI-CONF-03
   c) description: The set wake time for the wake-up light.

4. **ndsStartTime**
   a) type: TimeOfDay
   b) derived from: S-NDS-02, UI-CONF-01
   c) description: The time when the NDS will be started.

5. **msfStartTime**
   a) type: TimeOfDay
   b) derived from: S-MSF-02, UI-CONF-02
   c) description: The time when the MSF will be started.

The parameters of type *TimeOfDay* assume that the core controller, i.e., the control unit of the core automation layer, has this type of data. If this is not the case, each parameter of that type shall be split into two parameters of type *integer*, where the first stores the hour value of the set time and the second parameter stores the minute value of the time.

To prevent the user from reconfiguring the entire system in case of power outage, the core automation layer has a persistent memory component. The parameters are stored and read from there.

Light Programs

The light programs represent the heart of the controller functionality. Once triggered, each program (MSF, NDS, BWL) runs as a time-based script for the specified time and orchestrates its respective light output. Before the individual light programs are described in more detail, it is worth noting that the light levels are specified by illuminance (Lux) in the requirements, while the interface of the lights operates with brightness levels (0-100%). To convert from illuminance to brightness, the utility functions *getIndirectBrightnessForLux* and *getDirectBrightnessForLux* were specified for indirect lights and direct lights, respectively. As illuminance and brightness are proportional, the conversion is performed as a scaling operation, using the constants *indirectLightsBrightnessConversionRatio* and *directLightsBrightnessConversionRatio*. These scalars depend on the luminous flux of the lights as well as on the architecture of the bedroom. They have to be determined empirically during an initial configuration of the device and are passed to the device via the user interface. Once configured for the room, the parameters remain constant during use.

Millisecond Flashes Following the photobiological requirements (S-MSF-01 to S-MSF-06), the millisecond flashes (MSF) algorithm produces a light flash of 2 milliseconds duration every 20 minutes, for a total duration of 15 minutes. To reach the specified total illuminance of 1000 Lux during these 2 milliseconds, the indirect lights are set to a brightness level that results in 250 Lux and the direct lights are set to a level that results in 750 Lux. The respective brightness levels are calculated using the utility functions *getIndirectBrightnessForLux* and *getDirectBrightnessForLux*. As required, the color temperature for the flashes is set to 6000 Kelvin. After 15 minutes, the loop is discontinued and the flash sequence ends. The formal algorithm for the millisecond flashes is depicted in pseudo-code in Algorithm 5.1.

Algorithm 5.1: Millisecond Flashes

```
Input: msfStartTime
indirectBrightness ← getIndirectBrightnessForLux (lux: 250);
directBrightness ← getDirectBrightnessForLux (lux: 750);
while currentTime () < msfStartTime + 15 minutes do
    setLights (id: indirectLights, brightness: indirectBrightness,
      transitionTime: 0, colorTemperature: 6000);
    setLights (id: directLights, brightness: directBrightness, transitionTime:
      0, colorTemperature: 6000);
    wait (2 milliseconds);
    setLights (id: indirectLights, brightness: 0, transitionTime: 0);
    setLights (id: directLights, brightness: 0, transitionTime: 0);
    wait (20 seconds);
end
```

Naturalistic Dawn Simulation The naturalistic dawn simulation is specified as a twilight transition that follows naturalistic illuminance levels. Like in nature, the transition is parametrized by the geographical latitude of a given location, on the time of the year, on the level of cloud cover as well as the dampening of the light due to trees, windows or obstacles. Its computation is a non-trivial task. For their clinical trial that inspired this device concept [27], Terman et al. used a proprietary algorithm which was configured to 5 May at 45° latitude. Under a non-disclosure agreement, the lead author Michael Terman provided a list of illuminance values that correspond to 5-minute intervals from the beginning (0.001 Lux) to the end of the dawn (250 Lux). The values between the given reference values were interpolated to approximate the original curve (see Algorithm 5.2).

Algorithm 5.2: Naturalistic Dawn Simulation

```
dawnValues ← [...] ;  // Reference values from 0.001 lux to 250
  lux, in 5-minute intervals
foreach dawnValue in dawnValues do
    setLights (id: indirectLights, brightness:
     getIndirectBrightnessForLux (dawnValue), transitionTime: 300000,
     colorTemperature: 3000);
    ;                        // Each transition takes 5 minutes
end
;      // At the end of the loop, the maximum value remains
  active
```

Bright Wake-up Light The bright wake-up light is specified as a gradually increasing dawn signal that follows a quadratic illuminance curve to grow from zero to 2500 lux within 30 minutes. The start time of the bright is 30 minutes prior to the set wake. The direct light source is used to produce the signal. The color temperature of the light starts at 3000 Kelvin and transitions linearly to an eventual 5000 Kelvin. Algorithm 5.3 depicts the bright wake-up light control in pseudocode.

While the MSF algorithm stops after a time a leaves the lights as they were before it started, the NDS and BWL programs end with the respective lights turned on. Here, as enabled by requirement UI-CONF-04, the users must manually turn off the lights, typically when they get out of bed. The **dismissAlarm()** function turns off the lights and stops all currently active light programs. Note that **dismissAlarm()** is not designed to deactivate light programs that have not started yet. This way, the user can dismiss the MSF program if, for example, they woke up at during the flashes, but they will still get the NDS and BWL to facilitate a gentle awakening later in the morning. If the user does not want future light programs to trigger, they have the option to disable the alarm altogether, by setting the **alarmIsEnabled** parameter to *false*.

Algorithm 5.3: Bright Wake-Up Light

```
Input: wakeTime
maximumBrightness ← getDirectBrightnessForLux (lux: 2500);
bwlDuration ← 30 ;        // Wake-up light duration is 30 minutes
progress ← 0.0 ; // Represents progress of bright wake-up light
while currentTime () ≤ wakeTime do
    progress ← ((bwlDuration−(wakeTime−currentTime())) / bwlDuration)
    currentBrightness ← (maximumBrightness × (progress)^2)
    currentColorTemperature ← (3000 × (1 − progress) + 5000 × progress)
    setLights (id: directLights, brightness: currentBrightness,
     colorTemperature: currentColorTemperature, transitionTime: 1000)
    wait (1000 ms);
end
;                    // After wakeTime, the light remains active
```

Scheduler

The correct timing of the light programs depends on having a clock time in the first place. Therefore, a *clock* component in the core automation layer was specified to provide this clock time to the core controller. Using this clock time, a *scheduler* component calls an *evaluateTime(clockTime)* function that takes the current clock time as an argument. This function contains the logic to determine whether a light program shall be triggered and which one. The logic, visualized as a UML Flow Diagram in Figure 5.3, is the following: Every minute, the scheduler calls the *evaluateTime* function with the current time as an argument. If the configuration parameter **alarmIsEnabled** is set to *false*, the system is disabled and no light program shall ever be triggered. If the parameter is *true* and the current clock time equals the start time of a light program (as defined by **msfStartTime** for the MSF, **ndsStartTime** for the NDS and **wakeTime**−30min for the BWL), the respective light program is triggered.

Interface for the front end

The core automation layer must expose an interface to the user interface layer, so that the user can actually configure and control the device. To achieve this, all requirements with the application tags *configuration* or *user interaction* were mapped to interface functions. The configuration parameters in the *core controller* class were wrapped with setter and getter functions to allow the user to read and set their values. The function **dismissAlarm()** was exposed directly so that the user can trigger it manually.

Figure 5.4 depicts the core automation, including its interfaces to the user interface and lights layers as a UML class diagram.

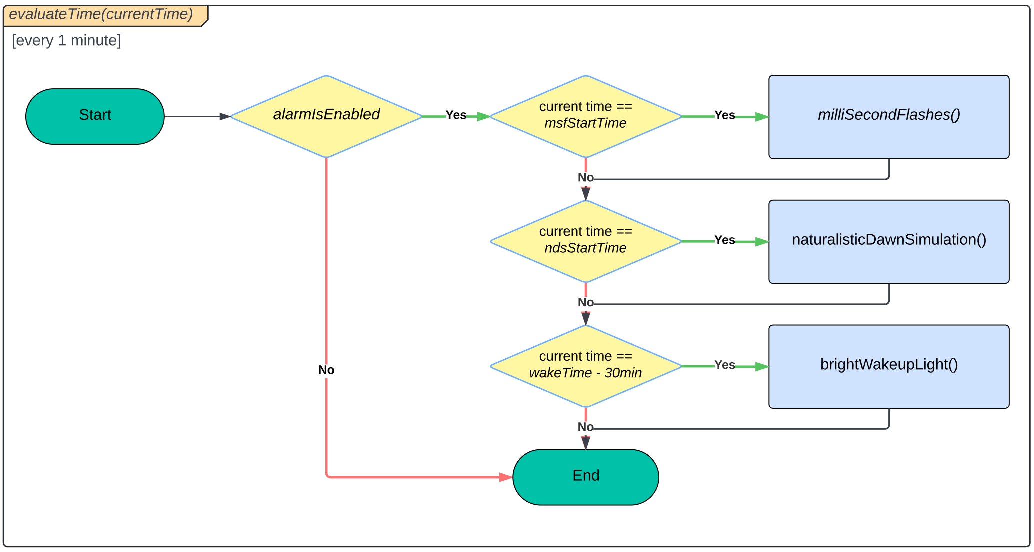


Figure 5.3: UML flow diagram of the **evaluateTime** function logic. The function is called once every minute by the *scheduler* component.

5.2.3 User Interface

The user interface (UI) enables the interaction between the user and the smart wake-up lighting device. The interaction comprises the configuration of the morning programs according to the requirements as well as the direct interaction with the lights. According to requirement UI-UX-04, the user interface was for a smartphone display and a wireless communication with the core controller was assumed. A priority was put on a simple and intuitive use, as required by UI-UX-04.

The user interface was divided into three sections, between which the user can navigate via a navigation bar. With this division into tabs, the user is only confronted with a small chunk of the interface's functionality, which serves the simplicity of the UI. The first tab, "*alarm*", lets the user configure the timing of the morning light program(s) as well as dismiss active alarms. The third tab, "*calibration*", enables the conversion between illuminance [lux] and the brightness levels [0-100%] with which the lights are operated. This conversion required an empirical determination of the respective lights' (direct/indirect) illuminance in the bed, for which a direct operation of the lights was needed beyond just the dismissal of active alarms. Since it was necessary to enable a direct setting of the lights by the user, another tab "*lights*", placed on the second position of the navigation, was added to the UI: In this tab, the user can turn each light into different light modes.

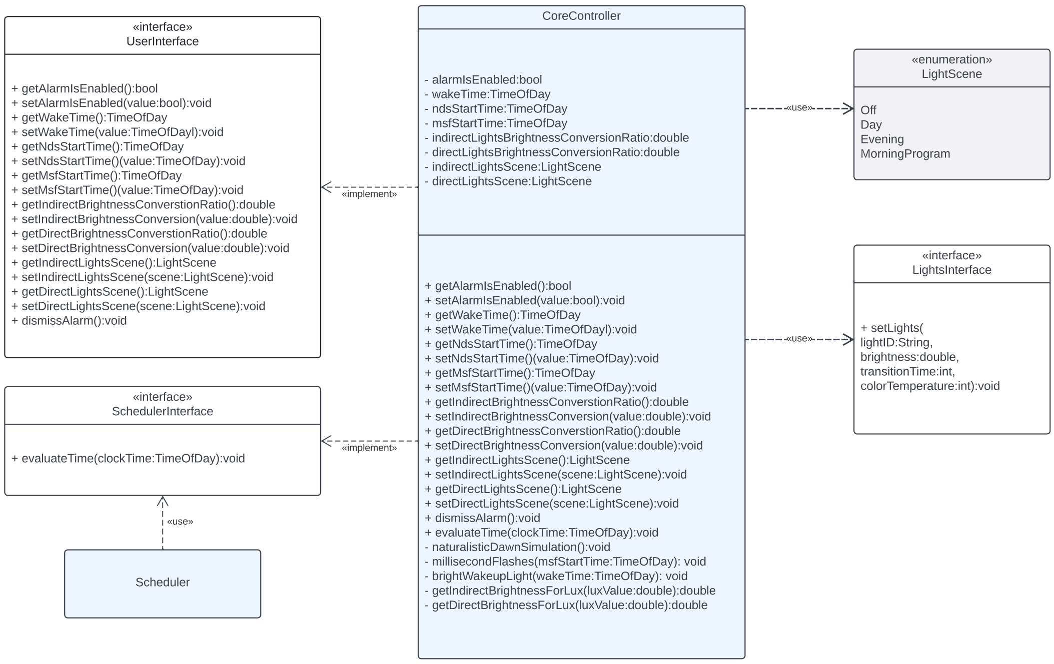


Figure 5.4: UML class diagram of the core automation layer: *CoreController* implements the interfaces *UserInterface* and *SchedulerInterface* while it uses the interface *LightsInterface*. The *Scheduler* class uses the *SchedulerInterface* every minute to trigger an evaluation of the current clock time.

