Eindhoven University of Technology

MASTER

Light and elderly

the effect of light exposure on well-being and sleep in the everyday life of elderly

van der Sande, R.

Award date:
2017

Link to publication

Disclaimer
This document contains a student thesis (bachelor's or master's), as authored by a student at Eindhoven University of Technology. Student theses are made available in the TU/e repository upon obtaining the required degree. The grade received is not published on the document as presented in the repository. The required complexity or quality of research of student theses may vary by program, and the required minimum study period may vary in duration.

General rights
Copyright and moral rights for the publications made accessible in the public portal are retained by the authors and/or other copyright owners and it is a condition of accessing publications that users recognise and abide by the legal requirements associated with these rights.

- Users may download and print one copy of any publication from the public portal for the purpose of private study or research.
- You may not further distribute the material or use it for any profit-making activity or commercial gain

Take down policy
If you believe that this document breaches copyright please contact us providing details, and we will remove access to the work immediately and investigate your claim.

Download date: 07. Nov. 2026

Eindhoven, August 6th, 2017

Light and elderly – The effect of light exposure on well-being and sleep in the everyday life of elderly

by Ruby van der Sande

0903750

in partial fulfilment of the requirements for the degree of

Master of Science
in Human Technology Interaction

Supervisors:
Dr. ir. K.C.H.J. Smolders
Prof. dr. ir. Y.A.W. de Kort
Dr. I.M.L.C. Vogels

Subject code: Master project Human-Technology Interaction 0PP06

Keywords: Elderly, light exposure patterns, light, well-being, sleep

i. Abstract

Sleep disturbances and depression are well reported problems among elderly that are often related to diseases such cancer, dementia and cardiovascular diseases. Earlier studies with samples that were dominated by younger participants and participants that suffered from seasonal affective disorders or dementia, suggest that light interventions can serve as potential countermeasures for these health related problems. However, yet little is known about the light exposure patterns as well as light-induced variations in well-being among the general population of elderly. The aim of the current study was to monitor and quantify light exposure patterns and the effect of these patterns on well-being and sleep (timing and quality) over the 24-hour day among elderly (65+ years). Based on earlier literature it was expected that the light exposure patterns of elderly and the influence of these patterns on their well-being and sleep would differ compared to the younger population. To enable the comparison with a relative young sample, the study of Smolders, de Kort and van den Berg (2013) - who investigated the effect of daytime light exposure on feelings of vitality in a relative young sample (mean age = 25 years, SD = 8.1) – was replicated with additional attention for the early morning and evening hours and sleep.

Findings provided new insights in the light exposure patterns of elderly. Comparisons with the study of Smolders et al. (2013) suggested that elderly of the current study were, on average, exposed to more intense light settings during the day compared to the younger sample of Smolders et al. (2013), whereas variations in light exposure patterns were found to be similar in both samples. Also, similar to the findings for the younger sample of Smolders et al. (2013), a significant relationship was found between light exposure and vitality in the morning. The relationship between light exposure and vitality during the day was less profound in the elderly sample of the current study compared to the younger sample of Smolders et al. (2013).

Additionally, the current study found that especially light in the morning was beneficial to improve both, well-being and sleep quality. Furthermore, it was suggested that light interventions in the afternoon would improve mood. Moreover, exposure to more intense levels of light exposure in the evening was associated with a longer sleep duration. However, the question remains whether this increase in sleep duration is beneficial or disadvantageous for the overall sleep quality and timing of elderly.

Overall, the findings of the current study provide better insights in the light exposure patterns and their effects on well-being and sleep among elderly. Results could be used to prevent sleep- and mood problems and to support well-being and health in elderly.

ii. Acknowledgement

Via this way I would like to thank several people that enabled me to write this thesis and helped me with this research. First, I would like to thank my first supervisor, Karin Smolders, for giving me the opportunity to conduct this research and for her valuable insights, feedback and the great amount of time and effort that she took to guide me throughout the process of my master thesis. Also, I am grateful to my second supervisor, Yvonne de Kort, for sharing her expertise and the effort and time that she took to give me thoughtful and critical feedback that enabled me to improve my work and to stay critical during the entire process. I would also like to thank Ingrid Vogels, for her willingness to take the time and effort for to fulfill the role as third assessor. Furthermore, I would like to thank Henk Herman Nap for sharing valuable insights about the target group of this research and I am grateful to Laura Huiberts, who took the time and effort to share her expertise and to give me valuable feedback. Also, I would like to thank Sima Ipakchian Askari for sharing her research experiences with me and helping me out with the search for participants.

Next, I would like to express my gratitude to all the participants that were willing to participate in this study and to share a part of their lives with me. This thesis would not have existed without their willingness to participate.

Also, I would like to thank my friends and family for their support and encouraging words. A special thanks goes to Matthijs van der Zande, who guided me through the programming process and saved me a lot of headaches and time.

Last, I would like to thank my boyfriend Ivo van Bon, for always believing in me and for his continuous support.

Ruby van der Sande

iii. Table of content

1. Introduction **1**
2. Theoretical framework **3**
2.1. Image forming and non-image forming photoreception 3
2.2. Image forming photoreception 6
2.3. Non-image forming photoreception 7
2.4. Light and elderly 11
2.5. Current study 15
3. Method **16**
3.1. Design 16
3.2. Participants 16
3.3. Measures 17
3.4. Procedure 22
3.5. Statistical analyses 23
4. Results **29**
4.1. Light exposure patterns 30
4.2. Sleep 33
4.3. Well-being 38
5. Discussion **55**
5.1. Light patterns of elderly 56
5.2. Light and sleep 59
5.3. Light and vitality 62
5.4. Light and mood 64
5.5. Strengths and limitations 66
5.6. Future research 67
5.7. Applications for findings of the current study 68
5.8. Conclusion 69
6. References: **70**
7. Appendices **78**

1. Introduction

The ageing population in our society increases substantially. Due to improvements in our healthcare system (e.g., the emergence of antibiotics) people tend to live longer than 60 years ago (Mackenbach, 2010). Centraal Bureau voor Statistieken (CBS) reported that in 2012, 2.7 million people in the Netherlands had an age above 65 years (Van Duin & Stoeldraijer, 2012). CBS expects that in 2040 this number will increase to 4.7 million. At the same time, compared with the elderly population, the population of people with an age between 20 and 64 years old decreases (Zorg voor Beter, 2017). This change in the composition of our society comes with several new challenges, for example, an increase in the need for healthcare. A prognosis for the care volume in the Netherlands from 2011 to 2030 by the Rijksinstituut voor Volksgezondheid en Mileu (Rijksinstituut voor Volksgezondheid en Milieu, n.d.) suggests that the care volume in the Netherlands increases up to 4 percent per year until the year 2030. This means that more money is needed to maintain the same quality of healthcare, whereas the number of people that can provide this (i.e., people that can work between 20 and 64 years) decreases. Therefore, the prevention of diseases in the elderly population becomes more and more important.

Frequently reported problems among elderly that are related to diseases such as cancer, diabetes, dementia and cardiovascular diseases are sleep disturbances and depression (Ancoli-Israel & Cooke, 2005; Turner & Mainster, 2008; Van Someren, 2000). Van Someren (2000) reported that 40 to 70 percent of the elderly population suffers from sleeping problems. These problems increase with age and are closely related to mental problems such as depression (Turner & Mainster, 2008; Van Someren, 2000).

A particular sleeping problem that is related to ageing is early morning insomnia (Monk, 2005). This is also known as an advance in the sleep-wake cycle. People with early morning insomnia fall asleep in the early evening and wake up in the early morning while the majority of the population is still asleep. Also, other forms of insomnia such as difficulty to fall asleep, difficulty to maintain sleep and the tendency to fall asleep during the day are frequently reported among elderly (Foley et al., 1995; Monk, 2005, Ancoli-Israel & Cooke, 2005). These sleeping problems are attributed to changes in the sleep-wake cycle that come with ageing (Herljevic, Middleton, Thapan & Skene, 2005). With ageing, the circadian rhythm becomes weaker and less synchronized (Ancoli-Israel, Ayalon & Salzman, 2008).

It has been suggested that part of these changes in circadian rhythmicity occur due to changes in the ageing eye, such as pigmentation of the lens (Gasio et al., 2003), and the reduction in the transmission of short wavelengths of light that comes with ageing (Benloucif et al., 2006).

Literature in light research suggests that bright light therapy and dawn/dusk simulations can positively impact sleeping problems and depression rates (e.g., Gasio et al., 2003; LeGates, Fernandez, & Hattar, 2014), and thus serve as potential countermeasures for these health-related problems. However, most research in this area is conducted with samples dominated by young participants (e.g., Gabel et al., 2013; Gradisar et al., 2011), elderly participants that suffer from dementia (e.g., Gasio et al., 2003; Van Someren, Kessler, Mirmiran & Swaab, 1997; Riemersma-van der Lek et al., 2008), or people that suffer from a seasonal affective disorder (SAD) (e.g., Avery, Kizer, Bolte, & Hellekson., 2001; Pinchasov, Shurgaja, Grischina, & Putilov, 2000). To date, insights in light exposure patterns as well as light-induced variations in well-being and sleep among the general population of elderly are therefore largely unknown.

The current research aims to monitor and quantify light exposure patterns and the effect of these patterns on well-being and sleep over the 24-h day among (relatively) healthy, independently living elderly during their daily routine. These findings will provide insights in whether - and at which moments of the day - a light intervention can be best presented to increase their quality of sleep and well-being. Given the potentially problematic sleep-wake rhythms and activity patterns of older persons and age-related changes in the eye, it is expected that light exposure patterns in elderly, and the influence on their well-being and sleep, are different compared to the younger population. For this reason we performed a replication of an earlier study of Smolders, de Kort and van den Berg (2013) - who investigated the effect of daytime light exposure on feelings of vitality in a relative young sample (mean age 25 years, SD = 8.1) - with this specific elderly population in mind and with additional attention to the hours in the early morning and late evening and sleep. The nature of the current study is explorative.

In the upcoming chapter a theoretical framework will be described. This framework illustrates the image forming and non-image forming pathways through which light influences human functioning, and explains the relation between them. It also describes the relation between light and well-being and the sleep-wake cycle. Furthermore, literature will be presented of the ageing eye and the relationship with well-being and sleep will be

explained. Last, the research question and the related sub-questions of the current study will be presented.

2. Theoretical framework

2.1. Image forming and non-image forming photoreception

2.1.1. The eye

To understand how light enters the eye and affects human functioning, it is essential to explain the design of the eye and the pathways of the brain that are connected to it. Figure 1 shows a schematic overview of the eye. Light enters the eye through the cornea, a transparent membrane at the opening of the eye. Thereafter it enters the pupil and the lens towards the retina. The retina is an area in the eye that is covered by cells that are called photoreceptors. These photoreceptors absorb photons and convert these into neural signals (Mather, 2009). Neurons that are called Ganglion cells transfer these neural signals from the eye towards the brain through two pathways that are called the image forming (IF) and non-image forming (NIF) pathways. This conversion and transfer of light information is called photoreception.