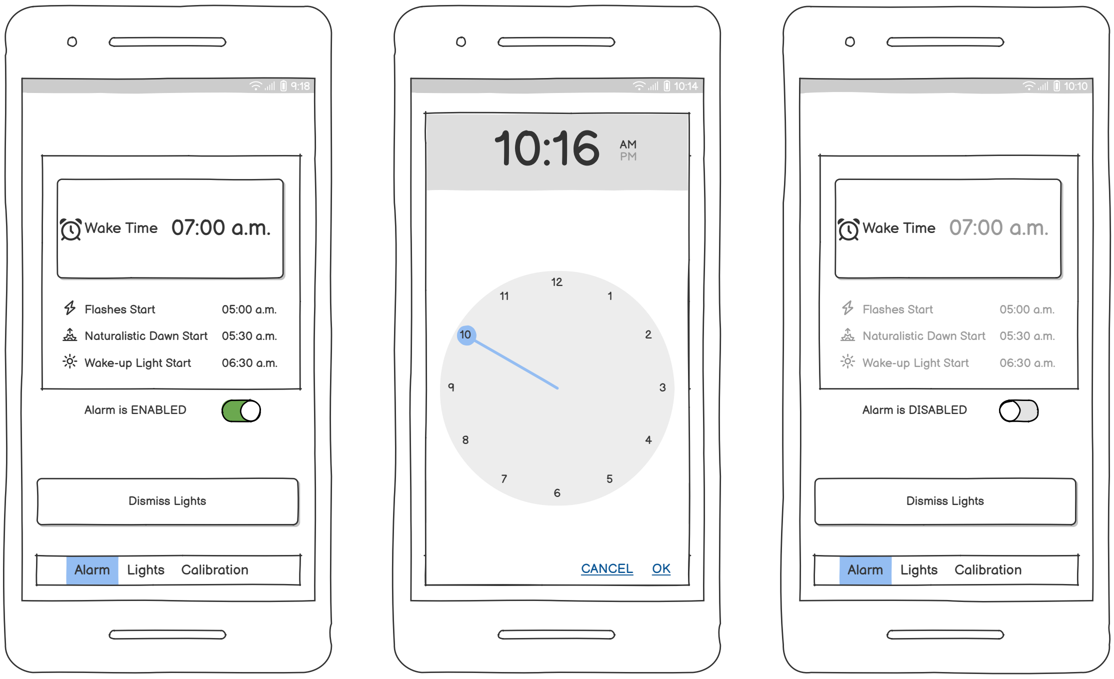
User Interface: Alarm screen

The *alarm* screen, depicted in Figure 5.5, was designed as the default screen of the UI. It includes the functionality needed for the daily interaction with the device: This is enabling or disabling the light programs, setting a wake time for the next day and dismissing active light programs.

Figure 5.9a represents an enabled alarm with a wake time set to 7:00 a.m. To satisfy requirement UI-UX-01 and let the user set the light programs as simply as setting a smartphone alarm, the timing af all three light programs is wake-time-based. The user sets the desired wake time and all three light programs (millisecond flashes, naturalistic dawn and bright wake-up light) are automatically derived from the wake time (as 2 hours prior, 1.5 hours prior and 30 minutes prior, respectively). For full transparency and a good expectation management, the derived start times of the light programs are displayed below the wake time. To set the wake time, a click on the "*wake time*" button opens a modal with a time picker (see Figure 5.9b). The user can enable or disable the scheduled light programs via a designated switch. When disabled, all schedules are greyed out to indicate that they will not trigger anything (see Figure 5.5c.

Finally, the user can dismiss active light programs via the "*dismiss lights*" button at the bottom of the screen. As required by UI-CONF-04 and further specified in Section 5.2.2, this button will cancel all running light programs and turn off all lights.

Regarding the programmatic interface between the UI and the core automation layer, the UI calls the respective setter functions to set the wake time and the start times of the light programs, as well as whether the light programs are enabled or disabled. Whenever a new time is set, the concerned UI fields are updated by calling the respective getter functions. Upon the click of the "*dismiss lights*" button, the interface function **dismissAlarm()** is called.



(a) Alarm screen (enabled). (b) Alarm time picker. (c) Alarm screen (disabled).

Figure 5.5: UI mock-up of the *Alarm* screen in different states.

User Interface: Calibration screen

The photobiological requirements, listed in Table 5.1.1, specify various illuminance levels for the morning light programs. Lights, on the other hand are specified in luminous flux [Lumens] and operated in brightness levels [0-100%]. How brightness levels translate to illuminance measured at a certain point depends on multiple factors, such as the gamma correction factor, the luminous flux of the luminants, the beam angle, distance from the light source and if indirect lighting with reflections is involved, also the room architecture. However, if the gamma correction factor is zero, all factors ultimately serve as a scalar in a linear relationship between brightness and illuminance. If this scaling constant is empirically measured, the calibration of the lights is a fairly simple task. To enable empirical measurements, a dedicated "calibration screen" was added to the user interface that guides the user through the calibration process. Figure 5.6 depicts the calibration screen as the third tab of the user interface.

The calibration procedure for each of the two lights (indirect, direct) is the following: At the measurement point of interest, the illuminance is measured when the respective light is turned off and again when the light is active at full brightness. The difference between the illuminance values corresponds to the illuminance added by the light. The point where the measurement should be taken is where the user's eyes are expected to be when they are lying in bed, looking up. Usually, this is on the pillow near the top end of the bed. Illuminance can be accurately measured with a dedicated *luxmeter* device but also, though less accurately, approximated with the light sensor of a smartphone and a dedicated app. For the experiments in the context of this thesis, a *luxmeter* device was provided to test users.

The calibration screen explains the calibration procedure to the user. For both lights, the screen offers a number field to input the measured illuminance different between the lights-on and lights-off scenarios for the respective light. This value represents the *brightness conversion ratio* for the respective light, which is set to and read from the core automation layer using the dedicated setter and getter functions provided by the automation layer's interface.

It is worth noting that the calibration procedure requires a possibility for the user to turn the separate lights to full brightness or off. This, among other functionality is provided by the UI's *Lights* screen.

User Interface: Lights screen

The lights screen offers the user the ability to directly control the device's lights. Each light can be manually set to one of the three states *off*, full brightness ("*Day*") and dim ("*Evening*"). The ability to switch between off-state and full brightness was required for the calibration of the lights. Although no *Evening* scene was explicitly required, the device's qualification as a high-quality room or reading light beyond "just" a smart wake-up light suggested the addition of corresponding light controls. Therefore, the *Day* and *Evening* modes were presented as optimized time-of-day-dependent light modes for the bed and bedroom. Having calibrated direct and indirect lights, the device is able to produce daylight and evening ambiences that perfectly match the official scientific recommendations for day and evening lighting by Brown et al. [53]. Since the user cannot be expected to be familiar with the scientific lighting recommendations, time-of-day-dependent scenes were preferred over a custom control of brightness and color temperature levels. The provision of just two different active light modes per light was therefore considered the optimal intersection between simplicity, versatility, and scientific recommendation.

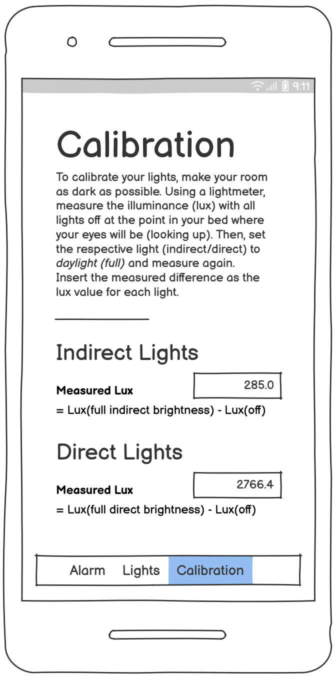


Figure 5.6: UI mock-up of the *Calibration* screen.

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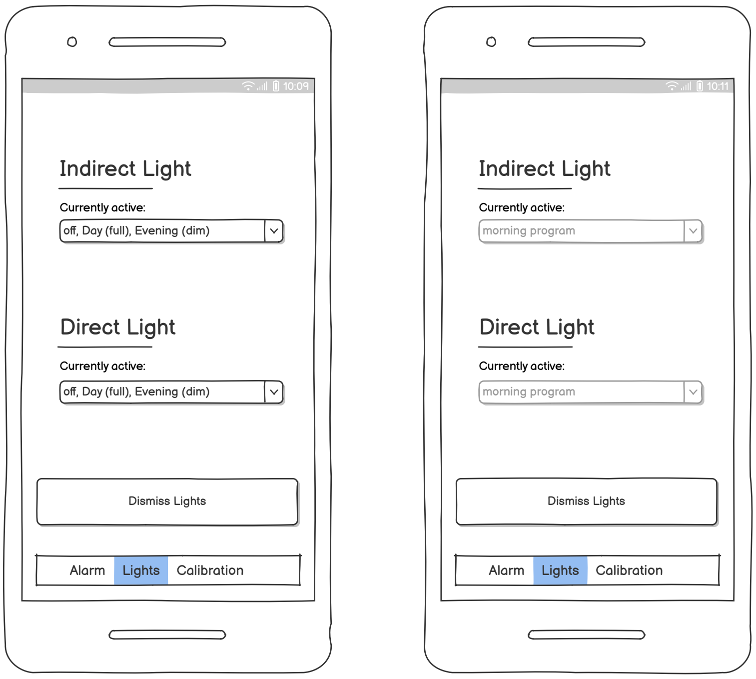
Figure 5.7 illustrates the *Lights* screen as the second tab of the user interface. Unless the device is in the process of producing a morning light program, the user is given direct control over the light scenes by a drop-down button offering the selectable states *off*, *Day* and *Evening* per light. A " *disable lights*" button, which is equal to the respective button on the *alarm* screen, gives the user the ability to quickly turn off both lights. The light scene selection makes use of the core automation layer's interface fuctions **getIndirectLightScene** and **setIndirectLightScene** or **getDirectLightScene** and **setDirectLightScene**, respectively.

There is one special case that has to be considered: Whenever one or multiple automated light programs are active, direct manipulation of the lights can interfere with the light programs, possibly leading to undesired results. To account for this case, a third active light mode "*morning program*" was introduced. *Morning program* is not selectable by the user but is triggered by the light programs. When active, the drop-down buttons to manually select the light scene are disabled. This scenario is illustrated in Figure 5.7b. Any light program blocks both drop-down buttons. To manually switch to a different scene, the user must dismiss the active light program(s) using the designated button, which sets both lights to off. This state change reactivates the drop-down buttons and, with it, the user's ability to manually control the lights.



(a) Lights screen (regular). (b) Lights screen (disabled).

Figure 5.7: UI mock-up of the *Lights* screen when no automated light program is active (Fig. 5.7a) and when an automated light program is active (Fig. 5.7b).

5.3 Implementation Iteration 1: Early Prototype

Having established the requirements and initial architecture, the implementation phase of this thesis concerned the implementation of the device in a way that satisfied the established specifications. The first implementation iteration was the creation of a functional prototype in hardware and software: The prototype should demonstrate that the concept was generally feasible to construct in practice. The iteration should provide early evidence that the specified lighting interventions were generally well received by test users.

The first implementation iteration was split into a technology selection phase, an implementation phase, and an evaluation phase. The latter included technical measurements to evaluate whether the prototype met the hardware requirements. Furthermore, complying with the user centered design principle *Empirical Measurement* [67], real-life tests of the created prototype by test users were conducted. After the test feedback interviews were conducted. The findings from the evaluation resulted in formulated updates of the requirements for the next iteration of development.

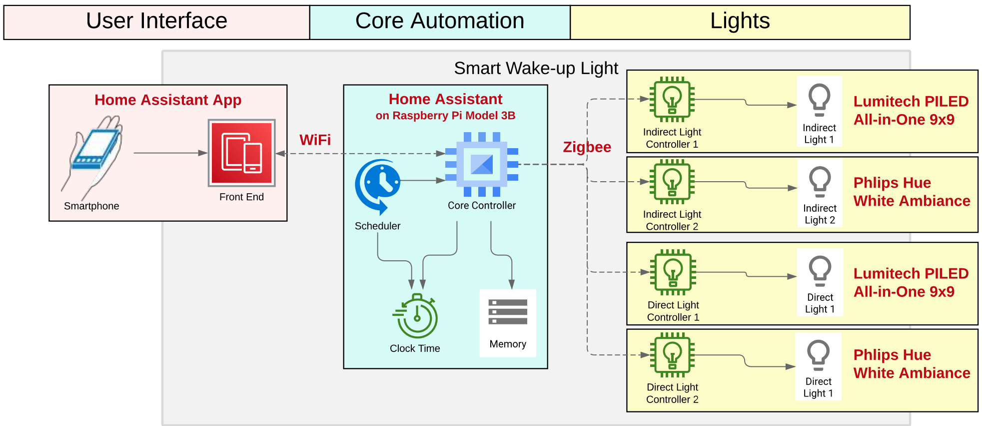


Figure 5.8: Visual model of the system architecture (described with black labels) and the technologies that implemented the architecture for the early prototype in practice (described with red labels). Dashed arrows represent wireless connections while solid lines represent wired or same-device communication.

5.3.1 Iteration 1: Technology and Hardware Selection

In the technology selection phase of iteration 1, the architectural model from Section 5.2 was mapped to concrete technologies, frameworks and products that implemented the abstract entities and interfaces. A visual overview of the technology selection is given in Figure 5.8.

Iteration 1: Lights

The following implementations for the smart light protocol, indirect lights and direct lights were selected:

- **Lights Interface:** *Zigbee*
- **Indirect Lights**
  1. Indirect Sublight: Lumitech *PILED System Pro All-in-one 9x9*[1]
  2. Indirect Sublight: Philips Hue *White Ambience*[2]
- **Direct Lights**
  1. Indirect Sublight: Lumitech *PILED System Pro All-in-one 9x9*

[1] https://lumitech.com/marketing/db/PI-LED_Area_System_Pro_AIO_9x9_en.pdf
[2] https://www.philips-hue.com/de-at/p/hue-white-ambiance-e14—smarte-lampe-tropfenform—470/8719514491106

2. Indirect Sublight: Philips Hue *White Ambience*

In-depth reasoning for the choice of the interface and luminaires is provided as Appendix D.

Iteration 1: Core Automation

To schedule and execute the automation logic, store the parameters and provide a wireless interface to the front end, the home automation framework **Home Assistant**[3] was used. Home Assistant is an open-source framework that runs on local device and supports parametrized scheduled automations out of the box. For the first prototype, it was run on a *Raspberry Pi 4 Model B*[4] mini-computer. The framework was chosen thanks to its suitability to implement the entire core automation layer, its availability as a free-of-charge open-source software and its active community.

The automation layer's components were implemented as follows:

- **Parameters: *Home Assistant* Input_Numbers** - Parameters were stored as *input_number* components in Home Assistant. Home Assistant persists these components on the Raspberry Pi's flash memory by default.
- **Algorithms: *Home Assistant* Scripts** - The algorithms and helper functions were implemented as *scripts* in Home Assistant. Scripts work as functions which procedurally execute code, support loops and conditions as well as input arguments and return values.
- **Scheduler: *Home Assistant* Automations** - Via *automations*, the defined algorithm scripts were configured to trigger based on time. Being connected to the local network via WIFI, the clock time was read online from an NTP server or, when offline, from the Raspberry Pi's real-time clock.
- **Communication with Lights: *Home Assistant* Phoscon ConBee II + DeConz Add-on** - The communication with the specified lights via the Zigbee protocol was enabled via the Phoscon *ConBee II*[5] Zigbee gateway. The gateway was connected to the Raspberry Pi via USB. Via the DeConz Add-on[6] by *Dresden Electronik*[7] in Home Assistant, the lights could be integrated as components into Home Assistant.
- **Interface to front end: *Home Assistant* REST API** - All of the scripts and components defined in Home Assistant were made accessible by default via Home Assistant's REST API. The interface can be accessed via WIFI when the accessing device is in the same local network as the Home Assistance instance.

[3]https://www.home-assistant.io/
[4]https://www.raspberrypi.com/products/raspberry-pi-4-model-b/
[5]https://phoscon.de/en/conbee2
[6]https://www.home-assistant.io/integrations/deconz/
[7]https://www.dresden-elektronik.de/

Iteration 1: User Interface

While any front end could communicate with the core automation layer via its exposed REST API, the Home Assistant framework offers a dedicated ***Home Assistant* mobile app**[8] as its recommended front end. With this app, users can build and customize their own "dashboard" to interact with the core automation layer. The app is availability for all major mobile operating systems and supports the connection with the Home Assistant API out of the box. The level of customizability of the dashboard was considered sufficient to implement the user interface for the first prototype while enabling high prototyping speed. Therefore, the Home Assistant mobile app was selected as the UI framework for the first implementation iteration.

5.3.2 Iteration 1: Implementation

After the technologies were selected and the hardware purchased, the first prototype was implemented in hardware and software.

Iteration 1: Hardware implementation

The physical construction of the prototype was assisted by Simon Bellink. The light panels were covered by acrylic glass. A wooden enclosure wrapped the lights, light controllers and cables. The indirect and direct light enclosures were connected via hinges, to create a foldable luminaire that can be transported easily. Since the prototype was not indended for permanent installation, a wooden stand was created that could be positioned behind the bed headboard. Using designated hooks, the device could then be mounted to the stand instead of the wall.

Apart from the wooden enclosing, for which woood had to be cut into custom shapes, the entire prototype was constructed using off-the-shelf hardware. The finished construction is depicted in Figure 5.9.

Separate from the luminaire, the Raspberry Pi running Home Assistant was positioned next to the user's network router and connected to the router via a LAN cable. This way, a local connection to any local network was possible without the need for individual network configuration on the device.

Iteration 1: Software implementation

Via the Home Assistant web interface, a connection between Home Assistant and the lights was established. Initial system parameters were defined and configured. The scripts and automations were set up according to the specifications from Section 5.2.

Finally, the user interface was implemented. Using *Views* components in the Home Assistant mobile UI, the user interface was divided into the three different sections *Alarm*, *Lights* and *Calibration*. The layout per section was created using *Markdown* components

[8]https://www.home-assistant.io/integrations/mobile_app/

(a) Early Prototype (*Day* scene).

(b) Early Prototype (*Evening* scene).

Figure 5.9: Photographs of the early prototype in different lighting scenes.

for texts and *Entity* components to interact with the various parameters. A *Button* component offered a manual trigger for the **dismissLights()** function. Due to limiting constraints of the framework, a top navigation bar, instead of a bottom navigation bar was used for navigation between the views.

The resulting UI is depicted in Figure 5.10.

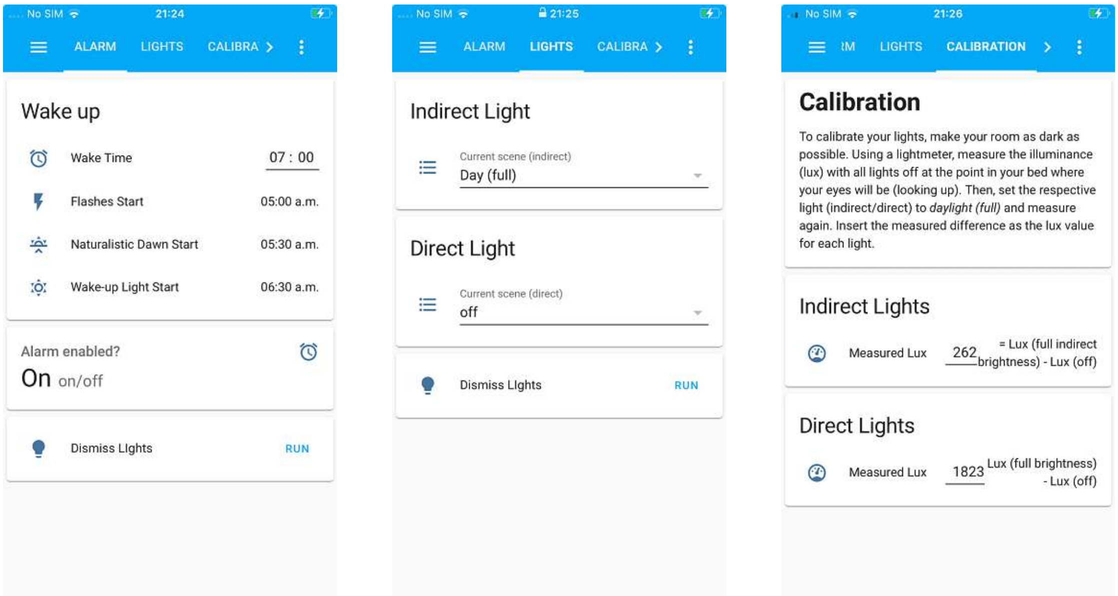
5.3.3 Iteration 1: Evaluation Results

To evaluate the early prototype, technical measurements were evaluated and compared against the system specifications. Then, user tests were conducted and feedback collected. The learnings from the tests were translated into refinements of the concept to be considered in the next implementation iteration.

Iteration 1: Technical Evaluation Results

Apart from the wooden enclosing, for which wood had to be cut into custom shapes, the entire prototype was constructed using off-the-shelf hardware. Therefore, the constructed prototype was a suitable candidate to address research question RQ3: "*How or to what extent can the hardware requirements for the conceptualized wake-up system be met by an arrangement of off-the-shelf hardware?*". The prototype's characteristics were compared against its hardware requirements from Table 5.1.3.

Lux measurements using a luxmeter in the bed revealed that, in a test environment representative of typical bedrooms, the peak illumination using indirect lights was 380 Lux, which is generously above the requirement of 250 Lux. The dimming ratio of 1:250,000 could not be precisely evaluated, since the luxmeter only supported low-light



(a) Alarm screen (b) Lights Screen (c) Calibration screen.

Figure 5.10: UI screenshots from iteration 1, using the *Home Assistant* mobile app.

measurement down to 0.01 Lux, an order of magnitude less precise than the required 0.001 Lux. However, a subjective assessment considered the dimming ratio as sufficient. The direct lights provided a maximum of 3010 Lux, which satisfies the requirement of 2500 Lux. On the other hand, the direct lights produced undeniable glare, caused by an insufficient level of diffusion by the diffusion foil. Therefore, hardware requirement HW-05 was not satisfied. All other hardware requirements related to light had already been met by the specification of the purchased lights.

Using the clock time on the Internet, the device had constant access to an accurate clock time. Regarding the requirements regarding the construction of the device, all requirements, except the visual appeal, which had to be assessed by the test users, were considered satisfied. The device withstood bumps and could be transported without risk of breaking.

A test of the lighting dynamics soon revealed that it was not possible to produce flashes of 2 milliseconds duration using the Zigbee wireless smart light protocol. The latency of the wireless protocol led to inconsistent light outputs with two commands that were only separated by 2 milliseconds. Consequently, the ability to produce flashes of such an ultrabrief duration had to be added to the hardware requirements. All other lighting dynamics could be reproduced with the chosen setup.

Finally, testing the different light modes of the device revealed that the LED drivers produced a clearly audible buzzing sound. Even when turned off, a slightly audible clicking noise of the drivers became apparent. Since undesired noises pose a threat to the user experience or even the user's ability to fall asleep, a silent operation was added as a hardware requirement for the next impelementation iteration.

The failed or added requirements are formally summarized in Table 5.6.

Iteration 1: User Test Results

Within a total time frame of 12 weeks, three participants (P01 - P03) from the target group used the first prototype for 3 weeks each in their respective bedrooms. The week following each user test was used for the transportation of the device and technical checks.

Table 5.5 lists the test user profiles and their device ratings after 3 weeks of use, according to the questionnaire described in Section 4.4.

Participant ID	P01	P02	P03
Participant Profile			
Age range	26-35	19-25	26-35
Gender	male	male	male
Est. chronotype	definite night owl	rather night owl	definite night owl
Ease getting up [1-5]	1	2	1
Test results (after 3 weeks use)			
Wake-up exp. [1-5]	4	5	4
Wake-up comp. [1-5]	4	5	5
Usability [1-5]	4	5	3
PMF metric [I will...]	somewhat miss it	miss it very much	miss it very much

Table 5.5: User test results for iteration 1: Participant profile and subjective post-test ratings of the wake-up experience with the device (**Wake-up exp.**), wake-up experience with the device compared to usual awakenings (**Wake-up comp.**), and satisfaction with the user interaction (**Usability**). Each category was rated on a scale from 1 (very bad/much worse) to 5 (very good/much better). The product-market-fit metric (**PMF metric**) rates how users feel at the thought of returning the device after use. It is a single-choice metric out of the three options *"I will not miss it"*, *"I will somewhat miss it"*, and *"I will miss it very much"*.

Both the quantitative and qualitative feedback indicated that the wake-up experience created by the device was generally well received. In a subjective comparison to their baseline, all participants reported an improvement in their wake-up experience. The light alone was reported to awaken the participants during the first days of use, but the audio alarm was required to awaken most days in weeks 2 and 3. As anticipated from the technical evaluation, glare was reported as a problem with the direct light at maximum intensity. Participant P01 expressed a wish for the ability to manually adjust the maximum brightness of the bright wake-up light. However, this request was not adopted as an additional system requirement, as the request was suspected to be a symptom of the direct light's glare and might not have been formulated if requirement HW-05, which addresses glare, had been satisfied.

An analysis of the participants' sleep time logs over the course of their respective test phase revealed substantial inconsistency in sleep schedule. Participant P01, for example, exhibited a 4-hour shift in wake time from night 15 to night 16. This stood in stark contrast to the naturalistic dawn study in which participants were asked to get up at the same time every day [27]. Since for this iteration, the timing for the naturalistic dawn simulation was coupled with the set wake time, an erratic sleep schedule led to an erratic lighting schedule, which conflicts with the goal of maintaining a consistent lighting schedule to stabilize the users' circadian rhythms. To maintain consistent lighting, either the users' wake times had to be consistent or the millisecond flashes and naturalistic dawn had to be decoupled from the users' day-to-day wake times. To give users maximal lifestyle flexibility, decoupling was chosen as the approach for the next iteration.

The interaction with the device through the smartphone and the designated user interface was rated neutral to positive by all participants. No problems were reported with respect to daily interaction on a conceptual level. Participant P03 reported occasional technical issues with the wireless availability of the core controller. Therefore, requirement UI-UX-02 which regards the reliability of the system was considered to be not satisfied. Rebooting the Raspberry Pi on which Home Assistant was running solved the problem in all cases.

What represented the most negative part of the feedback was the physical appearance of the early prototype. The device was not considered aesthetically pleasing, which failed the hardware requirement HW-10. Participant P01 reported feeling threatened by the size and perceived weight of the apparatus above him. Since perceived stability, in addition to the objective stability of the system, obviously influenced user experience, it was added as a hardware requirement for the next iteration of implementation. Moreover, the operational noise of the light controllers was negatively mentioned.

5.3.4 Iteration 1: Revision of Requirements

Table 5.6 lists the system requirements that had not been met by the first prototype, were updated, or newly added after the first implementation iteration.