A small part of the ganglion cells (1-2%) express the photopigment melanopsin. These are called intrinsically photosensitive retinal ganglion cells (ipRGC). ipRGCs show a peak sensitivity in the blue part of the light spectrum (~460 – 480 m) (Daneault, Dumont, Massé, Vandewalle & Carrier, 2016). A more pronounced explanation of these ipRGCs will be given in the section about NIF photoreception.

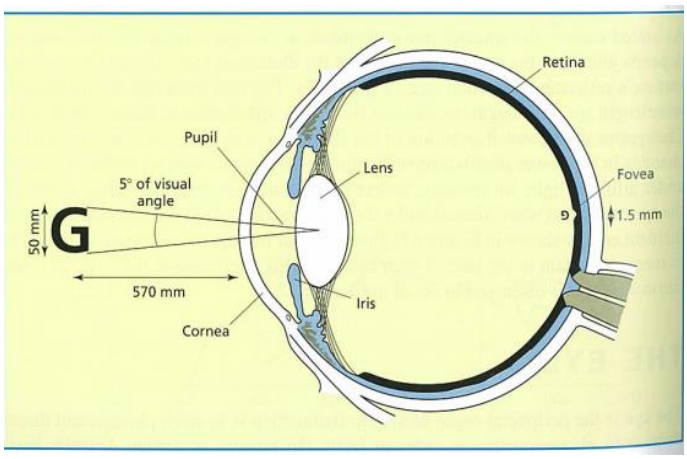


Figure 1. Schematic overview of the eye. Source: Mather (2009), Figure 6.8, p. 170.

2.1.2. The image forming and non-image forming pathways

The IF pathway is responsible for our vision, whereas the NIF pathway regulates our biological clock and accounts for numerous neurobehavioral responses. Figure 2 illustrates the IF pathway. The IF pathway projects light information that enters the eye trough the visual pathway to the visual cortex. The visual pathway consists of the optic nerve (i.e., the fibers of retinal ganglion cells) and the projections to six locations in the brain. Approximately 90% of the ganglion cells project to the lateral geniculate nuclei (LGN) which in turn project to the striate cortex or V1, located in the visual cortex. These projections from the LGN to the striate cortex are associated with conscious visual awareness (Mather, 2009).

The NIF pathway connects light information from the ipRGCs through the Retinohypothalamic tract (RHT) to subcortical regions that are related to the regulation of the sleep-wake cycle, melatonin secretion and pupillary constriction (Daneault et al., 2016; Figure 3). One of the most important areas where the RHT projects to is the suprachiasmatic nuclei (SCN). The SCN is a brain area located in the hypothalamus that plays a crucial role in the regulation of – among others – our sleep-wake rhythm (Mather, 2009). Another important area that receives projections from the RHT is the amygdala, a part of the brain that is responsible for emotional processing (Daneault et al., 2016). Figure 3 illustrates both pathways and their projections in the brain.

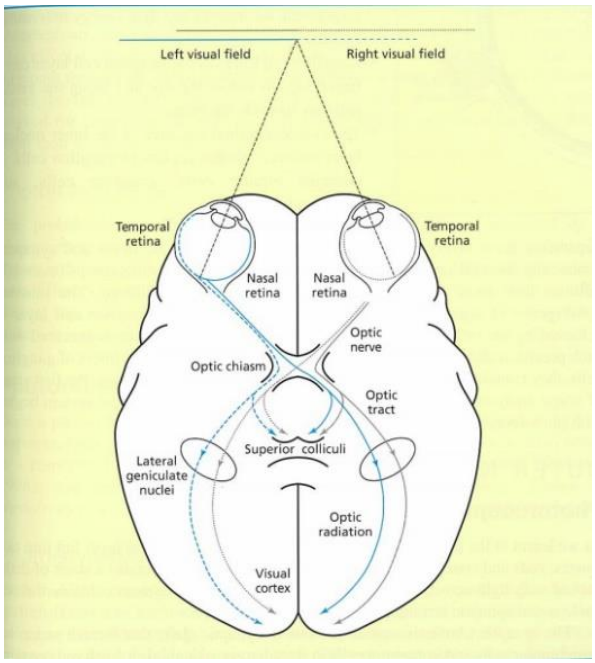


Figure 2. Overview of the visual system. Source: Mather (2009), Figure 7.1, p. 197.

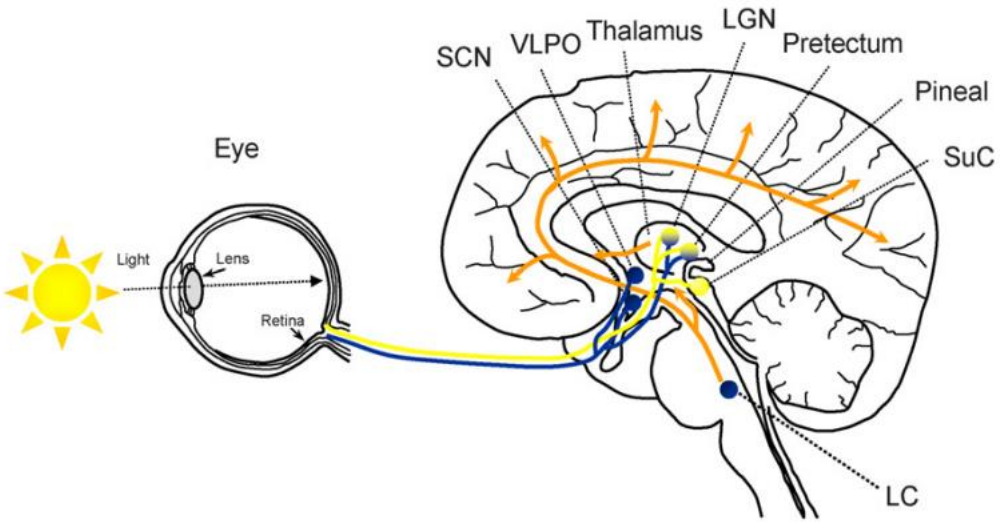


Figure 3. A simplified representation of the image-forming (indicated in orange) and non-image forming (indicated in blue) pathways. Source: Cajochen (2007). Figure 5, p. 459.

2.1.3. Framework for image forming and non-image forming effects

Through the IF and NIF pathways light is able to affect our mental well-being, health and performance. Figure 4 shows a framework, proposed by Smolders (2013) that structures the effects of light through these pathways. This framework distinguishes between IF and NIF photoreception (i.e., the conversion and transfer of light information). IF photoreception, refers to the photoreception within the IF pathway, whereas NIF forming photoreception refers to photoreception within the NIF pathway. The model displays potential effects of light on human functioning (i.e., visual performance and visual experience for the IF route, and circadian effects and acute effects for the NIF route). Based on this framework the effect of light on our mental well-being, health, and performance will be explained. Since the current study focuses on the NIF effects of light, a more deliberate explanation of these effects will be given compared to the IF effects of light.

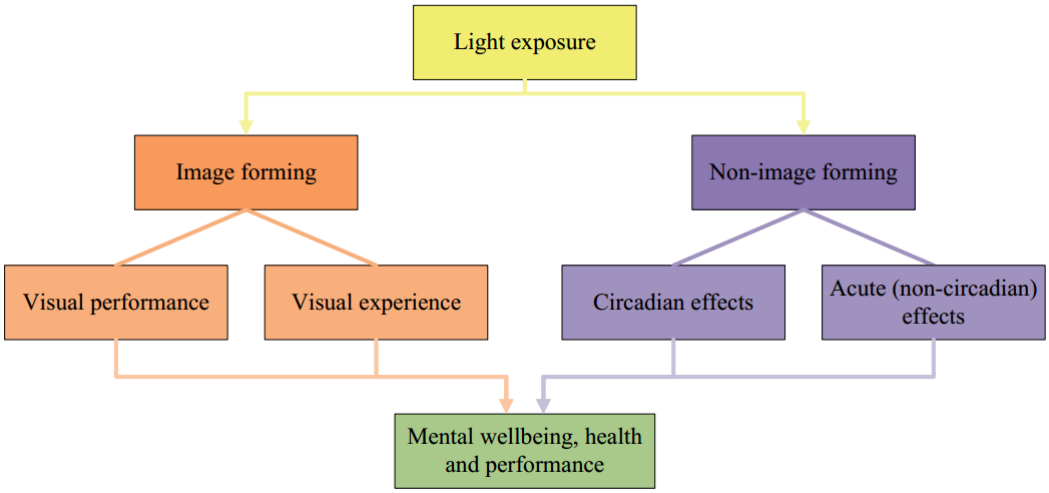


Figure 4. Overview of the image forming and non-image forming pathways and their sub-categories. Source: Smolders (2013), Figure 1, p. 4.

2.2. Image forming photoreception

Rods and cones are photoreceptors that are mainly involved in IF photoreception. Rods have a peak sensitivity at low light levels, whereas cones have a peak sensitivity at high light levels (Mather, 2009). This means that rods are mostly used in dark circumstances, whereas cones are mostly used during the day, and are responsible for color vision (Purves et al., 2001). Based on their spectral sensitivity, cone photoreceptors can be categorized into three types: S-cones, M-cones, and L-cones. S-cones have their peak sensitivity in the short wavelength region (~420 nm; blue), M-cones in the medium wavelength region (~535 nm; green), and L-cones in the long wavelength region (565nm; red; Mather, 2009). The peak sensitivity of rods is ~507nm (Daneault et al., 2016).

2.2.1. Image forming effects

IF effects can be subcategorized into visual performance and visual experience (Figure 4). Effects on visual performance are measured with the performance of visual tasks and are based on information processing and extraction of visual information (Smolders, 2013). For example, low light levels can be experienced as uncomfortable and make it more difficult to process visual information, which in turn influences our visual performance (Veitch & mcColl, 1995). Effects on visual performance can differ across people due to differences in the speed and accuracy of processing. Factors that may affect visual performance are: visual

capabilities (e.g., visual acuity, light sensitivity, color vision and contrast sensitivity), personal characteristics (e.g., age), and attention-related abilities (e.g., concentration and short-term memory) (Kretschmer, Schmidt & Griefahn, 2012).

Visual experience refers to the subjective experience of visual stimuli (e.g., light and color). For example, light can affect visual experience by creating a visual ambience that supports or counteracts people's mood, by its color, color temperature and illuminance (Kuijsters, Redi, de Ruyter, Seuntiëns & Heyndrickx, 2015). Additionally, color temperature can be associated with people's individual associations with color (Knez & Kers, 2000). Again, these effects can differ across people. Knez and Kers (2000) found a significant difference on the associations with color across age groups. Also, Dittmar (2001) found significant differences across age in color preferences. Moreover, individual differences and gender differences may also influence visual experiences (Kuijsters, Redi, de Ruyter & Heyndrickx, 2015).