While the first prototype was generally well received by the test users, a major limitation for this its results was the absence of the millisecond flashes in the morning light program, due to technical limitations of the prototype. It was not clear whether all participants would be able to sleep through the flashes and how they would have affected their wake-up experience at wake-up time. A correct representation of the flashes was considered the most critical factor for the next iteration. Furthermore, keeping the starting times of the flashes and the naturalistic dawn consistent throughout use was added to the requirements S-NDS-02 and S-MSF-02.

Regarding the user experience, the lack of operational reliability was the only, yet a significant failure.

Requirement ID	Description	Status
S-NDS-02	The Naturalistic Dawn Simulation shall start around, but not earlier, than 7.5 hours after the estimated DLMO. The starting time shall remain consistent throughout use.	updated
S-MSF-02	The Millisecond Flashes shall start around, but not earlier, than 8 hours after the estimated DLMO. The starting time shall stay consistent throughout use.	updated
S-MSF-04	The Millisecond Flashes shall occur as intermittent 2 ms flashes every 20 seconds.	failed
UI-UX-02	The system as a whole shall be reliable for consistent operation.	failed
HW-05	The direct light source shall use a large enough light emitting area to prevent glare at peak illuminance	failed
HW-10	The device should be visually pleasing and integrate well into users' bedroom interior.	failed
HW-11	The lights must support on-off-sequences of 2 milliseconds duration.	new
HW-12	The device shall remain silent throughout operation.	new

Table 5.6: Revised system requirements after iteration 1, split into photobiological requirements (prefix *S*), user interaction requirements (prefix *UI*), and hardware requirements (prefix *HW*). With reference to the initial system requirements from Table 5.1, this table only contains the requirements which had not been met, were subject to updates, or were newly added. The column *Status* indicates whether the respective requirement was newly added, whether an existing requirement was updated, or whether an existing requirement was failed.

The hardware had not met its requirements for the avoidance of glare and visual appeal, although the latter represented a nice-to-have requirement only. The list of hardware requirements was complemented by a dedicated hardware requirement for the creation of millisecond flashes, as well as a requirement for silent operation.

5.4 Implementation Iteration 2: Advanced Prototype

The second iteration of implementation comprised the technological revision of the first prototype based on the evaluation results depicted in Table 5.6. An advanced prototype was developed and constructed. Finally, the advanced prototype was tested by users in the target group, and the test results were evaluated.

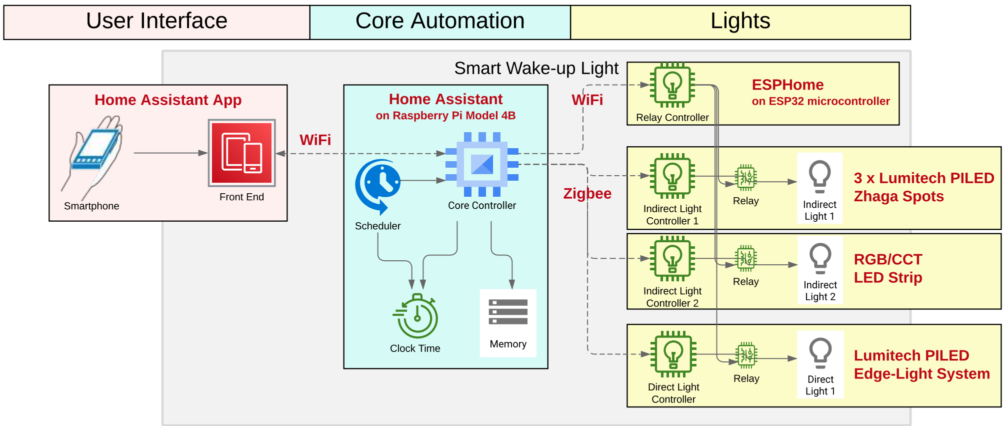


Figure 5.11: Visual model of the architecture in the implementation iteration 2. Architectural components are described with black labels. Technologies that implemented the architecture for the advanced prototype in practice are described with red labels. Dashed arrows represent wireless connections while solid lines represent wired or same-device communication.

5.4.1 Iteration 2: Technology and Hardware Selection

Based on the evaluation results from iteration 1, the implementation of the three architectural layers was reassessed. A new implementation was chosen for the *Lights* layer while the technology stack for *Core automation* and *User Interface* was kept similar to iteration 1. This section decribes individual technological choices of the advanced prototype and their rationale. The high-level implementation strategy for the system's architecture is visualized in Figure 5.11.

Iteration 2: Lights

For the second prototype, the mirrored backlight panel approach, where Lumitech *PILED All-in-one* panels were used for both indirect and direct lighting, was abandoned. Apart from new implementation choices for the lights per se, an additional control component *Relay Controller* was introduced to enable the Millisecond flashes (MSF) for both sides while keeping the Zigbee protocol as the main smart light protocol between the core automation layer and the lights. The following list comprises the lighting stack used for iteration 2.

- **Lights Interface:** *Zigbee*
- **Indirect Lights**

1. Bright indirect Sublights: 3x Lumitech *PILED Zhaga Spots*[9]
2. Dim indirect Sublight: RGB + CCT LED light strip[10]

- **Direct Lights**

  1. 120x30cm edge-lit panel using 4 x *Lumitech Edge Light System*

- **Millisecond Relay Controller:** *Espressif ESP32* microcontroller

Detailed reasoning for the lighting choices made in this iteration is provided in Appendix E.

Iteration 2: Core Automation

The same software technology stack was used for prototype as was used for the protoype 1, which is listed in Section 5.4.1.

To improve the reliability of the core controller, the Raspberry Pi 3B mini-computer that was running Home Assistant was replaced by a **Raspberry Pi 4B mini-computer**. The 4B model represented the next generation of the Raspberry Pi Series and offered an improved processor speed and RAM compared to its predecessor.

Iteration 2: User Iterface

The Home Assistant *dashboard* framework, running on the **Home Assistant mobile app**, was kept as the user interface for the advanced prototype.

5.4.2 Iteration 2: Implementation

Iteration 2: Hardware Implementation

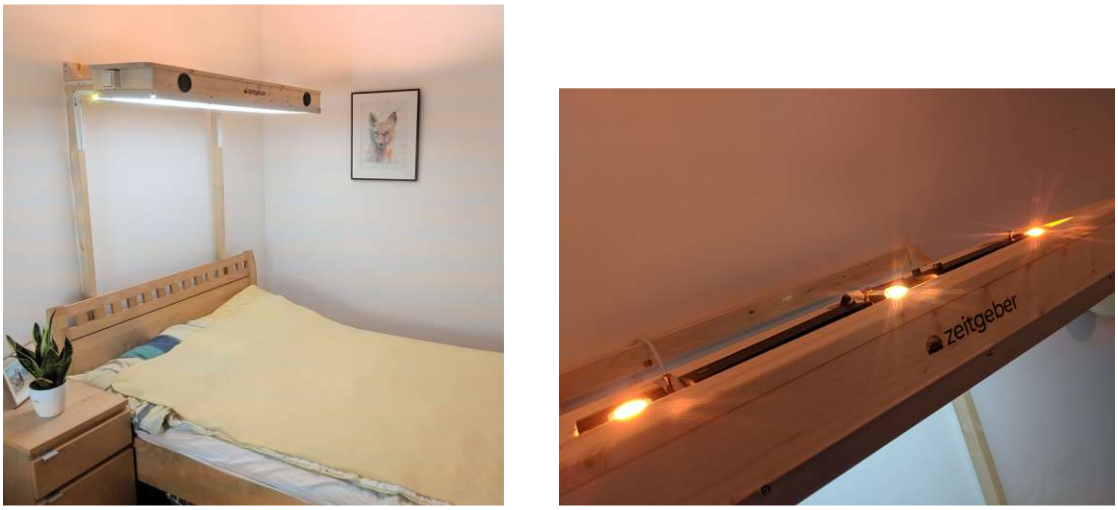
The various parts of the advanced prototype hardware were constructed or assembled, respectively, with the help of Simon Bellink and Saeed Helali. Bellink constructed the wooden frame and assembled the direct light panel while Helali implemented the wiring and the addition of the *millisecond relays* between the proprietary light controllers and the lights.

The construction resulted in a box-shaped 120 x 30 x 15 cm smart light module as the centerpiece of the device. The module was positioned 1.2 meters above the users' pillow and carried by a dedicated wooden stand. Figure 5.12a shows the finished prototype hardware. The downward-facing side of the lighting module was represented by the edge-lit LED panel, which defined the 120 x 30 cm base area of the module. The three indirect spot lights were positioned on the upward facing side, evenly spaced across the

[9]https://lumitech.com/marketing/db/PI-LED_Zhaga_SMD_LMU2_en.pdf
[10]https://www.amazon.de/-/en/Powered-Controller-Dimmable-Ambient-Smartthings/dp/B0B58YS4KC/

length of the module (see Figure 5.12b). The extensive metal cooling modules required to passively cool the 50 Watt spots caused the 15 cm height of the module. The significant height also left enough space to place all wires and controllers inside the wooden box.

The stand was designed to keep 30 cm distance between the wall and the constructed light module. This was an attempt to place the direct light panel more centrally in the viewing field of the person in bed (see the dotted lines in Figure 5.2 for reference). Lastly, an additional hardware switch on the side of the light module, visible in Figure 5.12a, served as an "emergency off" button to physically turn off all lights. This should be a last resort measure for the user if the core controller lost its wireless connection to the lights while they were turned on - a case that had occasionally been reported by users in iteration 1.



(a) Advanced Prototype (Wake-up mode).

(b) Advanced Prototype (viewed from above)

Figure 5.12: Photographs of the advanced prototype from different angles

Iteration 2: Software Implementation

In contrast to iteration 1, the *millisecond relay controller* required additional software for the *Lights* layer of the architecture. The designated ESP32 microcontroller was flashed with the smart home framework *ESPHome*. Within this framework, a callable script was created to activate the relays between the light controllers and the lights only for 2 milliseconds every 20 seconds. This created the desired flashing behavior without the need for short wireless command intervals. In the controller's default state, that is, while the millisecond flash script was not running, the relays were activated so that the lights could be controlled as usual by their proprietary controllers.

In the *Core Automation* layer, the *Millisecond Flashes* algorithm was adjusted so that during this light program, the proprietary indirect and direct light controllers should turn on the lights in a way that provides 1000 Lux to the user. At the same time, the millisecond relay controller was called to trigger its script that would only activate the relays for 2 milliseconds every 20 seconds. This resulted in 1000 Lux flashes for the user, as specified by requirement S-MSF-04. See Algorithm 5.4 for the new algorithm.

Algorithm 5.4: Millisecond Flashes (Advanced Prototype Variation)

```
Input: msfStartTime
indirectBrightness ← getIndirectBrightnessForLux (lux: 250);
directBrightness ← getDirectBrightnessForLux (lux: 750);
startMillisecondRelayScript ();
setLights (id: indirectLights, brightness: indirectBrightness, transitionTime:
  0, colorTemperature: 6000);
setLights (id: directLights, brightness: directBrightness, transitionTime: 0,
  colorTemperature: 6000);
wait (15 minutes);
setLights (id: indirectLights, brightness: 0, transitionTime: 0);
setLights (id: directLights, brightness: 0, transitionTime: 0);
stopMillisecondRelayScript ();
```

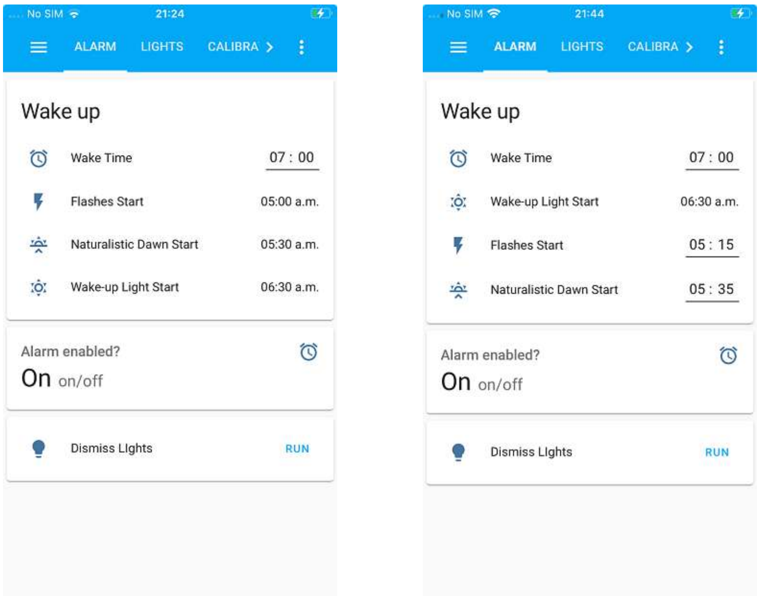
In the *User Interface* layer, the time-setting of the *Naturalistic Dawn Simulation* and the *Millisecond Flashes* was changed from being relative to the start time of BWL to being set as absolute times. This change allows the user to set times based on their DLMO, thereby implementing the requirement updates for S-NDS-02 and S-MSF-02, listed in Table 5.6. The new *Alarm* screen of the UI, in comparison to the alarm screen from iteration 1, is depicted as a screenshot in Figure 5.13. The rest of the UI remained the same as in iteration 1.