2.3. Non-image forming photoreception

As mentioned before, there are some retinal output neurons that are also photosensitive besides the photosensitive rods and cones, which are called photosensitive retinal ganglion cells (ipRGCs). IpRGCs differ from rods and cones in sensitivity to light and the time needed for a light response. Melanopsin, the photopigment of the ipRGCs, has its peak sensitivity in wavelengths between 460 – 480 nm (i.e., blue light; Lucas et al., 2014). IpRGCs have a relative large receptive field compared to other ganglion cells, which means that a large number of photons are necessary for a light response, resulting in a longer time needed to induce a response (Smolders, 2013).

Although the IF and NIF pathways are often presented as distinct pathways, these systems are not totally independent. For example, the ipRGCs contribute also to our visual pathway, for instance in conscious perception, spatial brightness, and speed motion (Daneault et al., 2016). Moreover, studies in free-running rhythms in blind individuals revealed that both pathways are involved in entrainment of the SCN (e.g., Czeisler et al., 1995; Chellappa & Cajochen, 2010).

2.3.1. Non-image forming effects of light

NIF effects of light can be subcategorized into circadian- and acute (non-circadian) effects (Figure 4). Circadian effects are effects that influence the biological clock, and thus affect our

sleep-wake cycle. Acute effects influence our behavior (e.g., performance), physiology (e.g., melatonin suppression, pupillary constriction) and subjective experiences (e.g., alertness, mood, and sleepiness; Smolders, 2013).

2.3.1.1. Circadian effects

Light can cause circadian effects that affect the regulation of our sleep-wake rhythm (Cajochen, Zeitzer, Czeizer, & Dijk, 2000). Our biological clock that regulates our sleep-wake rhythm has an internal rhythm of approximately 24 hours, and needs to be adjusted (i.e., entrained) to the 24-h. day through synchronization with the external light-dark cycle (Chellappa & Cajochen, 2010). Proper entrainment of our biological clock is vital because without an entrained clock we experience discomfort and risks of getting a disease are increased (Giménez, Beersma, Bollen, van der Linden & Gordijn, 2014). To understand how light is able to influence our sleep-wake cycle, it is important to explain the regulation of sleep. Therefore, in the following section, we will start with an explanation of sleep regulation. Thereafter, we will discuss the influence of light on our biological clock in more detail.

Sleep

Our circadian system plays a prominent role in the regulation of sleep. Two processes can be recognized with regard to the regulation of sleep and wakefulness: a homeostatic process (Process S) and a circadian process (Process C) (figure 5). The homeostatic process represents sleep debt: it increases exponentially while awake and decreases exponentially during sleep. It is dependent on people's behavior with regard to sleep times (sleep-wake behavior) and is influenced by prior sleep-wake history (Reichert, Maire, Schmidt & Cajochen, 2016). Factors such as work times influence this process. The circadian process represents the internal processes of our endogenous clock, with melatonin and core body temperature as markers (Borbély, Daan, Wirz-Justice, & Deboer, 2016; Dijk & Archer, 2010). It actively promotes wakefulness during the day and promotes sleep during the night by the production of an arousing-promoting signal. Sleep-wake behavior does not have an influence on this process, neither does prior sleep-wake history, instead this process is sensitive to light (Reichert et al., 2016).

Although regulated independently, it is suggested that these two processes do continuously interact with each other. Bobérly et al. (2016) reported a non-additive interaction between the homeostatic process and the circadian process. This continuous interaction indicates that both

processes can affect each other. The arousing-promoting signal of process C is larger during the day (promoting wakefulness), when sleep pressure increases and is lower during the night (promoting sleep), when sleep pressure decreases during sleep. In this way, sleep is promoted by process C when sleep pressure is high, whereas wakefulness is promoted by process C when sleep pressure is low. Ideally both processes are aligned with each other. Disruption of the interaction between these processes evokes circadian misalignment resulting in reduced sleep- and wake quality (Reichert et al., 2016).

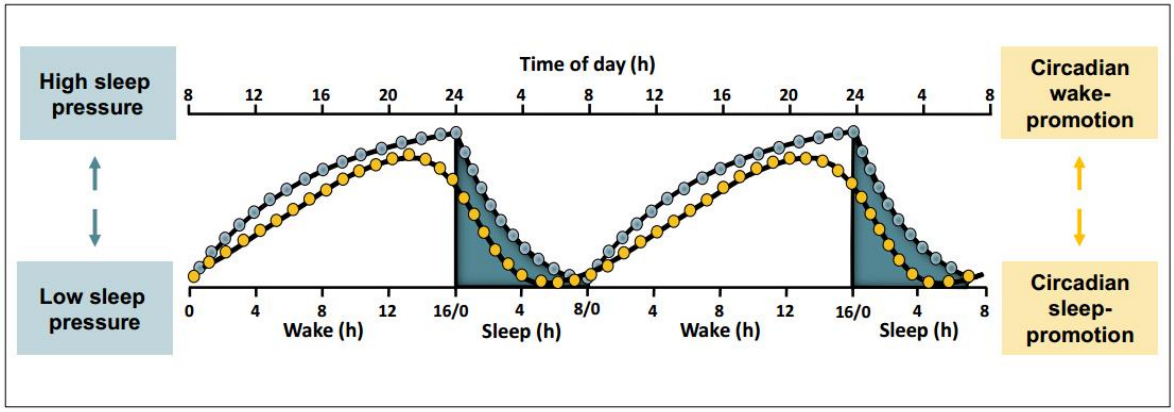


Figure 5. Representation of human sleep-wake regulation by the circadian- and homeostatic processes under entrained conditions. Source: Reichert et al. (2016). Figure 1, p. 4.

Timing and intensity

As indicated above, light is able to influence our circadian process. Dependent on the circadian phase, light is able to phase advance or phase delay our circadian rhythm (Cajochen et al., 2000; Gasio et al., 2003; Borbély et al., 2016). Bright light exposure during the late afternoon to the early night is able to delay the sleep-wake cycle (Ancoli-Israel & Cooke, 2005; Benloucif et al., 2006), whereas bright light during the late night and early morning is able to evoke a phase advance (Borbély et al., 2016; Benloucif et al., 2006) A stable entrainment to the 24-h. day results from a combination of phase delays and phase advances (Benloucif et al., 2006). Several studies (e.g., Brainard et al., 2001; Lockley, Brainard & Czeiler, 2003) that investigated the effect of light at different wavelengths during the night on melatonin suppression reveal that the circadian timing system is most sensitive to short wavelengths, i.e., blue-enriched light (~460 – 480 nm).

Light intensity can also affect the circadian timing system. For example, a study of Zeitzer, Dijk, Kronauer, Brown and Czeisler (2000) revealed that exposure to dim light

during the night caused a relative small circadian phase shift, whereas exposure to bright light evoked a relative large phase shift of the melatonin rhythm.

2.3.1.2. Acute effects

Besides circadian effects, light can also cause acute effects on neurobehavioral performance and physiology (Lucas et al., 2014; Smolders, 2013). For example, bright light can positively affect people's mood (Obayashi, Saeki, Iwamoto, Ikada, & Kurumatani, 2013), subjective alertness (Cajochen et al., 2000) and subjective vitality (Patronen & Lönnqvist, 2000). The effect of light on these factors has been of interest in many studies. Although the findings of light on acute effects are consistent during the night in laboratory settings, results during the day seem to be mixed. In the section below part of these findings will be described with a distinction between laboratory studies and field studies.

Laboratory studies on acute effects

Several laboratory studies revealed that acute effects, such as subjective alertness, can be evoked with light during the night (e.g., Cajochen et al., 2005; Revell, Arendt, & Skene, 2006). For example, Cajochen et al. (2000) investigated the effect of a variety of illuminances between 3 to 9100 lux on objective- and subjective alertness in the early biological night for 6.5 hours. They found an acute alerting effect of both objective- and subjective alertness in response to light within the illuminance range of typical room light (90 – 180 lux). Additionally, the acute effects of light seem to be wavelength dependent. A study of Lockley et al. (2006) investigated wavelength dependent sensitivity on objective- and subjective alertness. They compared the effects of light exposure of 450 nm and 555 nm for 6.5 hours during the biological night. Results of the study showed that light of the shorter wavelengths resulted in higher objective and subjective alertness.

Earlier laboratory studies that measured the acute effects of light during the day showed mixed results. A study of Smolders, de Kort and Cluitmans (2012), who investigated whether acute effects of light did also appear during the day, showed that a higher amount of illuminance had a positive effect on subjective alertness, vitality and objectively measured performance. They did not find a relationship between a higher amount of illuminance and mood. Similarly, a study of Phipps-Nelson, Redman, Dijk and Rajaratnam (2003) showed that daytime bright light exposure could reduce subjective sleepiness and improve performance (measured with a psychomotor vigilance task). In contrast, Kaida, Takahashi and Otsuka (2007) did find a positive effect of natural bright light (>2000 lux) on positive

mood in a laboratory study. Furthermore, a study of Huiberts, Smolders and de Kort (2016) showed no effect of illuminance levels on subjective alertness and vitality.

Field studies on acute effects

Field studies on the acute effects during the night are mainly conducted in the context of night shift workers. Although most field studies that investigated the effect of light exposure during the night were focused on circadian effects (e.g., sleep timing and sleep duration), a few studies also measured subjective sleepiness. These studies reveal mixed results. For example, a study of Lowden, Åkerstedt and Wibom (2004) found a significant reduction in subjective sleepiness in participants that were exposed to bright light (2500 lux), compared to participants who were exposed to normal light (300 lux). In contrast a study of Bjorvatn et al. (2007) did not reveal any significant relation between light exposure during the night and subjective sleepiness in night shift workers.

Similarly, results of field studies on the acute effects of light during the day are mixed. Though some researchers found significant effects of light on factors such as mood and vitality, others who investigated the same effects during the day did not find significant effects. For example, a study of aan het Rot, Moskowitz and Young (2008) showed that above-average exposures to light was associated with better mood, less quarrelsome behavior, and more agreeable behaviors in mildly seasonal healthy individuals. The effect on mood that they found did occur even after a short-term exposure. Additionally, Patronen and Lönnqvist (2000) found that bright light exposure during winter has a positive influence on mood and health related quality of life in office employees. However, a study of Hubalek, Brink and Schierz (2010), who investigated the effect of light exposure on sleep quality, mood, pleasure, and arousal did not find any significant effects.

Implications of literature on acute effects

Overall, acute effects as a response to light are observed both, in laboratory as well as field studies. Moreover, earlier literature reveals that these effects did occur during the night and during the day. Although results are not always inconclusive, there are implications that effects and associations exist between light exposure and acute effects.

2.4. Light and elderly

Although exposure to light appears to have an influence on circadian timing and neurobehavioral performance factors, it is unclear whether these results can be generalized over the whole population. A particular group that seems to react differently to light is the older population. In the following section differences in the NIF effects of light between elderly and younger individuals and the implications for these differences will be described.

2.4.1. Differences in the non-image forming pathway

Earlier studies suggest that the amount of average daily light exposure might be lower in older- compared to younger populations (e.g., Nioi, Roe, Gow, McNair and Aspinall, 2017; Benloucif et al., 2006). Also, it has been reported that changes in the sleep-wake cycle occur with ageing (Herljevic et al., 2005). Research suggests that age related changes in the eye such as pigmentation of the lens, reduction of the short wavelength light that reaches the retina, reduction in pupil size, and a decrease of photoreceptor sensitivity are related to these changes in the sleep-wake cycle (e.g., Benloucif et al., 2005; Herljevic, et al., 2005; Daneault et al., 2016).

2.4.1.1. Studies on circadian effects of light in elderly

Daneault et al. (2016) suggest that brain areas related to acute effects of light react differently in elderly (mean age = 61, *SD* = 4.4) compared to younger individuals (mean age = 22.8, *SD* = 4). More specifically, they conducted a neuroimaging study where subjects were placed in a fMRI scanner in a darkness condition or under blue monochromatic light, and completed 28 blocks of the auditory working memory two-back task. Daneault et al. (2016) found similar brain activations in elderly and younger participants with respect to areas that are associated with vision (e.g., LGN and occipital areas), whereas activation in brain areas that concern alertness and cognition regulation decreased. In other words, elderly individuals had a decreased response to light in these areas compared to younger individuals. This suggests that the IF and NIF responses to light in elderly differ in their strength compared to the younger population and that mainly the NIF responses are affected by ageing.

Additionally, Herljevic et al. (2005) suggest that, compared to younger individuals (mean age = 24, *SD* = 3), elderly individuals (mean age = 57, *SD* = 5) need a higher amount of short wavelength light to entrain their circadian system. They found that elderly have a significant reduction in their melatonin response (i.e., melatonin suppression) to short-wavelength light at night. In contrast, Najjar et al. (2014) did not find any differences in melatonin suppression as an effect of light exposure at night between elderly individuals (mean age = 59.4, SD =

.99) and younger individuals (mean age = 25.8, *SD* = .73). They explain differences in the NIF effects on elderly compared to younger individuals by a change in the peak sensitivity to short wavelengths. Najjar et al. (2014) reported that lens transmittance decreases particularly for short-wavelength light in elderly individuals, while melatonin suppression remains the same compared to younger participants. They found that the peak of non-visual sensitivity, assessed with melatonin suppression, was shifted to longer wavelengths in the older individuals compared to the younger individuals. More specifically, it was found that peak sensitivity of melatonin suppression was shifted from 484 nm in the young individuals to 494 nm in the elderly individuals. Another explanation for the finding of no significant differences in melatonin suppression after light exposure at night between elderly and younger individuals is suggested by Giménez et al. (2014). They conducted a study that investigated the effect of reduced blue light exposure (as observed in elderly due to, for example, yellowing of the ocular lens), in a young sample (mean age = 23.5, *SD* = 4.6). For this, subjects wore Soft Orange Contact Lenses (SOCL). They found that, indeed a decrease in melatonin suppression occurred when the participants wore these lenses. However, after a continuous exposure to reduced short wavelengths (by wearing the SOCL) of two weeks, the sensitivity of melatonin suppression increased. Giménez et al. (2104) explain these results stating that the NIF system is able to adapt to changes in the spectral composition of light exposure. Overall, the general consensus from earlier studies is that the melatonin response decreases with ageing. However, it is yet unclear what the main cause of this reduced response is.

Turner and Mainster (2008) explored the circadian effects of age-related losses in crystalline lens transmittance and pupillary area. They calculated the age-related decline in retinal illuminance by multiplying human crystalline lens transmittance at different ages with data obtained from a study of Barker and Brainard (1991), and with the corresponding photopic pupil area of those ages obtained from a study of Yang, Thompson and Burns (2002). Based on these calculations, they argue that elderly need much higher room illuminance levels than younger individuals to avoid free-running (i.e., not properly entrained) circadian rhythms. According to Turner and Mainster (2008) young people with normal vision start to free-run at constant illuminances under 80 - 200 lux, whereas elderly with the age of 65 will start to free-run at room illuminance under 256 - 640 lux. This suggests that elderly need more intense illuminance levels compared to young people to entrain their circadian rhythm. Furthermore, Turner and Mainster (2008) argue that age-related changes in the eye (i.e., reduction in crystalline lens transmission and pupillary

miosis) caused a decrease in circadian photoreception, suggesting that effects of the NIF pathway of the eye change by ageing.

Although the current body of literature is inconclusive about the causes of the decline in the NIF-effects as a response to light exposure of the ageing eye, the general consensus is that changes in NIF-effects as a response to light exposure do occur with ageing. The question remains whether the cause of this decrease is due to light exposure levels or that these changes do occur within the NIF pathway.

2.4.2. Studies on the acute effects of light in elderly

To investigate the effect of light exposure during the day on acute effects such as level of alertness, vitality, and cognition, several field studies have been conducted. To our knowledge, no laboratory studies have been conducted with regard to acute effects of light exposure specifically for the elderly population.

A field study conducted by Grandner, Kripke and Lange (2006) investigated the effect of daily light exposure on social and emotional functioning and the quality of life in elderly woman (mean age = 67.68, *SD* = 7.86). The women wore a wrist actigraph for one week and filled in self-report questionnaires during a visit at the Woman's Health Initiative (WHI) offices. Grandner et al. (2006) found an increase in social and emotional functioning and quality of life in relation to an increase in light exposure. This effect was more profound in the morning compared to the rest of the day. Notice that the data that was used for this study was not collected for the goal of this study. Grandner et al. (2006) state that, because of this, the intervals between the subjective data collection and the light measurements were too long.

Another field study on the NIF effects of light exposure during the day was conducted by Ichimori, Tsukasaki and Koyama (2015). They investigated the effect of daily light exposure (illuminance levels) on subjective sleep quality and psychosomatic health in elderly (mean age = 82.8, *SD* = 5.3) who lived at home and required care, for three sequential days. Illuminance levels where assessed with three illuminance loggers. One was placed outside on the rooftop of a nearby facility. Outdoor illuminance was calculated based on these measurements. The others were placed inside the houses of the participants. One measured light near the pillow of the participant, and the other was placed at a location where the participant usually sat (e.g., the living room). Furthermore, participants wore an activity meter attached to their waist and an actigraph that was attached to their wrist. During the measurement period, the experimenters visited the participants' home to assess a lifestyle questionnaire. Results of this study revealed a significant relationship between illuminance

levels and depression rates, suggesting that exposure to less intense illuminance were related to higher depression rates.

A recent field study of Nioi et al. (2017) explored seasonal differences in light exposure and the relation with health and well-being in elderly (age range = 72 – 99 years; mean age and SD were not reported) who live in care houses. They measured light exposure and sleep-wake patterns on 4 sequential days in two different seasons (i.e., summer and winter). At the beginning of these 4 days, health and well-being were assessed. Results revealed differences in mean illuminance levels (summer = 466 lux; winter = 65 lux) and bright light exposure (> 1000 lux; summer = 46 minutes; winter = 3 minutes) between seasons. Furthermore, statistically significant differences were found in daytime physical activity (i.e., higher physical activity during summer compared to winter).

2.5. Current study

Although the studies described above shed some light on the effect of light exposure in the everyday life of elderly and its acute and circadian effects, it is unclear whether the effect of light during the day on factors such as mood and vitality varies throughout the day. An earlier study of Smolders et al. (2013) that assessed the effect of light exposure throughout the day on feelings of vitality and mood revealed a significant and positive relation between the experienced amount of light and feelings of vitality in the younger population. The question remains whether the same effect, with the same sensitivity patterns to illuminance levels, would hold for the elderly population.

Therefore, the current research investigates the influence of daily light exposure on markers of well-being (mood and vitality) in elderly. Since sleeping problems do occur more often in the elderly population compared to younger individuals (e.g., Ancoli-Israel & Cooke, 2005; Monk, 2005), and earlier research suggests that besides acute effects circadian effects would also differ between the elderly and the younger population, the influence of daily light exposure on sleep timing and sleep quality will be investigated as well.

2.5.1. Research question and sub-questions

Specifically, the research question of the current study is: What is the influence of daily light exposure on mood, vitality and sleep (timing and quality) in elderly? Sub-questions are: (1) Are light patterns of daily light exposure different in elderly compared to the younger population? (2) Is there a connection between these lighting patterns and sleep behavior of

elderly? And (3) Is there a similar link between light exposure and vitality as observed in the younger population?

Additionally, both, studies among younger participants (e.g., Smolders et al., 2013; Huiberts, Smolders & de Kort, 2015), and among elderly participants (e.g., Grandner et al., 2006) suggested that especially an increase of light in the morning was associated with an improvement of acute NIF-effects such as an increase in vitality and social and emotional functioning. Therefore, the following sub-question was assessed as well: (4) Is there a time-of-day effect of light exposure on well-being and sleep quality of elderly? And if so, which times are best to support elderly with light interventions in order to improve their well-being and sleep quality?

3. Method

3.1. Design

The study consisted of an experience sampling method combined with continuous light exposure- and activity measurements using two wearable devices, data gathered with a sleeping diary, and a pre-study questionnaire. Data was collected between April 28th 2017 and May 24th 2017.

3.2. Participants

Twenty elderly (65+ years) participated in the study (12 males and 8 females, mean age = 71.18 years, *SD* = 3.71, age range = 65 - 79). Participants were recruited via the universities' own local database (i.e., JF Schouten), the sport center of Eindhoven University of Technology, the KBO (Catholic union for elderly) Eindhoven, and via an advertisement on Facebook. The participants all lived in Eindhoven region (51° 44' N, 5° 48' E).

Elderly with moderate or more severe physical- or cognitive impairments were excluded. The latter was tested by the subscale Forgetfulness of the Cognitive Failures Questionnaire (CFQ) (*M*= 75.24, *SD* = 8.67; Broadbent, Cooper, FitzGerald & Parkes, 1982). This scale was scored on a 5-point Likert scale ranging from (0) 'never' to (4) 'very often' and consisted of eight items. Only the cut-off score of the full questionnaire (including all subscales of the CFQ) was found in literature (e.g., Postma, Bouma, Ankersmit & Zeeman, 2014), which was 44 or more based on a total score of 100. Therefore, the total score of the Forgetfulness scale was set to 100 (resulting in a maximum of 12.5 points per item) with a cut-off score of 44 or more. Subsequently, the cognitive abilities of all participants were tested at the start of the

study with the Mini-Mental State Exam (MMSE; *M* = 29.48, *SD* = .81; Folstein, Folstein & McHugh, 1975). The cut-off score that was used for this questionnaire was 24. This was based on the general cut-off score set by Folstein et al. (1975).