5.4.3 Iteration 2: Evaluation Results

Analogous to the evaluation of iteration 1, the advanced prototype was first evaluated regarding its satisfaction of the technical requirements. Afterwards, a second set of user tests was performed to gather user experience feedback. Finally, the evaluation results were turned into learnings, which served as the foundation for the third and final prototype iteration.

Iteration 2: Technical Evaluation Results

The second iteration of the prototype generally retained its quality of being constructed with off-the-shelf components. The assembly of the direct LED panel, as well as the addition of the relays both required a certain electronics expertise, but neither was considered as exceeding the scope of a do-it-yourself (DIY) project. Therefore, this version continues to address research question RQ3. The prototype was evaluated according to the hardware requirements specified in Table 5.1.3 and its amendments from Table 5.6.



(a) Alarm screen (iteration 1) (b) Alarm screen (iteration 2)

Figure 5.13: UI screenshots of the old and the revised *Alarm* screen. Flashes Start and Dawn Start are now manually set.

Measurements in a simulated bedroom environment demonstrated that the indirect lighting from the three LED spots now produced a combined illuminance of 539 Lux, exceeding the 250 Lux requirement. Additionally, the dimming function performed satisfactorily, meeting the dimming requirement with a subjective assessment confirming adequate light control for the purpose.

Direct illumination was significantly improved as a result of the use of a diffuse LED panel, which effectively reduced glare, a primary concern in the previous iteration. The direct illuminance now reached a peak of 2140 Lux, which falls below the original 2500 Lux requirement but only by a small margin. This iteration thus offers enhanced visual comfort while achieving a suitable brightness level close to the target.

However, temperature testing of the edge-lit direct panel enclosure revealed an issue with heat dissipation, as the metal became uncomfortably hot upon touching. This aspect should require attention in subsequent iterations to ensure safety and usability. Conversely, the frame was verified to be sturdy, able to withstand handling and moderate impacts without damage, meeting all structural requirements.

In terms of lighting dynamics, this iteration succeeded in producing flashes of the specified duration, addressing a major limitation identified in the previous version. The performance of the flashing function were found to be consistent with the required specification from S-MSF-04 and HW-11.

Finally, the LED drivers in this iteration performed silently, eliminating the prior audible buzzing and clicking noises. Thus, silent operation was considered successfully achieved, meeting the updated hardware requirement HW-12 for auditory comfort.

Overall, iteration 2 demonstrates substantial improvements in meeting the hardware specifications while highlighting areas for further refinement, particularly in thermal management and maximal illuminance of the direct-light panel.

Iteration 2: User Test Results

For the user tests in iteration 2, three new participants (P04 - P06) from the target group received the advanced prototype to use it for 3 weeks. The installation of the device in the users' bedrooms was performed by Simon Bellink, Saeed Helali, and myself.

The new approach to the timing of the NDS and MSF required expert assistance in the configuration of the device. Therefore, an initial assessment conversation was held with the participants. Based on their current habitual wake times, their desired habitual wake times, and estimated current DLMO, the recommended light program start times were defined. After each week of use, a 15-minute conversation between me and the respective user offered the opportunity to update the start times based on their experiences in the past week.

The participant profiles and their device ratings after 3 weeks of use are shown in Table 5.7.

Participant ID	P04	P05	P06
Participant Profile			
Age range	26-35	19-25	26-35
Gender	male	female	female
Est. chronotype	definite night owl	rather night owl	rather night owl
Ease getting up [1-5]	2	1	1
Test results (after 3 weeks use)			
Wake-up exp. [1-5]	4	4	5
Wake-up comp. [1-5]	5	4	4
Usability [1-5]	4	3	5
PFM metric [I will...]	miss very much	miss very much	miss very much

Table 5.7: User test results for iteration 2: Participant profile and subjective post-test ratings of the wake-up experience with the device (**Wake-up exp.**), wake-up experience with the device compared to usual awakenings (**Wake-up comp.**), and satisfaction with the user interaction (**Usability**). Each category was rated on a scale from 1 (very bad/much worse) to 5 (very good/much better). The product-market-fit metric (**PMF metric**) rates how users feel at the thought of returning the device after use. It is a single-choice metric out of the three options *"I will not miss it"*, *"I will somewhat miss it"*, and *"I will miss it very much"*.

As the flashing functionality was usable for the first time in iteration 2, the participants' experience with this feature was of particular concern. The flashing feature was generally well tolerated and two out of three participants (P05 and P06) reported that they mostly stayed asleep throughout the flashing period. However, participant P04 experienced flashes-induced sleep disturbances during the first nights and requested to disable them. To accommodate this, the start time of the flashes was changed to occur around noon.

As in iteration 1, the general user interaction with the device was positively received. However, despite the controller hardware update from Raspberry Pi 3 to Raspberry Pi 4, connectivity issues with the wireless controller impacted the overall experience: In two out of three trials, participants encountered situations in which the controller had to be manually restarted to reestablish the connection. In particular, participant P05 faced recurrent connectivity disruptions, which required remote troubleshooting assistance. This issue posed a significant impairment to the user experience, highlighting the need for improved connectivity reliability in the third iteration of the development.

The newly implemented diffuse LED panel of the advanced prototype successfully reduced glare compared to the first prototype and delivered less illuminance than the original 2500 Lux specification at maximum brightness. Despite all this, participant P04 still found the direct light to be uncomfortably bright in the mornings, expressing a wish for the ability to manually adjust its maximum brightness level.

No complaints were expressed regarding the perceived stability or the visual appearance of the advanced prototype, which hints at a satisfactory level of visual appeal. Furthermore, there were no complaints about operational noises of the advanced prototype, confirming the technical evaluation that this issue had been successfully solved.

Finally, participant P04 noted a usability issue related to leaving the device unattended. Spending some nights away from home during the test, he had forgotten to deactivate the morning light program. This caused the lights to activate automatically in the morning and remain on throughout the day until his return. This unintended operation was an inconvenience and points to the potential benefit of integrating an automated shutdown feature to prevent unnecessary energy consumption.

5.4.4 Iteration 2: Revision of Requirements

The outcomes of the second iteration prompted several key revisions to the system requirements, to be implemented in the third and final development cycle. While iteration 2 successfully implemented the millisecond flashes — a core feature missing in the initial prototype — other requirements were not met or showed limitations, requiring reconsideration and adjustment.

Requirement ID	Description	Status
S-BWL-03	The Bright Wake-up Light shall have a maximum intensity of at least 1500 lux.	updated
UI-CONF-06	The user shall be able to set the maximum relative brightness of the Bright Wake-up Light [1% - 100%].	new
UI-CONF-07	The user shall be able to activate or deactivate the Millisecond Flashes.	new
UI-CONF-08	The user shall be able to set the maximum relative brightness of the Millisecond Flashes [1% - 100%].	new
UI-UX-02	The system as a whole shall be reliable for consistent operation.	failed
UI-UX-07	The device shall automatically turn off all lights when they have been on for 3 hours without any user activity.	new
HW-05	The direct light source shall use a large enough light emitting area to prevent glare at peak illuminance	failed
HW-09	No part of the device that can be touched by the user must be so hot that it inflicts pain upon touch.	failed

Table 5.8: Revised system requirements after iteration 2, split into photobiological requirements (prefix *S*), user interaction requirements (prefix *UI*), and hardware requirements (prefix *HW*). With reference to the previous system requirements (Table 5.1, revised by Table 5.6), the table only contains the requirements which had not been met, were subject to updates, or were newly added. The column *Status* indicates whether the respective requirement was newly added, whether an existing requirement was updated, or whether an existing requirement was failed.

Adjusting Maximum Illuminance (S-BWL-03, UI-CONF-06, HW-05, HW-09)

The maximum illuminance requirement for the Bright Wake-up Light, initially set at 2500 Lux, was not fulfilled by the newly introduced LED panel in this iteration. While the maximum illuminance reached 2140 Lux, it was accompanied by issues with glare (failing requirement HW-05) and overheating of the metal enclosure (failing requirement HW-09), inflicting pain upon touch. These outcomes indicate constraints within the current design's capacity to deliver high illuminance while maintaining user comfort and safety. Specifically, achieving 2500 Lux would require either a substantial increase in panel size or a decrease in distance between the panel and the user. However, placing the light source closer to the users would limit their flexibility in bed, such as the ability to comfortably sit, which could be expected to negatively impact user experience and user acceptance. Alternative placements, such as positioning the light to the user's side, would likely result in uneven bed illumination, a problem which was already discussed in the hardware architecture section (see Section 5.2).

These findings align with earlier concerns raised by lighting expert Exp03, who advised that 2500 Lux might be excessive for this application (see Section 5.1.3). Additionally, a review of the intended biological impact of the device reveals that while 2500 Lux meets the threshold for "bright light therapy" (BLT), which is typically associated with mood improvement, the recommended duration at 2500 Lux is two hours per day [20]. This duration is unlikely to be met by users in this context. Anticipating this limitation, the 2500 Lux had never been the system's discriminative feature for mood improvement in the first place. Naturalistic Dawn Simulation alone demonstrated efficacy in mood improvement similar to the gold-standard 10,000 Lux BLT, without necessitating BLT-level intensity or an extended period of time spent awake in bed [27].

Based on these considerations, requirement S-BWL-03 has been updated to specify a maximum illuminance of 1500 Lux, instead of 2500 Lux, for the Bright Wake-up Light. From a biological standpoint, already 250-500 Melanopic Equivalent Daylight Illuminance (M-EDI) Lux have been shown to effectively suppress melatonin production in most humans, thereby promoting wakefulness [53]. Given this lower threshold, an LED light source delivering 1500 Lux is expected to comfortably exceed the necessary melanopic intensity across a range of color temperatures, thus achieving the desired circadian impact without reaching the problematic glare or heat levels encountered at 2500 Lux.

This revised level maintains the biological efficacy needed to support the user's morning activation while optimizing for comfort and practicality within the device's design constraints. To further enhance user satisfaction, an additional configuration feature was introduced: requirement UI-CONF-06 allows users to configure the direct light's maximum illuminance. This configuration should allow light-sensitive users to find an optimal balance between biological activation and satisfactory user experience, which was considered critical from a user-centered design perspective.

Dissatisfactory System Reliability (UI-UX-02)

The operational reliability of the system, specified by requirement UI-UX-02, was the only requirement other than glare that both prototype iterations failed to satisfy. The revision from iteration 1 to iteration 2 had concerned the hardware on which the core automation layer operated. However, the repeated connectivity problems between core controller and the lights in this iteration hint at either the wireless connection itself being the problem or the Zigbee implementation of Home Assistant - using the ConBee II Zigbee gateway - being the problem. Either way, the current Home-Assistant-based architecture must be reconsidered and options towards more robust, potentially wired smart light controls should be explored. In addition to an increased reliability, wired light controls would eliminate the communication delay between core controller and lights which caused the failure of the flash functionality in iteration 1.

Auto-turn-off feature (UI-UX-06)

To ensure safety and save electric energy, the device should turn off all lights when running idle for an extended period of time with the lights turned on. A waiting period of 180 minutes before turning the lights was considered suitable, as it was considered long enough to not trigger during time spend awake in bed on weekends or in the evening.

Flash Configurability (UI-CONF-07, UI-CONF-08)

While the Millisecond Flashes were well-tolerated by two of the three participants, they did cause sleep disruptions for one participant. Following the user-centered rationale of aiming at an optimal balance between efficacy and comfort, new configuration options were added for the flashes: One the one hand, sleep disruptions may be mitigated by a reduction in flash illuminance. On the other hand, the user should have the opportunity to deactivate the flash feature altogether if repeated sleep disruptions threaten the overall user experience. The adjustability of the Millisecond Flashes paves the way for experiments and iterations on the user's end towards optimal personalized effectiveness of the system.

5.5 Final System Specification

As the final result of the thesis, this section specifies the conceptualized smart wake-up sytem in a final set of system requirements. Furthermore, the initial system design, formulated in Section 5.2, is revisited and updates are made where the insights from the prototyping phase demand adaptation of the initial design.

5.5.1 Final System Requirements

Table 5.9 summarizes the findings of the thesis' analysis and implementation phases into a comprehensive set of requirements for the smart wake-up lighting device. The specification addresses the research questions RQ1 and RQ2, at a point where the initial respective requirements, formulated in Sections 5.1.1 and 5.4, have been revised by user feedback from two prototype iterations.

Table 5.9: Final system requirements for the smart wake-up light device. Requirement IDs have domain-specific prefixes, where **S** stands for scientific requirement, **UI** stands for user interaction requirement, and **HW** stands for hardware requirement.

Requirement ID	**Description**
Naturalistic Dawn Simulation	
S-NDS-01	The Naturalistic Dawn Simulation shall have a duration of 90 minutes.