Additionally, to check whether our sample was representative for the elderly population with regard to the health of their eyes, all participants filled in a questionnaire that assessed the health of their eyes. These questions assessed the symptoms (on a scale of 0 – 4, and based on four pictures that showed the view of someone with an eye disease; Appendix A) of the four most common eye diseases in the elderly population (i.e., cataract, glaucoma, macular degradation, and diabetic retinopathy). Twelve participants needed glasses or contact lenses to have a sharp view, one of the participants suffered at the moment from an eye disease (cataract), and four participants suffered from an eye disease in the past. These latter participants had surgery to heal from these eye diseases. Eleven participants reported a score of 2 or higher on some of the symptoms of the questionnaire (e.g., dry eyes, red eyes, tearing eyes). These results showed that – with regard to the health of their eyes - our sample consisted of a typical elderly sample. With some eye complaints that are related to ageing, but no major problems.

3.2.1. Sample size

The study had an explorative nature. It is one of the first studies that measures light, well-being and sleep - during seven sequential days - among elderly. Given the character of the study and the time and devices available for the data collection it was decided to use a simulation approach for the power analysis. One thousand simulations were employed for one of the main analyses: the relationship between light and vitality. Estimated variances and effect size (.12) were based on Smolders et al. (2013). The simulation revealed that a sample size of 20 participants would allow adequate power (>95%; with a coefficient of at least 0.05).

3.3. Measures

3.3.1. Light exposure

Light exposure was continuously measured by a light logger (Martin, 2015) clipped on top (as close as possible to the eye) of the shirt of the participant. The light logger uses a TAOS TCS34725 color sensor clip that measures light with 4 sensors: Three that have a color filter (red, green and blue), and one without color filter. Data was extracted by using the windows

application: LightLogControl. The base lighting parameters that were estimated within the application were the tristimulus values X, Y (i.e., the illumination E_v), and Z (based on the spectral responsitivity of the CIE human standard observers tristimulus filters), and the circadian irradiance E_{ec} (based on the response curve of the human circadian system). The sample period was set to 160 seconds.

3.3.2. Pre-study questionnaire

At the start of the experiment, the personal characteristics of the participants were assessed by a pre-study questionnaire on paper (Appendix B). This questionnaire was identical to the 'online questionnaire' used in Smolders et al. (2013). It measured age, gender, trait vitality, light sensitivity, chronotype, general sleep quality, individual strength, and general health. Two variables (eye diseases and neuroticism) that were measured in the study of Smolders et al. (2013) were excluded in this questionnaire. Additionally, a pilot study was conducted to explore whether the concepts that were represented with the items of this questionnaire were well understood by elderly individuals. During this pilot study the concepts of the questions in the questionnaires that were used in the current study were assessed with a 'Think-aloud protocol'. Based on the results of the pilot study no adjustments were made.

The Subjective trait level vitality scale of Ryan and Frederick (1997; $\alpha = .87$) was used to measure trait vitality ($M = 4.77$, $SD = .88$). This scale consisted of seven items that were measured on a 7-point Likert scale ranging from (0) 'not at all true' to (7) 'very true'.

Subjective light sensitivity ($M = .87$, $SD = .76$) was measured with two items of the questionnaire of Smolders et al. (2013) ('How much trouble do your eyes give when you are exposed to bright light?' and 'How much do you suffer from headaches when you are exposed to bright light?') and two newly designed questions ('Do you suffer from night blindness?' 'Do you use sunglasses because the light is too intense?'), participants could answer these questions on a scale ranging from (0) 'not at all' to (4) 'very much'. The reliability of these four questions was $\alpha = 59$.

The Dutch Munich Chronotype Questionnaire (MCTQ) was used to assess chronotype (Roenneberg, Wirz-Justice, & Merrow, 2003). Chronotype was calculated by the formula of Roenneberg et al. (2004). Subsequently, a median split was used to determine early and late chronotypes (11 early chronotypes, 9 late chronotypes).

The Pittsburgh Sleep Quality Index (PSQI; Buysse, Reynolds, Monk, Berman & Kupfer, 1989) was used to measure general sleep quality (*M* = 6.20, *SD* = 2.73). The Pittsburgh Sleep Quality Index consisted of 19 questions. From these 19 questions a global score (i.e., general sleep quality) was calculated based on the scoring instructions for the PSQI (Buysse et al., 1989). This global score had a range of (0) 'no difficulty' to (21) 'severe difficulties in all areas'.

Individual strength (*M* = 4.83, *SD* = .78) was assessed by the Checklist Individual Strength (Beurkens et al., 2000; α = .87). This checklist consisted of 20 items that were measured on a scale ranging from (0) 'not at all true' to (7) 'certainly true'.

Finally, five items of the Dutch version of the SF-36 Health Survey (General health perception subscale, RAND-36; Van der Zee, Sanderman, Heyink, & de Haes, 1996; α =.69) measured general health (*M* = 3.36, *SD* = .65). Four of the items were measured on a scale ranging from (0) 'completely incorrect' to (4) 'completely correct'. One item was measured on a scale ranging from (0) 'bad' to (4) 'excellent'.

For the analyses the items of the questionnaire were re-coded where needed.

3.3.3. Sleep

3.3.3.1. Activity measures (Actiwatch)

Objective sleep was measured with an actiwatch (Philips Respironics Pro) worn by participants on their wrist. The actiwatch contains an accelerometer (Micro-electro-mechanical Systems) that detects wrist movement. The sampling rate that was used was 30 seconds. The Actiware software calculated based on these wrist movements whether the participant was active, resting or sleeping. An actography report, that shows the sleep-wake cycle of the participants, could be extracted from this.

3.3.3.2. Subjective measures (Sleeping diary)

Subjective sleep was measured by a sleep diary that was identical to the sleep diary used in Smolders et al. (2013; Appendix C). Based on the results of the pilot study it could be assumed that all concepts of the sleep diary were clear. However, the lay-out did not always support the readability of the questionnaire. Therefore, the lay-out of the sleep-diary was adapted based on the Interface design guidelines of Echt (2002) with the feedback of the pilot study in mind. Participants were asked to fill in the questionnaire as soon as possible after waking up.

The sleep diary consisted of five questions that assessed sleep timing ((1) bed time, (2) time of awake, (3) length of sleep, (4) sleep latency, (5) times awake during the night) and six questions that assessed sleep quality on a 5-point Likert scale ((1) how did you sleep; very bad - very good; (2) well-rested after waking up; certainly not - fully; (3) calm sleep; very restless - very calm; (4) slept until the time that you wanted to wake up; woke up much to early - yes; (5) the ease of waking up; very difficult - very easy; (6) the ease of falling asleep; very difficult - very easy). For the analyses, one variable was created that represented all six items of subjective sleep quality. This variable was created based on the results of a factor analysis. Appendix D describes this factor analysis in more detail.

3.3.3.3. Objective vs. subjective sleep data

Sleep onset and sleep offset were measured by both the objective- and subjective sleep measures. As a general rule, the objective data was used for the analyses with regard to sleep timing. The objective data that was used for this were the calculated sleep on- and offset data per participant per day that were obtained from the Actiware software. Subsequently, the data of the objective- and subjective measures were compared per participant. In case a large difference (>1.5 h.) for sleep onset or sleep offset was found between the objective and subjective data, the actography reports from these participants were investigated in more detail. By eye-balling the specific actogram of this report we determined, based on the visualized light and activity data, which measurement (objective or subjective) looked more reliable. For example, when the sleep onset of participant X at day Y of the Actiwatch data was 9:42 p.m. and the sleep onset of the same participant at the same day was 11:45 p.m. according to the sleep diary of this participant, we investigated the actography report of this participant (Figure 6). When the Actogram of participant X at day Y showed that between 9:42 p.m. and 11:45 p.m. there was a lot of activity and there were relatively high levels of light, and these activity and light levels decreased after 11:45 p.m. (Figure 6), the subjective sleep onset was used for further analyses of participant X at day Y. Additionally, in case we were not able to explain the differences between the objective and subjective data by means of the Actograms the data was entered as missing data.

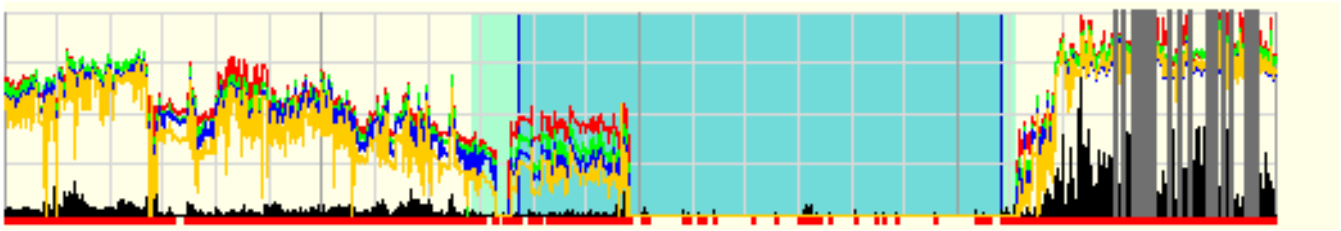


Figure 6. Example of Actogam.

3.3.4. Experience sampling

For seven days the participants received eight questionnaires a day on their smartphone. The MovisensXS application (app) was used to send the questionnaires at random intervals to the phones of the participants. Participants used the app on their own smartphone, or borrowed a smartphone from the university if necessary.

The start- and end times for the random sampling (8:00 a.m. and 9:30 p.m. respectively) of the random intervals were based on the average midsleep of elderly (+ 60 years; *M* = 3:17 a.m., *SD* = 0:46; Wittman, Dinich, Merrow & Roenneberg, 2006). Based on a sleep duration of eight hours this would mean that the average sleep times of elderly above 60 years old lies between 7.17 a.m. (+/- 46 minutes) and 11.17 p.m.(+/- 46 minutes). Because we wanted to avoid influencing the sleep times of the participants by the alarms of the questionnaires we made the intervals slightly narrower (8 a.m. – 9.30 p.m.).

The questionnaire of the experience sampling consisted of eleven questions that assessed feelings of vitality, tension, mood, sleepiness, prior napping time and contextual characteristics. These questions were based on the questions used in the ESM-study of Smolders et al. (2013).

Vitality was measured by one question (‘how do you feel at the moment?’) with a response scale ranging from (0) ‘energetic’ to (6) ‘washed out’. Tension was measured by one question (‘how do you feel at the moment?’) with a response scale ranging from (0) ‘tense’ to (6) ‘calm’.

Mood was measured by the question (‘how do you feel at the moment’) with a response scale from (0) ‘happy’ to (6) ‘sad’.

Sleepiness was assessed by the Karolinska Sleepiness Scale (Åkerstedt & Gillberg, 1990) that consisted of the question ‘Select which of the statements below best describes how you feel right now’, with the response options: (0) ‘extremely alert’, (1) ‘very alert’, (2) ‘rather alert’, (3) ‘alert’, (4) ‘rather alert’, (5) ‘neither alert nor sleepy’, (6) ‘some signs of

sleepiness', (7) 'sleepy, but no effort to keep awake', (8) 'sleepy, some effort to keep awake', (9) 'very sleepy, great effort to keep awake, fighting the sleep'.

Additionally, the questionnaire contained one question about the number of minutes a participant took a nap the hour previous to the questionnaire ('for how many minutes did you take a nap in the previous hour? If you did not take a nap, please fill in 0').

The experience sampling questionnaire also consisted of questions that assessed the location and activity of the participants. Two questions assessed whether the participants were indoors or outdoors and whether they were alone or together with others. These questions were each assessed with a dichotomous item. Another question that assessed the location of the participants assessed whether the participants were in a build or natural environment. This question had a response scale ranging from (0) 'build environment' to (4) 'natural environment'.

The number of the activities where the participants had engaged in during the hour prior to the questionnaire were assessed with three items that assessed 'physical effort', 'mental effort' and 'social interaction'. The response scales of these items ranged from (0) 'not at all' to (6) 'very much'. All questions were tested in the pilot study. Based on the results the question about the napping time was rephrased.

3.4. Procedure

One day prior to the start of the measurement period, participants met the experimenter for an introductory session. During this introductory session the participants received a light logger, actiwatch and a sleep diary. Furthermore, the participants installed the MovisensXS app on their mobile phone, the experimenter coupled the device with the web-based platform of MovisensXS and explained how to operate the app. In case the participants borrowed a smartphone, the app was already installed and coupled to the platform before the introductory session started. In that case the experimenter explained the use of this phone to make sure that the participants knew how to unlock the screen and fill in the questionnaires. Additionally, participants filled in the pre-study questionnaire, and the experimenter administered the MMSE. The pilot study showed that participants would like to have an instruction of the study and all devices on paper. Therefore, an information sheet was handed over during the information session with contact information of the experimenter.

The duration of the sampling period was seven days. During these days the participants continuously wore the light logger and actiwatch. Additionally, they received eight

questionnaires per day on their mobile phone on a random interval between 8:00 a.m. and 9:30 p.m., and filled in a sleep diary every morning after awaking. The minimum amount of time between two questionnaires of the ESM-questionnaire was set to forty minutes. The MovisensXS app alarmed the participants to fill in a new questionnaire by a sound of eight seconds, and after this the phone displayed a message to fill in the questionnaire within fifteen minutes. The alarm was repeated at four times within these fifteen minutes. If unanswered, they then disappeared and the next questionnaire would show up after a minimum time of forty minutes. After the seven days, a debriefing session took place in which the participants handed in the devices and the sleep diary. Furthermore, participants were debriefed and received a compensation of fifty euros.

3.5. Statistical analyses

Two datasets were created for the statistical analyses. Dataset 1 included the mean light levels per hour (i.e., hourly circadian irradiance and hourly photopic light), and the variables related to sleep. For the analyses related to sleep that were performed with dataset 1 the light exposure levels were averaged within the analyses to day level (i.e., daily circadian light exposure and daily photopic light exposure). For these daily light measurements only light measurements between 7:00 a.m. and 11:59 p.m. were used. This interval was chosen based on the observed mean midsleep (M = 3.74, SD = .45, range = 1.95 – 4.68) and the mean sleep duration (M = 7.51, SD = .90, range = 4.97 – 9.67) of all participants. This indicated that the average sleep times of all participants were between midnight and 7:30 a.m. Since all measurements within this dataset were calculated on an hourly basis starting at the top of the hour, the start-times of the daily intervals were rounded to 7:00 a.m. Furthermore, from this daily interval, separate dummy variables for the morning (7:00 a.m. – 1:00 p.m.), afternoon (1:00 p.m. – 7:00 p.m.) and evening (7:00 p.m. – 23:59 p.m.) were created to explore whether light exposure at a specific time of the day was a better predictor for sleep. More specifically, the hourly light exposure measures were aggregated to these specific intervals and a filter variable was used to make sure that only one light measure per interval per day was used for every participant within the analyses.

Dataset 2 included the average light levels (circadian and photopic) for the interval from the hour prior to the ESM questionnaire to the start of the ESM questionnaire, the ESM data, and the personal characteristics of the participants. The light data within these intervals in this dataset are referred to as: Hourly circadian light exposure and Hourly photopic light

exposure. Note that the ESM questionnaires were assessed between 8:00 a.m. and 9:45 p.m. (the alarms were set between 8:00 a.m. and 9:30 p.m. with the possibility to fill in the questionnaire until 15 minutes after the alarm), and therefore the range of the hourly light measurements was between 7:00 a.m. and 9:45 p.m. To explore whether light exposure at specific times was a better predictor for well-being, separate intervals were created for the morning (8:00 a.m. – 1:00 p.m.), afternoon (1:00 p.m. – 7:00 p.m.) and evening (7:00 p.m. – 10:00 p.m.). Note that the interval for the last measurement was set to 10:00 p.m. instead of 9:45 p.m. to make sure that also the data of participants that took a bit more time to upload the last questionnaire of the day was taken into account.

The hourly light data of both datasets were calculated by using Matlab 2015b. Only hourly measurements that include at least 50% of illuminance data within the interval (i.e., the hour) were included in the datasets. Next, all light data within the hourly time spans were $\log_{10}$ transformed to fit this data into a normal distribution. For dataset 1: 1327 light measures were used (measurements during the day and night) for the analyses that explored the hourly changes in light exposure throughout the day, and 131 light measures were used for the analyses for sleep (i.e., daily light exposure). For dataset 2: 956 light measures were used for the analyses. The response rate for the ESM questionnaires was 95.71% and the response rate for the sleep diaries was 99.29%. Note that for this latter dataset the interval for the experienced light exposure prior to the questionnaire was set to one hour. This was based on the study of Smolders et al. (2013), who found only subtle variations in predictive strength for different time spans (i.e., 2h prior, 1h prior, 30 min. prior, 15 min. prior, 10 min. prior, and 5 min. prior), and used, based on this, the 1 h. intervals in their final analyses.

For both datasets the correlation between circadian light exposure and photopic light exposure was investigated. It was found that these variables were highly correlated within both datasets (dataset 1: $r = .99$, $p < .01$; dataset 2: $r = .97$, $p < .01$). Therefore, results of analyses that explore light exposure will only be reported for circadian light exposure.

3.5.1. HLM analyses

Hierarchical linear model (HLM) analyses were performed to explore variation in light exposure, sleep and affective state within- and between persons by means of intra-class correlations. Additionally, HLM analyses were used to explore whether light exposure and time of day were significant predictors for sleep and well-being (i.e., vitality and mood). The default option (i.e., independent) for the covariate structure, that assumed one unique variance parameter per random effect, was used for all HLM's. Due to the use of two

datasets, we will explain the models used for the statistical analyses and the related assessment for outliers and assumptions per dataset.

3.5.1.1. Dataset 1 (hourly circadian irradiance, daily circadian irradiance and sleep)

The relationship between hourly circadian irradiance and time of day, as well as the inter- and intra- individual variations of hourly circadian irradiance, were explored with HLM analyses that contained two random intercepts. A random intercept for participant ID, and a random intercept for day. This indicated that the hourly circadian irradiance measurements were nested within a day, which in turn was nested within a participant.

The relationships between light exposure and sleep (i.e., subjective sleep, sleep duration and midsleep), as well as the variations in sleep between persons and measurement days were explored with a HLM that contained only one random intercept (i.e., id). This indicated that the daily measurements were nested within a participant.

Preprocessing the data

Before running the analyses for dataset 1 the data was examined for the existence of outliers. Cases that were far from the regression line (>3SD) were considered as outliers. The regression lines that were checked were the regressions between the sleep variables (i.e., subjective sleep quality, sleep duration and midsleep) and hourly circadian light exposure. Three outliers were found. These outliers were found for the relationship between circadian light exposure and objective indicators for sleep timing (i.e., sleep duration and midsleep). Analyses were performed with and without these outliers. Based on the outcome of these analyses it was decided to set these outliers to missing data points because they did affect the results.

Furthermore, we investigated the bed and wake times of the participants. It was found that only one participant, at one day, went to sleep later than 3:00 a.m., and that the first wake time was at 4:00 a.m. To make a clear distinction between the start of the day and the end of the day, in order to investigate the hourly illuminance levels as a function of time of day, we therefore considered the participant that went to sleep later than 3:00 a.m. as an outlier, and recoded all times into time since midnight (e.g., 25 instead of 1:00 a.m.), until the end of the day. In this way, the model assumed that the day for all participants would end at latest on

2:59 a.m. and could start at 3:00 a.m. or later (instead of the default start-time at 0:01 a.m. and end-time at 23:59 a.m.).

Assumptions for HLM analyses

The assumptions for a HLM that were checked were: normality of the residuals, no or little multicollinearity, linear relationships and homoscedasticity. First the assumption of multicollinearity was checked. To assess the assumption of multicollinearity the correlation between the independent variables that were used in the HLM analyses for dataset 1 were investigated by using Pearson's correlation. Moderate to high correlations were considered to be a problem for multicollinearity. Results revealed no moderate to high correlations (Appendix E.1). However, since the models that were used in the analyses contain a nested structure, it was still possible that two or more independent variables that did not correlate moderately or high with each other based on Pearson's correlation test, did correlate within the nested structure. A clear indication of a problem with multicollinearity within a HLM is that, when adding an independent variable to an existing model, the coefficients and/or p-values of the independent variables that were already in the model change substantially. Therefore, when adding a new variable to an existing model, the coefficients and p-values of the other independent variables in the model were compared with earlier models. In dataset 1 no substantial changes did occur. Therefore, we concluded that dataset 1 did not have a problem with multicollinearity.

Next, before running the HLM analyses normality of residuals, as well as homoscedasticity and linear relationships were checked. Prior to each HLM analysis we performed a regression model with all variables that would be included in the HLM. Thereafter we assessed several post estimations of the regression to check these three assumptions. First, normality of the residuals was checked by obtaining the residuals and plotting them on a histogram. Results revealed that for the HLM analyses between Hourly circadian light exposure and the third degree polynomial function of time the residuals were normally distributed, for all other HLM analyses that were be performed with dataset 1 the residuals were not normally distributed (Appendix E.2). The robust option was used for all HLM analyses where the assumption for normality was not met. Next, homoscedasticity was checked with the Breusch-Pagan / Cook-Weisberg test for heteroscedasticity. Results revealed that homoscedasticity was violated for several analyses (Appendix E.2). To control for heteroscedasticity the robust function for the HLM's was used. Last linearity relationships

for all HLM analyses were assessed with graphs of the residuals against the fitted values of the prior regression analyses. Based on these graphs, no violations of linearity were found.

Statistical data analyses dataset 1

First, the light exposure patterns of the participants were investigated. Variations within (i.e., day-to-day and moment-to-moment variations) and between persons (i.e., inter-individual variations) in light exposure patterns were explored with an unconditional HLM with Hourly circadian irradiance as dependent variable. Based on this unconditional model, intra-class correlations (ICC's) were investigated to calculate the percentages of variance that occurred between persons, measurement days (nested within persons) and measurement occasions (nested within days for each participant). Additionally, the ICC's were investigated for specific time intervals (i.e., the morning, afternoon and evening). These time intervals were: 7:00 a.m. – 1:00 p.m. (morning), 1:00 p.m. – 7:00 p.m. (afternoon), and 7:00 p.m. – 11:59 p.m. (evening).