Continued on next page

Requirement ID	Description
S-NDS-02	The Naturalistic Dawn Simulation shall start around, but not earlier, than 7.5 hours after the estimated DLMO. The starting time shall remain consistent throughout use.
S-NDS-03	The Naturalistic Dawn Simulation shall have a maximum intensity of 250 lux.
S-NDS-04	The Naturalistic Dawn Simulation shall transition from 0.001 to 250 lux.
S-NDS-05	The Naturalistic Dawn Simulation shall use diffuse light.
S-NDS-06	The Naturalistic Dawn Simulation shall use a warm-white 3000K CCT LED light.
Bright Wake-up Light	
S-BWL-01	The Bright Wake-up Light shall have a duration of 30 minutes.
S-BWL-02	The Bright Wake-up Light shall start 20 minutes before the set wake time.
S-BWL-03	The Bright Wake-up Light shall have a maximum intensity of at least 1500 lux.
S-BWL-04	The Bright Wake-up Light shall follow a quadratic curve for brightness change.
S-BWL-05	The Bright Wake-up Light shall use broad-field direct light.
S-BWL-06	The Bright Wake-up Light shall use a neutral-white 3000K - 5000K CCT broad-spectrum LED light.
Millisecond Flashes	
S-MSF-01	The Millisecond Flashes shall have a duration of 15 minutes.
S-MSF-02	The Millisecond Flashes shall start around, but not earlier, than 8 hours after the estimated DLMO. The starting time shall stay consistent throughout use.
S-MSF-03	The Millisecond Flashes shall have a maximum intensity of 1000 lux.
S-MSF-04	The Millisecond Flashes shall occur as intermittent 2 ms flashes every 20 seconds.
S-MSF-05	The Millisecond Flashes shall use diffuse light.
S-MSF-06	The Millisecond Flashes shall use a cool-white 6000K CCT broad-spectrum LED light.
System Configuration	
UI-CONF-01	The user shall be able to set the start time of the naturalistic dawn simulation.
UI-CONF-02	The user shall be able to set the start time of the millisecond flashes.
UI-CONF-03	The user shall be able to set the alarm time manually.
UI-CONF-04	The user shall be able to dismiss an active alarm manually.

Continued on next page

Requirement ID	**Description**
UI-CONF-05	The user shall be able to activate or deactivate an alarm.
UI-CONF-06	The user shall be able to configure the maximum relative brightness of the Bright Wake-up Light [1% - 100%].
UI-CONF-07	The user shall be able to activate or deactivate the Millisecond Flashes.
UI-CONF-08	The user shall be able to configure the maximum relative brightness of the Millisecond Flashes [1% - 100%].
User Experience	
UI-UX-01	The user interaction with the device shall be simple and intuitive. After the initial configuration, the daily use should be similarly easy as the setting of a smartphone alarm.
UI-UX-02	The system as a whole shall be reliable for consistent operation.
UI-UX-03	The system shall be able to reliably wake people up at their desired wake times.
UI-UX-04	The device shall offer a digital user interface that can be accessed wirelessly via common smartphones or tablets.
UI-UX-05	The device shall provide optional advanced settings for power users.
UI-UX-06	The device shall support recurring alarm schedules with minimal user interaction.
UI-UX-07	The device shall automatically turn off all lights when they have been on for 3 hours without any user activity.
Hardware Requirements	
HW-01	The device shall produce the diffuse light for the naturalistic dawn simulation and millisecond flashes using an indirect light source.
HW-02	The indirect light shall have a dimming ratio of at least 1:250,000.
HW-03	All lights shall provide a color rendering index (CRI) of 90 or higher.
HW-04	The device should produce the peak intensities of the bright wake-up light using a user-facing direct light source.
HW-05	The direct light source shall use a large enough light emitting area to prevent glare at peak illuminance.
HW-06	The device shall have access to an accurate clock time at any time.
HW-07	The device shall be robust enough to be touched and moved without the risk of breaking.
HW-08	The device shall withstand incidental bumps with no danger of the device falling down on the user.

Continued on next page

Requirement ID	Description
HW-09	No part of the device that can be touched by the user must be so hot that it inflicts pain upon touch.
HW-10	The device should be visually pleasing and integrate well into users' bedroom interior.
HW-11	The lights must support on-off-sequences of 2 milliseconds duration.
HW-12	The device shall remain silent throughout operation.

The requirements are structured into several key sections that represent distinct aspects of the system:

Naturalistic Dawn Simulation (NDS): This requirements section outlines requirements for simulating a gradual sunrise effect, as it has been validated in studies from Terman et al. [27] and Avery et al. [25], and has been recognized as a first-line treatment for SAD by the American Psychiatric Association [18]. The requirements include specific parameters for intensity, color temperature, and duration. Beyond mood improvement, the scientific findings in which the requirements are rooted include benefits regarding circadian alignment through a significant advance of the user's circadian phase [12]. Synchronizing circadian timing with social wake times is a known factor to reduce chronic sleep inertia [9]

Bright Wake-up Light (BWL): This section specifies requirements for an alarm-time-dependent gradual increase in illumimance to acutely mitigate sleep inertia. The parameters include intensity thresholds, lighting dynamics, and optimal color temperatures to ensure effectiveness. The requirements are based on research on the efficacy of commercial wake-up lights to reduce sleep inertia upon awakening [16, 80], as well as the potential of bright light to acutely increase alertness [55].

Millisecond Flashes (MSF): These requirements specify an innovative feature that uses ultra-brief, high-intensity light pulses to shift circadian phase during sleep to induce a better circadian alignment. The concept has been described by Zeitzer et al. [15] and was successfully applied by Kaplan et al. to facilitate an increase of 43 minutes total sleep time per night for adolescents [84]. This section specifies the timing, duration, and characteristics of the flashes, including intensity and color spectrum.

System Configuration: This section describes concrete user interaction requirements. Five critical user stories have been identified throughout this thesis, which are covered by the noted configuration requirements:

1. The user performs an initial calibration of the lights.

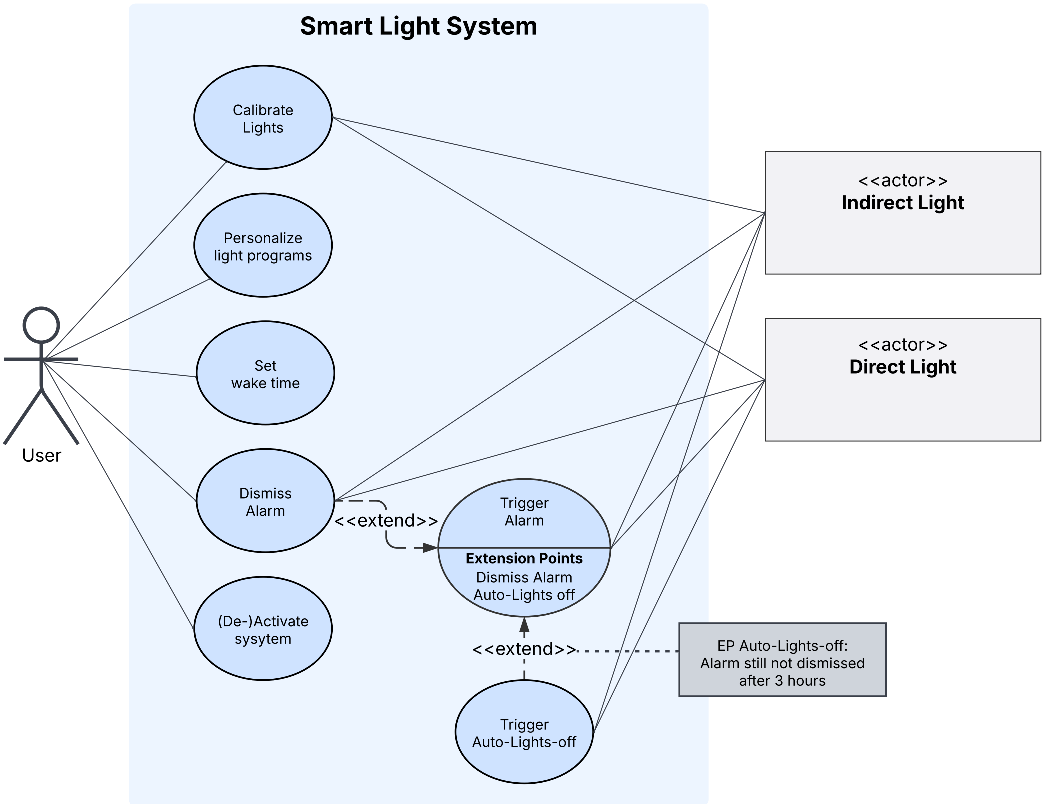


Figure 5.14: Use case diagram of the interaction between user and smart light system.

2. The user configures the dosing and timing of NDS, MSF and BWL according to personalized recommendations from an expert, considering constraints of personal light sensitivity.

3. The user sets their desired wake time for the next day.

4. The user dismisses an active alarm in the morning.

5. The user activates or deactivates the entire system when they plan to spend the night away from home or when they return from a period spent out of home.

Figure 5.14 visualizes the user stories in the form of a use case diagram.

User Experience: This section addresses usability aspects, such as reliability, simplicity, and seamless integration into daily routines.

Hardware Requirements: This section captures physical and functional requirements of the device, including durability, safety, and aesthetic design. Specifications also address relevant technical performance of the setup, such as dimming ratios, color rendering, and silent operation.

Table 5.9 provides a detailed breakdown of these requirements, structured with domain-specific prefixes for clarity: S for photobiological requirements, UI for user interaction requirements, and HW for hardware requirements. Each section is the result of insights derived from the analytical requirements engineering phase of this thesis, as well as user feedback and practical technical considerations gathered from the prototyping phase of this thesis.

5.5.2 Final System Design

The final system design keeps the main ideas of the initial design phase, specified in Section 5.2, while making some adjustments based on the results of the prototyping phase.

Final System Architecture

The final system specification builds upon the initial design, preserving the core architectural principles while refining the details based on user feedback and iterative development. As in the initial design, the system follows a three-layer architecture consisting of:

1. **Lights Layer:** The lights layer forms the hardware foundation of the system, comprising the components responsible for the actual light output. The lighting design adheres to a bi-directional LED configuration, with one light source providing indirect illumination to the room and another delivering direct light to the user. This setup is mounted above the bed headboard, ensuring optimal light distribution and glare minimization. The overall design is illustrated in Figure 5.2.

2. **Core Automation Layer:** This layer serves as the brain of the system, managing the parametrized automation of the morning light presentation. It orchestrates the timing and operation of the various lighting programs, such as naturalistic dawn simulation and bright wake-up light, according to user-defined schedules. While the individual lighting algorithms remain unchanged from the initial design, their combined reproduction logic has been updated from all wake-time-based to fixed, manually settable MSF and NDS start time while the BWL start time remain wake-time. This was to warrant a consistent timing for MSF and NDS throughout inconsistent sleep-wake times, a necessary characteristic to stay aligned with the study settings from which these light programs were derived [27, 84].

3. **User Interface Layer:** The user interface (UI) serves as the primary interaction point between the user and the smart wake-up light. It is accessed wirelessly via mobile devices such as smartphones or tablets. The UI allows users to configure lighting parameters, set schedules, and control the device directly.

By adhering to this layered architecture, the final specification ensures that the system remains modular and adaptable to evolving user needs.

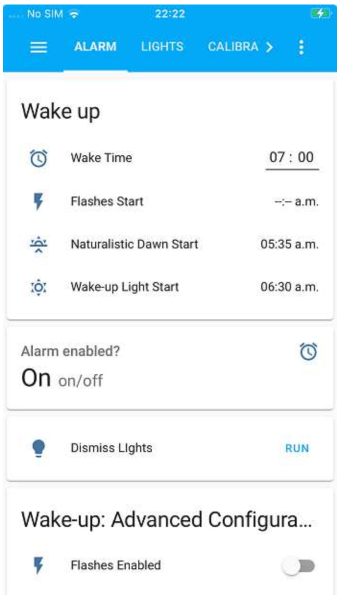
Final User Interface

As specified by requirement UI-UX-04, the final user interface enables the user to interact wirelessly with the device via a mobile end device. The interface retains the core ideas from the initial design (see Section 5.2.3), notably its division into 3 main sections:

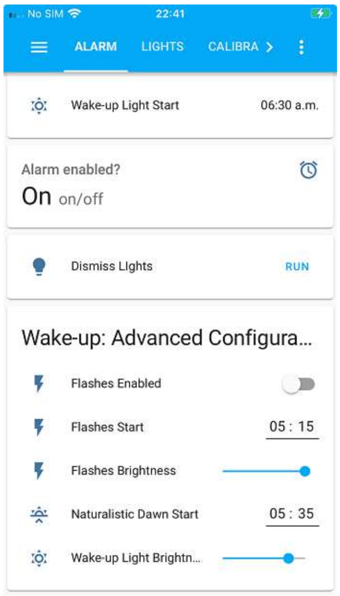
1. **Alarm Screen:** For configuring wake times, enabling/disabling alarms, and dismissing active light programs.
2. **Lights Screen:** Allows direct control of the device's light modes, providing options for scenes optimized for day and evening.
3. **Calibration Screen:** Guides users through calibrating the lights to match the required illuminance levels at the user's eye level. This structure ensures a user-friendly approach to configuring and managing the device's features.

While the core concept has persisted, the UI has been refined based on learnings from the two prototyping iterations. Key updates include the reconfiguration of the Alarm screen, allowing users to set absolute times for light programs, and the introduction of an advanced configuration section on the *Alarm* screen, in alignment with requirement UI-UX-05 (i.e. "offer optional advanced settings for power users"). In the advanced configuration section, the user can customize the relative brightness of the MSF and the BWL, as required by the new requirements UI-CONF-06, UI-CONF-07, and UI-CONF-08. In addition to the newly added configurability, the setters for the MSF start time and NDS start time have been moved into this section. If the MSF are enabled, the main wake-up section shows the MSF start time. If the MSF are disabled, the main wake-up section now shows "–:–", indicating that the MSF are disabled.