Subsequently, experienced light exposure (i.e., Hourly circadian irradiance) was modeled over Time of day to explore structural variations in the light exposure patterns of the participants as function of time of day. Thereafter, the relationship between time of day and hourly light exposure was investigated with three hierarchical linear models. The first one investigated a linear fit of the data with hourly light exposure as dependent variable and time of day as independent variable. The second one investigated a parabolic fit with the same model where time of day squared was added as an independent variable. The last model investigated a third degree polynomial fit with hourly light exposure as dependent variable and time of day, time of day squared and time of day to the third power as independent variables.

Additionally, the relationship between daily light exposure and sleep (i.e., Subjective sleep quality, Sleep duration and Midsleep) was investigated with separate HLM analyses. First we investigated the inter- and intra-individual variations in Subjective sleep quality, Sleep duration and Midsleep with separate unconditional HLM's. Next, Daily circadian irradiance was added to these models to investigate the relationship between sleep and daily circadian irradiance of the day prior to the sleep episode. Subsequently, separate HLM analyses were performed to investigate whether the timing of the exposure to light (i.e., morning, afternoon or evening) prior to the sleep episode did affect the strength of the prediction of circadian irradiance on sleep. To this end, the aggregated variables of hourly circadian irradiance for

morning (7:00 a.m. – 1:00 p.m.), afternoon (1:00 a.m. – 7:00 p.m.), and evening (7:00 p.m. – 11:59 p.m.) were used as predictors in the HLM analyses (separate analyses per variable).

3.5.1.2. HLM analyses for dataset 2 (hourly light exposure prior to ESM questionnaire, feelings of vitality and mood)

The inter- and intra-individual variations of the affective states (i.e., feelings of vitality and mood) and the relationships between the affective states and time of day, light exposure and possible confounds were explored with HLM's that contained two random intercepts.

Preprocessing of the data and check for assumptions

Also for dataset 2 the data was examined for the existence of outliers. No outliers were found. Subsequently the assumptions for HLM's were checked for dataset 2. An identical approach to dataset 1 was used. First multicollinearity was assessed. To this end, Pearson's correlations test was used to investigate whether there were moderate to high correlations between two or more independent variables (Appendix F.1.). It appeared that Chronic fatigue and Trait vitality ($r = .58$, $p < .01$), Chronic fatigue and General health ($r = .59$, $p < .01$) and Being outdoors and Being in nature ($r = .66$, $p < .01$) were moderately correlated. Therefore, it was expected that, when adding these variables at the same this would result in an incorrect interpretation of the effect of these individual predictors. To enable the interpretation of individual predictors, it was decided to avoid the existence of moderately to high correlated variables within the same model. Again, it was still possible that two or more independent variables that did not correlate moderately or high with each other based on the Pearson's correlation test, did correlated within the nested structure. Therefore, independent variables were added to the HLM's in a stepwise manner, starting with the main variables of interest. When adding a variable resulted in a substantial increase in the p-value or a substantial change in the coefficient of another variable that was already in the model, the relationship between these two variables was assessed by a separate HLM with one of these variables as dependent variable and the other variable as independent variable. In case a significant linear relationship between these variables was found within the nested structure, the last added variable was removed from the model. Note that this does not indicate that this removed variable was an insignificant predictor within the model. It only suggests that a substantial part of the variance within this variable was explained by the other variable within the model.

Next, the assumptions for normality of the residuals, homoscedasticity and linear relationship were assessed for all HLM analyses that were performed with dataset 2.

Appendix F.2 shows the outcome of all assumption tests. Normality of residuals was rejected for all HLM analyses. Therefore, the robust option was used for all HLM's. Furthermore, for almost all analyses the homoscedasticity assumption was violated, since the robust option was already used for the HLM's this was not a problem. The assumption for linearity was met for all analyses.

Statistical data analyses dataset 2

For the analyses of the data in dataset 2 the relationships between light exposure and well-being (i.e., vitality and mood) were investigated. First, separate unconditional models of vitality and mood were performed to explore the inter- and intra-individual variations within vitality and mood. Subsequently, the relationship between time of day and vitality and the relationship between time of day and mood were investigated with separate HLM's that assessed a linear, a parabolic and a third degree polynomial fit of the data. Subsequently, Hourly circadian light exposure was added as a predictor to investigate whether vitality or mood was significantly related to the intensity of light exposure the hour prior to filling in the questionnaires and controlling for systematic variation in affective state as a function of Time of day.

Next, possible covariates were added in a step-wise manner to investigate their influence on vitality and mood. These covariates were categorized into type of activity (i.e., Social interaction, Physical activity and Mental effort), environmental variables (i.e., Being in nature, Being outdoors and Being with others (instead of being alone)), sleep (i.e., Prior sleep duration, General sleep quality and Prior nap), and personal characteristics (i.e., Light sensitivity, Trait vitality, Chronic fatigue, General health and Chronotype). As indicated above, covariates that had a high correlation with other covariates were excluded from the model to enable the assessment of individual predictors within the final model.

Last, separate HLM analyses were performed to explore whether the relationship between hourly circadian light exposure and feelings of vitality and the relationship between hourly circadian light exposure and mood differed for measurements in the morning, afternoon and evening. All variables, except for the dichotomous variables (i.e., Chronotype, Prior nap and Being outdoors), that were used in the HLM's were centered to the overall mean of all sessions by using Z-scores in order to compare the coefficients of the various models.

4. Results

4.1. Light exposure patterns

First, the overall light exposure patterns of all participants were investigated. Table 1 shows the mean, median, standard deviation and range of circadian- and photopic light exposure over different time spans. Table 2 and 3 show the distribution of hourly light exposure, and the distribution of light exposure at different time spans.

Table 1. *Mean, median, standard deviation and range of circadian- and photopic light exposure over different time spans.*

	M	Median	SD	Range
Hourly circadian irradiance (W/m^2)	-1.76	-1.67	2.60	-9.37 – 4.33
Hourly photopic light (lux)	5.11	5.16	2.44	-2.30 – 11.01
Daily circadian irradiance (W/m^2)	-1.35	-1.29	2.42	-9.37 – 4.33
Daily photopic light (lux)	5.48	5.55	2.27	-2.30 – 11.01
Morning circadian irradiance (W/m^2)	-1.04	-.71	2.54	-9.37 – 4.33
Morning photopic light (lux)	5.77	6.05	2.42	-2.30 – 11.01
Afternoon circadian irradiance (W/m^2)	-.86	-.93	2.30	-7.59 – 4.10
Afternoon photopic light (lux)	5.94	5.84	2.17	-.91 – 10.72
Evening circadian irradiance (W/m^2)	-2.38	-2.68	2.05	-7.66 – 3.08
Evening photopic light (lux)	4.55	4.18	1.86	-1.06 – 9.87

Note. The light exposure measures of both circadian and photopic light were computed and expressed on a logarithmic scale.

Table 2. *Distribution of circadian light exposure at different time spans in percentages.*

	<.05 W/m^2	.05 - .25 W/m^2	.25 – 1.00 W/m^2	1.0 – 2.00 W/m^2	> 2.00 W/m^2

Hourly (0:00 a.m. – 11:59 p.m.)	29.24	25.39	19.22	7.69	18.46
Daily (7:00 a.m. – 11:59 p.m.)	23.08	25.39	21.04	8.53	21.96
Morning (7:00 a.m. - 1:00 p.m.)	19.55	24.36	20.68	10.76	24.65
Afternoon (1:00 p.m. – 7:00 p.m.)	14.90	23.21	25.50	8.02	28.37
Evening (7:00 p.m. – 11.59 p.m.)	43.86	30.26	14.04	5.26	6.58

Table 3. *Distribution of photopic light exposure at different time spans in percentages.*

	< 50 lux	50 – 200 lux	200 – 500 lux	500 – 1000 lux	>1000 lux
Hourly (0:00 a.m. – 11:59 p.m.)	28.64	24.19	13.49	9.19	24.49
Daily (7:00 a.m. – 11:59 p.m.)	23.26	23.73	14.37	9.92	28.73
Morning (7:00 a.m. – 1:00 p.m.)	18.41	21.45	12.82	11.66	35.66
Afternoon (1:00 p.m. – 7:00 p.m.)	14.90	21.49	20.06	9.17	34.38
Evening (7:00 p.m. –	42.98	30.26	9.21	7.90	9.65

11:59 p.m.)

An unconditional hierarchical linear model (HLM) was performed to explore the variance in hourly circadian irradiance levels between persons, measurement days and hours (see Table 4). These results revealed that most of the variance in hourly light exposure occurred within participants on an hour-to-hour basis.

Additionally, we explored the variance in circadian irradiance levels for different parts of the day (i.e., morning (7:00 a.m. – 1:00 p.m.), afternoon (1:00 p.m. – 7:00 p.m.) and evening (7:00 p.m. – 11:59 p.m.; see Table 4). Note that the hourly circadian irradiance measurements were aggregated for each of these intervals. Therefore only variance between persons and variance between measurement days were taken into account. These results revealed substantial variation between persons and between days within persons for the various indicators. Moreover, the extent to which the variance in light exposure varied between and within persons differed for the various parts of the day.

Table 4. *Variance in circadian light exposure for daily circadian light exposure, and morning, afternoon and evening light exposure (in percentages).*

	Variance between persons	Variance between measurement days	Variance between hours
Hourly circadian irradiance levels	3.08	1.09	95.83
Daily circadian irradiance levels	13.81	86.19	-
Morning circadian light exposure	55.52	44.48	-
Afternoon circadian light exposure	25.70	74.30	-
Evening circadian light exposure	73.25	26.75	-

Figure 7 shows a scatterplot of hourly circadian irradiance as a function of time of day (local clock time). To explore which relation would best fit the data various HLM analyses were performed with different functions of time of day. First a linear relationship was

assessed with a HLM with hourly circadian irradiance as dependent variable and Time of day as independent variable [model fit: X2(1) = 2.18, p =.14]. Results revealed that Time of day (B = -.02, z = -1.47, p =.14) was not significantly related to Hourly circadian irradiance, indicating that the relationship between Hourly circadian irradiance and Time of day was not linear as can also be observed in Figure 7. Thereafter, a HLM with hourly circadian irradiance as dependent variable and Time of day and Time of day squared as independent variables was performed. The model revealed a significant model fit [X2(2) = 32.74, p < .01]. Both, the relationship between Hourly circadian irradiance and Time of day (β = 0.31, z = 5.04, p < .01), as well as the relationship between Hourly circadian irradiance and Time of day squared (β = - 0.01, z = - 5.54, p < .01) were significant. Finally, a HLM with Time of day, Time of day squared and Time of day to the third power as independent variables revealed a significant model fit [χ2(3) = 36.95, p < .01] with Time of day (β = 0.72, z =3.99, p < .01), Time of day squared (B = - .04, z = -3.29, p < .01) and Time of day to the third power (β < 0.00, z = 2.59, p = .01) as significant predictors. Although the two latter models revealed both a significant model fit, the latter model revealed a better fit (log likelihood = -1706.92, compared to -1726.73 (for a parabolic function)). This suggests a third-degree polynomial trend for the relationship between time of day and hourly circadian irradiance.