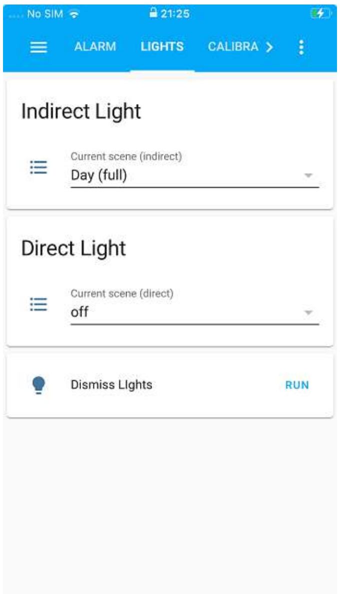
Screenshots of the final implementation of the user interface are provided in Figure 5.15. These include the Calibration screen, and the Lights screen and 2 screenshots of the - now scrollable - Alarm screen.



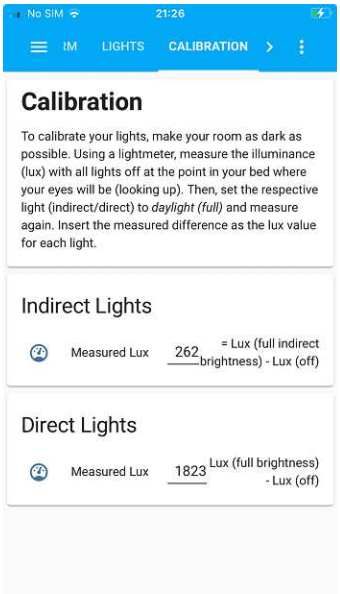
(a) Alarm screen (top)



(b) Alarm screen (bottom)



(c) Lights screen



(d) Calibration screen

Figure 5.15: Screenshots of the final UI proposition. While Lights screen and Calibration screen have stayed the same throughout both iterations, the Alarm screen was updated based on user feedback between iteration 1 and iteration 2, as well as after iteration 2.

CHAPTER 6

Discussion

In this chapter, the findings of Chapter 5, both theoretical and practical, are discussed. After a general discussion, the three research questions (RQ1, RQ2, RQ3) of this thesis and the findings thereof are discussed in detail.

The goal of this thesis was to develop a smart light device that reproduces the most effective, scientifically validated morning light interventions for the improvement of morning alertness and mood, and combines them into a single, pleasant wake-up experience for everyday use. To the best knowledge of the author, the concept established in this thesis is the first to combine the three scientifically validated morning light interventions *Naturalistic Dawn Simulation* (NDS), *Millisecond Flashes* (MSF) and bright light. Moreover, it represents the first application of NDS and ambient MSF outside of research trials.

The results of this work demonstrate that the integration of these three light interventions into a single system is feasible and can be used in day-to-day life. User feedback indicates that the device provides value, although higher operational reliability and a larger sample size are needed to gain statistically meaningful insights on the system's effectiveness on the target metrics, i.e., alertness upon awakening and mood. In particular, the comparative effectiveness of the device with current state-of-the-art (SOTA) products remains an open question. A dedicated comparative study with more participants could provide additional insights into this aspect.

The decision to mount the device above the bed headboard with a bi-directional lighting design received positive feedback from users. The downward-facing light offered direct illumination for interventions that need bright lighting, while the upward-facing light offered diffuse background illumination that could also reduce the glare induced by the bright direct light. This setup not only enabled a high-fidelity reproduction of the lighting interventions but also allowed the device to serve as a circadian-friendly room light and a biologically optimized reading light. These features turned out valuable for user acceptance, significantly enhancing the device's perceived value in the bedroom even before the its effect on morning alertness and mood could be experienced.

The conceptualized user interaction with the system required minimal interaction after the initial configuration and was generally well received. Based on the users' statements that they would *"miss [the device] very much"* after their test, it can be assumed that users would use the device on a daily basis because of the pleasant wake-up experience it creates. Assuming that the device can achieve similar mood-improving results as NDS did in its largest trial [27], which was a 49% remission rate for seasonal affective disorder (SAD), the proposed smart wake-up light could yield not only promising reactive but also preventative effects against SAD in winter. Although this appears promising, future research is required to estimate the effect size of the system on improving winter mood in practice.

Two major constraints emerged throughout the implementation phases of the thesis: Firstly, achieving morning light intensities of 2500 lux posed significant challenges, particularly in balancing high illuminance with user comfort. Issues such as glare or overheating conflicted with the functional specification of 2500 lux. Secondly, operational reliability remained a major drawback for the prototypes: The Raspberry-Pi-based framework "Home Assistant", on which the main automation logic was implemented, was often unavailable or lost the wireless connection to the lights. While the system's concept holds promise, the DIY assembly of stock hardware, which the prototypes represented, repeatedly displayed connectivity issues between system components. A wired, commercial-grade implementation would likely improve reliability by eliminating the complications associated with DIY setups, such as the interplay between different brands and protocols.

Lastly, as a potentially limiting factor, it was shown that an important prerequisite for user acceptance is the device's aesthetic appeal, which presents a potential challenge due to the subjective nature of design preferences and the diversity of bedroom interiors. Moreover, the setup required a free vertical wall behind the bed and minimal environmental light interference (e.g., through blackout curtains), which are potential barriers for a scalable distribution.

6.1 Research Question 1

> What are the functional requirements of the wake-up system to alleviate problems in late chronotype subjects?

The findings demonstrate that the functional requirements for MSF and NDS were reproducible, while the reproduction of 2500 Lux bright light presented challenges for the BWL. A posteriori, the inclusion of bright-light-therapy-grade illuminance appears to be an unnecessarily high demand for the device, considering that the main therapeutic potential of the device comes from NDS anyway. Conversely, bright light of 500 melanopic

EDI (Lux) and above is sufficient to suppress the release of melatonin and, thus, support acute alertness in the morning [53]. This significantly lower illuminance level can be easily achieved with the current prototypes and represents the bright light goal in the final system requirements.

A significant strength of the system compared to current SOTA products was its calibration mechanism, which allowed users to specify lux values instead of relative brightness. This approach allowed the system to precisely match the illuminance levels that were described in the studies on which the system concept was based.

Combining different light interventions into a single application proved feasible: MSF and NDS were found to be perfectly compatible, while BWL and NDS partially conflicted in the final 30 minutes of the sequence. The addition of the BWL appeared to be generally well received by the user test participants in this thesis. However, considering that exceedingly high illuminance impaired the therapeutic benefits of dawn simulation in an early study by Avery et al. [97], this conflict should be investigated with caution. The addition of bright light after awakening, rather than before awakening, represents an alternative approach that may be worth exploring in future work.

An important insight from this thesis is that the reproduction of study settings goes beyond just the reproduction of the light specifications: While the reference studies by Terman for NDS [27] and Kaplan for MSF [84] employed fixed wake-up times, real-life products need to account for variable schedules. In this thesis, this challenge was addressed by decoupling the timing of NDS and MSF from the users' flexible wake times, in order to keep the lighting schedules consistent. It remains unclear how the sleep irregularity of the users impacts the effectiveness of the device in the field. Conversely, the observations may also point to potentials or necessity, respectively, of user education regarding circadian health: Kaplan et al. have shown that the addition of cognitive-behavioral therapy (CBT) to the MSF intervention was a pre-requisite for actual behavior change in their test population. Considering that sleep irregularity is associated with a later circadian phase [1], worse mood [2] and reduced life expectancy [3], integrating circadian health education into the user journey represents an avenue for improvement worth exploring.

6.2 Research Question 2

> How can the user interface and human-system interaction look like so that users appreciate the usability of the system?

User feedback revealed a generally positive reception of the interface and interaction design. After the initial calibration and configuration, the system required only two main

[1] https://pubmed.ncbi.nlm.nih.gov/28607474/
[2] https://jamanetwork.com/journals/jamanetworkopen/fullarticle/2821240
[3] https://academic.oup.com/sleep/article/47/1/zsad253/7280269

touchpoints during daily use: setting the alarm time in the evening and dismissing the alarm in the morning. This corresponded to the users' general expectations towards an alarm clock and was well received. As long as the system was immediately responsive to the users' inputs, the UI allowed a frictionless execution of these two daily touchpoints. Conversely, the inability to control the device, caused by connectivity issues, surfaced as perhaps the biggest threat to the system's usability. Since users often rely on a tight schedule in the morning, any issue that induces a delay in their morning routine can be expected to drastically impair the users' experience with the system.

The sense of control as a factor for good user experience also extended to other aspects of the human-device interaction. In the user tests, the millisecond flashes represented a novel experience for all users. Although the users could mostly sleep through the flashes, some premature awakening due to the flashes - or even the dawn simulation - did happen. The ability to immediately dismiss the light program via the app represented a valuable lifeline to respond to this issue and allowed users to regain control over their sleep. Nevertheless, these instances were experienced as a grave nuisance by users. Interestingly, the unplanned sacrifice of just a few minutes of sleep opportunity in the morning were perceived as a much graver issue by users than the same or even a greater loss of sleep in the evening would be. Added to the requirements with UI-CONF-07 after iteration 2, the configurability of the illuminance of the flashes provides the users with a mid-term response (after the dismissal of the lights as a short-term response) to mitigate this nuisance. If a user awakens prematurely on one day, setting the flash intensity to a lower level gives them the power make a premature awakening in following nights less probable.

As a completely different yet promising approach to mitigate a bad user experience due to premature awakenings could be expectation management. Mentioning the possibility of premature awakenings in the initial briefing of the user and framing it as unproblematic seemed to make users more forgiving about the actual incidents. Unfortunately, as the flashes only worked in the latter of the two implementation iterations, both flash configurability and expectation management as mitigative approaches could not be systematically tested and remain a topic for future exploration.

During the user tests of the second implementation phase, an important variant of the morning user journey emerged as the case where users were absent but had forgotten to deactivate the device. This case was addressed by an automated turn-off mechanism, which was added to the final system requirements in Section 5.9 and is also illustrated in the use case diagram of Figure 5.14.

An important limitation to the scalability of the current user journey is represented by the onboarding procedure for the device: In the user tests, the entire onboarding process was conducted or at least guided by the author. To not exceed its scope, the thesis did not cover how the device could assist users in successfully performing the configuration by themselves. A smart onboarding flow, as proposed by Alicia Schwabenbauer [98], could address this gap by recommending parameters and adapting them over time. Apart from the technical configuration, the onboarding procedure could include a sort of expecation management mentioned earlier in this section. Even beyond that, it represents an opportunity to educate the user about the principles of circadian health and motivate healthy lifestyle changes that add to the benefit of the device itself - a path for future work identified in Section 6.1.

Although the basic interaction flow was well accepted in user tests, there was obvious room for improvement regarding the UI: The Home Assistant interface used for testing was unpolished and interaction was tideous at times. A dedicated user interface, such as a mobile app, represents a clear direction for future work.

Lastly, the scope of this thesis limited the user interaction to digital interaction interfaces. For future iterations, the addition of physical modes of interaction, such as buttons or the connectivity to light switches could enable a quick and effortless interaction, reducing the need for a smartphone in the bedroom for every interaction with the device.

6.3 Research Question 3

> How or to what extent can the hardware requirements for the conceptualized wake-up system be met by an arrangement of off-the-shelf hardware?

Apart from the bright light limitation discussed earlier in this chapter, it was possible to find suitable off-the-shelf hardware for the controller and all lighting requirements. A combination of lights with different maximum brightness levels achieved the dimming ratio of 1:250,000 for the NDS, which was specified by requirement HW-02. Furthermore, although current consumer-grade smart lighting protocols lacked the support for MSF, the addition of a smart relay between the stock controllers and lights successfully enabled on-off sequences of only 2 milliseconds (see requirement HW-11).

Poor reliability of the system represented the most significant limitation of the stock component approach regarding research question 3. The wireless interplay of different brands and protocols, orchestrated by Home Assistant running on a Raspberry Pi, undermined its stability. Therefore, none of the two prototypes in this thesis could satisfy the reliability requirement UI-UX-02. Poor robustness of the system may be the biggest shortcoming of the DIY approach. An industrially produced, wired model of the same architecture could likely improve the system's robustness substantially. Furthermore, an industrial implementation based on a professional product design would likely manage to address issues with the visual appearance of the device that participants voiced in the user tests.

Finally, the first implementation iteration led to the insight that the power adapters of lights are prone to making audible buzzing or clicking noises. Whether industrially produced or constructed as an assembly of stock hardware, this risk for a good user experience must be considered.

CHAPTER 7

Conclusion and Future Work

This master's thesis presents the development and implementation of a concept for a smart wake-up system that integrates three scientifically validated morning light interventions into a single, pleasant wake-up experience. This thesis represents the first attempt to achieve such an integration and the first ambient consumer application for NDS and MSF overall, thereby closing a significant translational gap in light therapy and circadian science. The results of this work demonstrate the feasibility of combining these interventions - Naturalistic Dawn Simulation (NDS), Millisecond Flashes (MSF), and Bright Wake-up Light (BWL) - both from a technical perspective and in terms of user interaction design. User tests have shown that the proposed system concept was well accepted by users, indicating the potential of the approach.

The benefits of the individual morning light interventions are well established, with evidence indicating their effectiveness in improving mood during winter [27], advancing circadian phase [12], and facilitating longer sleep duration [84]. However, these interventions had not previously been implemented in consumer-grade devices. The aim of this thesis was to bridge this gap between research and practice by conceptualizing a system that could reproduce the morning light interventions in a usable way for daily application in the private bedroom. Furthermore, to enable accessibility for a broad audience, it was investigated how such a system could be assembled as a DIY project using off-the-shelf hardware components.

A user-centric development approach was employed to achieve these goals. System requirements were derived from literature reviews, interviews with scientific and technical experts, and an analysis of user interviews. An initial system architecture was conceptualized, encompassing the three layers *user interface*, *core automation*, and *lights*. This architecture was implemented in two prototypes, which were tested by a total of six users over two iterations (each prototype being tested for nine weeks). Following the user-centric design methodology, the feedback obtained from these tests was used to refine the system requirements and system design, resulting in a final system specification.

The key findings of this thesis represent its main contributions to the field:

- This thesis proposes the first system concept to the successfully combine NDS, MSF, and BWL into a single wake-up experience. Variability of sleep schedules was identified as a major difference between the study settings and real-life application of the interventions. To account for this challenge, an algorithm was developed to make NDS and MSF robust against sleep irregularities while flexibly adjusting the BWL to the users' set wake time.

- The user tests show that the conceptualized morning light application is appreciated by evening chronotypes who struggle with sleep inertia. A digital user interface, operated via a mobile device, was demonstrated as a suitable medium for the daily interaction with the device.

- The attempt to construct such a system with readily available stock hardware revealed operational reliability as the primary shortcoming of this otherwise successful approach.

7.1 Future Directions

While the thesis successfully demonstrates the feasibility of the concept, several open questions and challenges remain, suggesting avenues for future research:

System Effectiveness: Future studies should evaluate the effectiveness of the combined light interventions against the isolated interventions they incorporate, as well as against commercially available wake-up lights. These studies should assess metrics such as sleep inertia upon awakening, mood improvements during winter, and markers of sleep health. Ideally, such research should involve a sufficiently large target group and employ a parallel or crossover trial design that compares the proposed concept with a state-of-the-art commercial wake-up light.

Smart Onboarding and Configuration: To enable a scalable distribution of the system, the need for human guidance in the system configuration must be removed. A smart onboarding process could guide users through initial setup, suggest suitable presets, and facilitate adjustments over time. The work of Alicia Schwabenbauer [98] provides a valuable foundation for this. As noted in her own thesis, future directions could include a data-driven optimization loop using machine learning algorithms. Another avenue worth investigating is the integration of wearable device data to dynamically adjust settings based on metrics such as heart rate, sleep stage, or other biomarkers. Lastly, addressing the challenge of configuring the system for use by two people sharing a bed will be relevant for its adoption by a broader audience.

Usability Improvements: Great usability is essential for the system's success in the field. A dedicated mobile app could streamline the user interface and interaction flow. Additionally, physical interface options, such as onboard buttons or integration with smart light switches, should be explored. Optimizing usability for individuals with bed partners should also be prioritized to ensure a seamless user experience.

Multiple findings of this thesis suggest that a commercial implementation of the proposed concept could significantly improve the satisfaction of the system requirements: An industrial-grade production model could overcome the limitations of DIY setups, including issues related to system reliability and aesthetic integration into home environments. Moreover, a commercial distribution would make the conceptualized smart light accessible to a non-tech-savvy audience at scale.

7.2 Final Remarks

In conclusion, this thesis represents a step toward an optimal support of circadian health through ambient lighting. Unlike other pillars of health, such as exercise or nutrition, circadian health is primarily influenced by environmental factors. Unfortunately, this pathway of passively influencing human health is currently working against societal well-being: The widespread exposure to artificial LED lighting at night is known to disrupt circadian rhythms and is associated with significant health risks [99]. The system proposed in this thesis offers a counterbalance to these disruptions, providing individuals with a tool to maintain circadian health in dynamic and unpredictable real-life contexts. By combining an inherently pleasant user experience with scientifically validated interventions, the concept holds promise as a practical solution that could potentially help millions of people attain better sleep and mental health [27, 84, 22].

List of Figures

List of Tables

List of Algorithms

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Appendix

A: Interview Guideline: Exp01 (Expert on Light Therapy)

Note: Participant names have been anonymized.

Between questions 4 and 5, the expert was presented the preliminary smart light concept derived from the literature analysis. The key concept was represented by a combination of three light interventions *Naturalistic Dawn*, *Millisecond Flashes*, and *Bright Wake-up Lighting*.

1. What do you consider the biggest challenges regarding the application of light therapy in the field?
2. Why have Bright Light and Naturalistic Dawn not yet been investigated in a combined form?
3. Despite the promising trial results of naturalistic dawn simulation in the 2000s, there is currently no available consumer application for it. Why do you think that is?
4. What is important to consider if I want to build a naturalistic dawn simulator device?
   a) What hardware and software setup was used to produce the naturalistic dawn in the trials?
   b) What have been the biggest challenges with the dawn simulation in trials?
5. What do you think of the idea to combine the three light applications?
6. How would you recommend positioning the lights in the bedroom to achieve the desired ambience?
7. What do you consider important if I want to ensure a good user experience with my smart light?

B: Interview Guideline: Exp02 (Expert on Light & Sleep)

Note: Participant names have been anonymized.

Between questions 4 and 5, the expert was presented the preliminary smart light concept derived from the literature analysis. The key concept was represented by a combination of three light interventions *Naturalistic Dawn*, *Millisecond Flashes*, and *Bright Wake-up Lighting*.

1. What do you consider the biggest challenges regarding the application of light therapy in the field?
2. Why have Bright Light and Naturalistic Dawn not yet been investigated in a combined form?
3. Why have the flashes not been picked up by the industry yet?
4. What is important to consider if I want to reproduce the millisecond flashes during sleep?
   a) What recommendations do you have regarding the dosing and timing of the flashes?
   b) What have been the biggest challenges with flashes in your trials?
5. What do you think of the idea to combine the three light applications?
6. How would you recommend positioning the lights in the bedroom to achieve the desired ambience?
7. What do you consider important if I want to ensure a good user experience with my smart light?

C: Interview Guideline: Exp03 (Lighting Expert)

Note: Participant names have been anonymized.

The interview was conducted in German language. In the beginning of the interview, the expert was presented the vision and the preliminary set of requirements for the smart light system.

1. Was sind Ihre Gedanken zu dem Konzept?
2. Welche Empfehlungen haben Sie für die Umsetzung des Beleuchtungskonzepts?
3. Welche Herausforderungen sehen Sie?
4. Welche Leuchtmittel würden Sie für eine solche Anwendung empfehlen?
5. Welche anderen Faktoren sind Ihrer Meinung nach wichtig zu beachten?
6. Welche Technologien oder Frameworks würden Sie für die Steuerung und Automatisierung des Lichts empfehlen?
7. Welche Aspekte sollten wir bei der Konstruktion und Installation der Leuchte beachten?
8. Wie stehen Sie zur Idee, die Leuchte an der Wand zu montieren?

D: Lighting Selection for Iteration 1

This appendix section contains reasoning behind the choice of lighting hardware for the prototype iteration 1, listed in Section 5.4.1.

Lights Interface: *Zigbee* Based on the interview with lighting expert Exp03 (see Section 5.1.3), the most promising two smart light protocols to implement the lights interface (described in Section 5.2.1) were *Zigbee* as a wireless protocol on the one hand, and *DALI DT-8* as the wired industry standard on the other hand. Out of this two, Zigbee was found to be supported by most consumer-grade smart light products. DALI DT-8 required more technical proficiency for the setup while Zigbee, as a consumer-oriented protocol, was designed for ease of installation. Furthermore, the required hardware components required for the DALI DT-8 setup were more expensive than the wireless Zigbee setup. Lastly, the wireless nature of Zigbee allowed more freedom in the design of the prototype, notably the physical location of the core automation layer. Therefore, **Zigbee** was selected as the protocol to implement the lights interface for the first prototype.

Indirect Lights

1. **Indirect Sublight: Lumitech *PILED System Pro All-in-one 9x9***[1] - One powerful, color-temperature-dynamic LED smart light was looked for to produce the mid- to high-illuminance parts of the naturalistic dawn simulation as well as the millisecond flashes. It was found in the **PILED System Pro: All-in-one 9x9 LED** panel from the Austrian Lighting company Lumitech[2]. The product provides 6000 Lumens, dimmability and the patented PILED technology offers a wide color temperature range of 1800 to 16000 Lumens at a CRI over 90. The panel consists of a 45x45 cm aluminum PCB on which the diods and microelectronics are soldered. The Zigbee protocol was supported out of the box.

2. **Indirect Sublight: Philips Hue *White Ambience***[3] - Sublight 2 serves the purpose of a small smart light that complements the large Sublight 1 with smooth dimmability in the low-illuminance part of the naturalistic dawn simulation. For this purpose, a smart light bulb "**White Ambience**" by the Dutch lighting manufacturer Philips Hue[4] was chosen. The E14 version of the bulb provides 470 Lumens at maximum intensity, *Zigbee* support, a color temperature range from 2200 - 6500 Kelvin and is dimmable. The CRI of 80 was below the specification of CRI $\geq$ 90. However, since the lamp is only relevant for the very lowlight ambiances, this was considered acceptable. Since, despite the E14 version being the smallest version of

[1] https://lumitech.com/marketing/db/PI-LED_Area_System_Pro_AIO_9x9_en.pdf

[2] https://lumitech.com/

[3] https://www.philips-hue.com/de-at/p/hue-white-ambiance-e14—smarte-lampe-tropfenform—470/8719514491106

[4] https://www.philips-hue.com/

the bulb, 470 Lumens were still much more than the specified 80 Lumens, black tape was used to cover parts of the bulb and thereby reduce the maximal Lumen output to 80.

Direct Lights Since the selected indirect lighting products qualified for the direct lighting setup as well, the direct lights were selected in a way that the bed-facing lights mirrored the ceiling-facing lighting equipment:

1. **Direct Sublight: Lumitech *PILED System Pro All-in-one 9x9*** - Out of the box, the Lumitech lights satisfied all direct lighting specifications except for the minimization of glare. When looked at directly, the individual diods of the PILED panel were clearly visible and glaring. To create an evenly bright light area, a frosted foil was used as a diffusion layer.

2. **Direct Sublight: Philips Hue *White Ambience*** - While a small sublight had not been explicitly required for the direct lights, early hardware experimentation made clear that an increased dimming resolution with the help of a small complementary light, analogous to the concept described for the indirect lights, benefitted the visual appeal of the wake-up light sequence. Therefore, another Philips Hue White Ambience smart LED bulb was used for this purpose.

E: Lighting Selection for Iteration 2

This appendix section contains reasoning behind the choice of lighting hardware for the prototype iteration 1, listed in Section 5.4.

Indirect Lights

1. **Bright indirect Sublights: 3x Lumitech *PILED Zhaga Spots*[5]** - Three 50 Watt smart spotlights from Lumitech were chosen to produce the main indirect light output. Delivering 4000 Lumens each, the maximum luminous flux amounted to 12,000 Lumens. The lights were chosen after a conversation with a Lumitech representative regarding the noise experienced with the company's controllers in iteration 1. The spot controllers were expected to be silent. Furthermore, using spots enabled a slimmer design for prototype 2, which was hoped to contribute to a less intimidating and more visually pleasing appearance of the device. Using the same PILED technology, the spotlights offered a CRI > 90, a color temperature range from 1800 to 16,000 Kelvin. Like the PILED panels, the spots supported Zigbee out of the box.

2. **Dim indirect Sublight: RGB + CCT LED light strip[6]** - For the low illuminance lighting, the smart light bulb from iteration one were replaced by a smart light strip. With a CRI > 80 and a color temperature range from 2700 to 6500 Kelvin and Zigbee support, the light strip offered similar light specifications as the Philips bulb. Unlike the bulb, however, the light strip could be cut. Also, the light strip was flat and enabled a slimmer device design. It was trimmed to a length that corresponded to 80 Lumens as a maximal light output.

Direct Lights The direct lights were implemented by an **edge-lit LED panel** that was made using 4 x **Lumitech Edge Light System** edge lights. Each module provided 2600 Lumens, resulting in 10,400 Lumens in total. The choice was motivated by two factors: On the one hand, the controllers of the edge lights were promised to be silent by the Lumitech representative. On the other hand, an edge-lit LED panel offered a perfectly homogenous light-emitting area across its 120 x 30 cm panel surface. Therefore, a considerable reduction in glare, compared to the approach from prototype 1, was expected. The Lumitech edge lights provided a CRI > 90, Zigbee support and a color termperature range from 1800 to 16,000 Kelvin.

Millisecond Relay Controller The problem that Zigbee, as a wireless smart light protocol with a certain latency, did not support Millisecond command intervals, required an approach outside the Zigbee scope to produce the millisecond flashes. Advised by

[5] https://lumitech.com/marketing/db/PI-LED_Zhaga_SMD_LMU2_en.pdf

[6] https://www.amazon.de/-/en/Powered-Controller-Dimmable-Ambient-Smartthings/dp/B0B58YS4KC/

the electrical engineer Saeed Helali, the solution was found in a smart relay that could enable or disable the power supply for all lights on a millisecond interval basis. This relay represented an additional layer of control on top of the regular light controller. The relay worked with transistors instead of a mechanical approach, so that it would operate silently. It was operated by an **ESP32 microcontroller**, which received commands by the core automation layer. **ESPHome** was chosen as a framework to program the microcontroller, as it is officially supported by Home Assistant.

Figure 5.11 illustrates how the millisecond relay controller adds a binary control to the different lights and communicates with the core automation layer via WiFi.