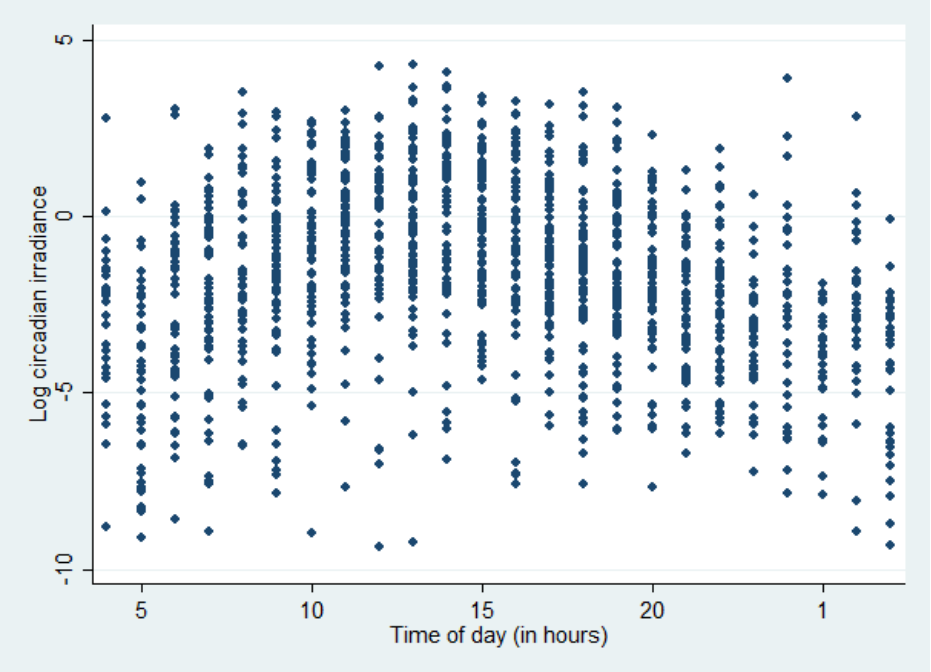


Figure 7. Variation in hourly circadian irradiance levels over time

4.2. Sleep

Table 5 shows the variance that occurred between persons and measurement days within persons for Subjective Sleep, Sleep duration and Midsleep that were assessed with separate unconditional HLM analyses.

Table 5. *Explained variance that occurred between persons and measurement days for subjective sleep quality, sleep duration and midsleep (in percentages).*

	Between persons	Between measurement days
Subjective sleep quality	57.12	42.88
Sleep duration	42.26	57.74
Midsleep	34.77	65.23

A HLM with Daily circadian light exposure as a predictor revealed no significant relationship between the average daily circadian light exposure (B = .12, z = 1.49, p = .14) and Subjective sleep quality. Adding Chronotype as a covariate did reveal that chronotype was not a significant covariate within this model (B = .28, z =.77, p =.44). Similar separate HLM analyses were performed for Sleep duration and Midsleep. These analyses revealed that there were no significant relationships between Daily circadian light exposure (B = -.05, z = -.50, p = .62) and Sleep duration, and between Daily circadian light exposure (B = -.06, z = -.39, p = .70) and Midsleep. Adding Chronotype as a covariate to these models revealed that chronotype was not a significant covariate for the model of sleep duration (B = -.13, z = .83, p = .70), neither for the model of midsleep (B = -.13, z = -.51, p = .61).

4.2.1. Timing of light exposure

Figure 8 shows the variation in subjective sleep quality scores for exposure to morning, afternoon and evening circadian light on the day prior to the night of sleep. Separate HLM analyses were performed to investigate the relationship between Subjective sleep quality and morning, afternoon and evening circadian light exposure of the day prior to the sleep episode (see Table 6).

Results suggested a significant relationship between Morning circadian light exposure and Subjective sleep quality (B = .25, z = 2.55, p = .01). Indicating that participants reported higher sleep quality when they were exposed to more intense levels of circadian light exposure during the morning of the previous day. Adding Chronotype as a covariate revealed that chronotype was not a significant predictor (B = .26, z = .78, p = .44).

No significant relationships were found between Subjective sleep quality and Afternoon circadian light exposure (B = .13, z = 1.23, p = .22) and between Subjective sleep quality and Evening circadian light exposure (B = -.17, z = -1.62, p = .10). Chronotype was not a significant covariate for the relationship between Subjective sleep quality and Afternoon circadian light exposure (B = .20, z = .57, p = .57), neither for the relationship between Subjective sleep quality and Evening circadian light exposure (B = .32, z = .93, p =.35).

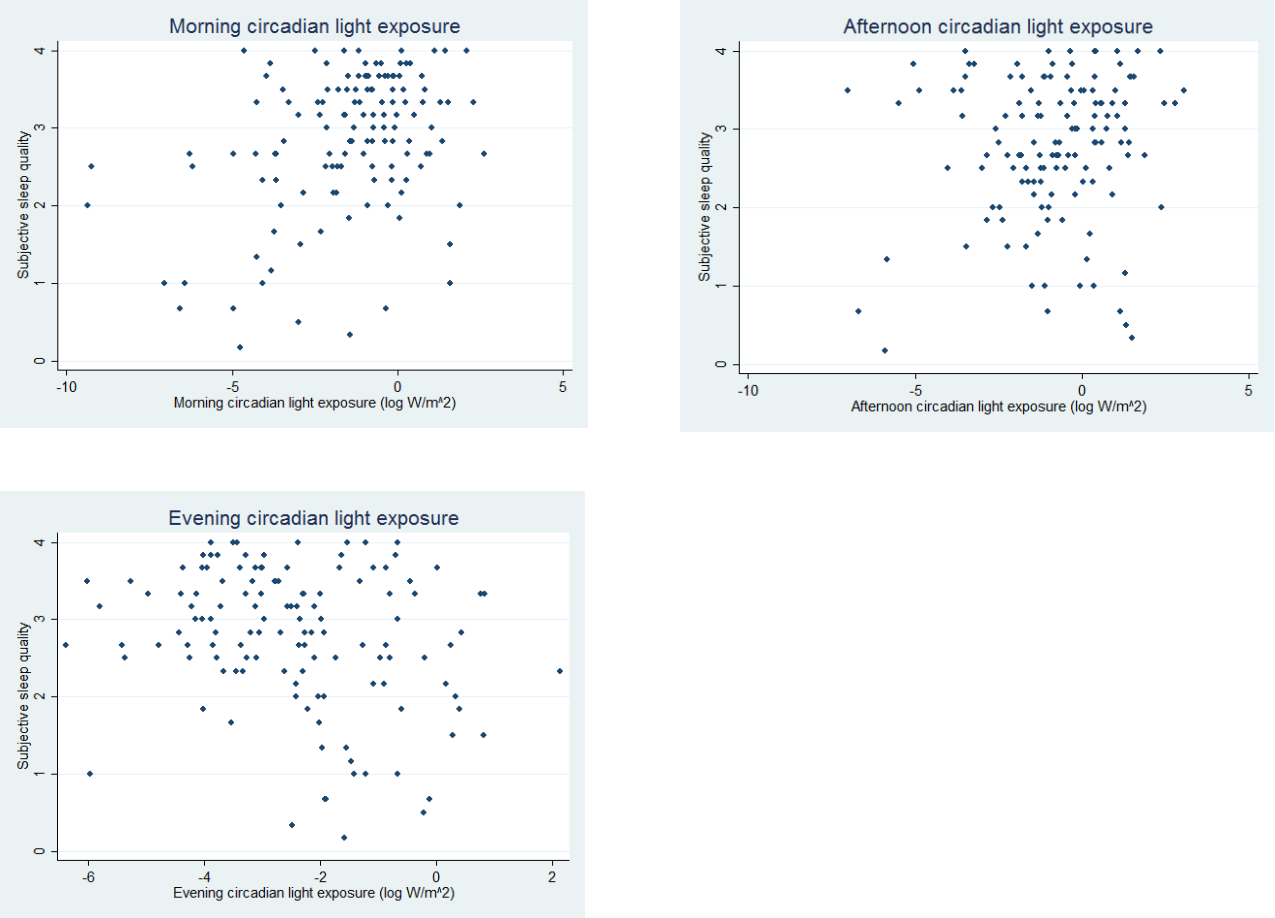


Figure 8. Scatterplots that show the variation of subjective sleep quality scores for prior morning, afternoon and evening circadian light exposure.

Table 6. *Statistics of predictors for sleep*

	X2	Df	P	Z	Standardized B
Subjective sleep quality					
Daily circadian irradiance	2.22	(1, 129)	.14	1.49	.12
Morning circadian irradiance	**6.49**	**(1, 128)**	**.01**	**2.55**	**.25**

Afternoon circadian irradiance	1.50	(1, 129)	.22	1.23	.13
Evening circadian irradiance	2.63	(1, 126)	.10	-1.62	-.17
Sleep duration					
Daily circadian irradiance	.25	(1, 106)	.62	-.50	-.05
Morning circadian irradiance	.17	(1, 109)	.67	.42	.05
Afternoon circadian irradiance	3.34	(1, 106)	.07*	-1.83	-.20
Evening circadian light exposure	**5.77**	**(1, 107)**	**.02**	**2.40**	**.23**
Midsleep					
Daily circadian light exposure	.15	(1, 107)	.70	-.39	-.06
Morning circadian light exposure	1.95	(1, 110)	.16	1.40	.17
Afternoon circadian irradiance	3.77	(1, 107)	.05*	-1.94	-.29
Evening circadian light exposure	1.31	(1, 108)	.25	1.14	.13

Note. Significant predictors are indicated in bold. Significant trends are indicated with a star (*).

Similarly, separate HLM analyses were performed to investigate the relationship between sleep duration and prior morning, afternoon and evening circadian light exposure. Results revealed a significant relationship between sleep duration and Evening circadian light exposure (B =.23, z = 2.40, p = .02) (see Table 6). Indicating that participants slept for a longer duration of time when they were exposed to more intense levels of circadian light during the evening. Adding chronotype as a covariate to this model revealed that chronotype was not a significant covariate within this model (B = -.07, z = -.24, p =.70). Furthermore, a trend near significance was found for the relationship between sleep duration and Afternoon circadian light exposure (B = -.20, z = -1.83, p = .07), suggesting that participants who were

exposed to more intense levels of circadian light exposure in the afternoon tend to sleep for a shorter duration of time during the upcoming night. Adding Chronotype to this model revealed that chronotype was not a significant covariate within this model (B = < -.00, z = -.02, p = .99). No significant relationships were found between sleep duration and Morning circadian light exposure (B = .05, z = .42, p =.67) (see Table 6). Chronotype was not a significant predictor in any of these models (all p > .10). Figure 9 shows the variation of sleep duration for prior morning, afternoon and evening circadian light exposure.

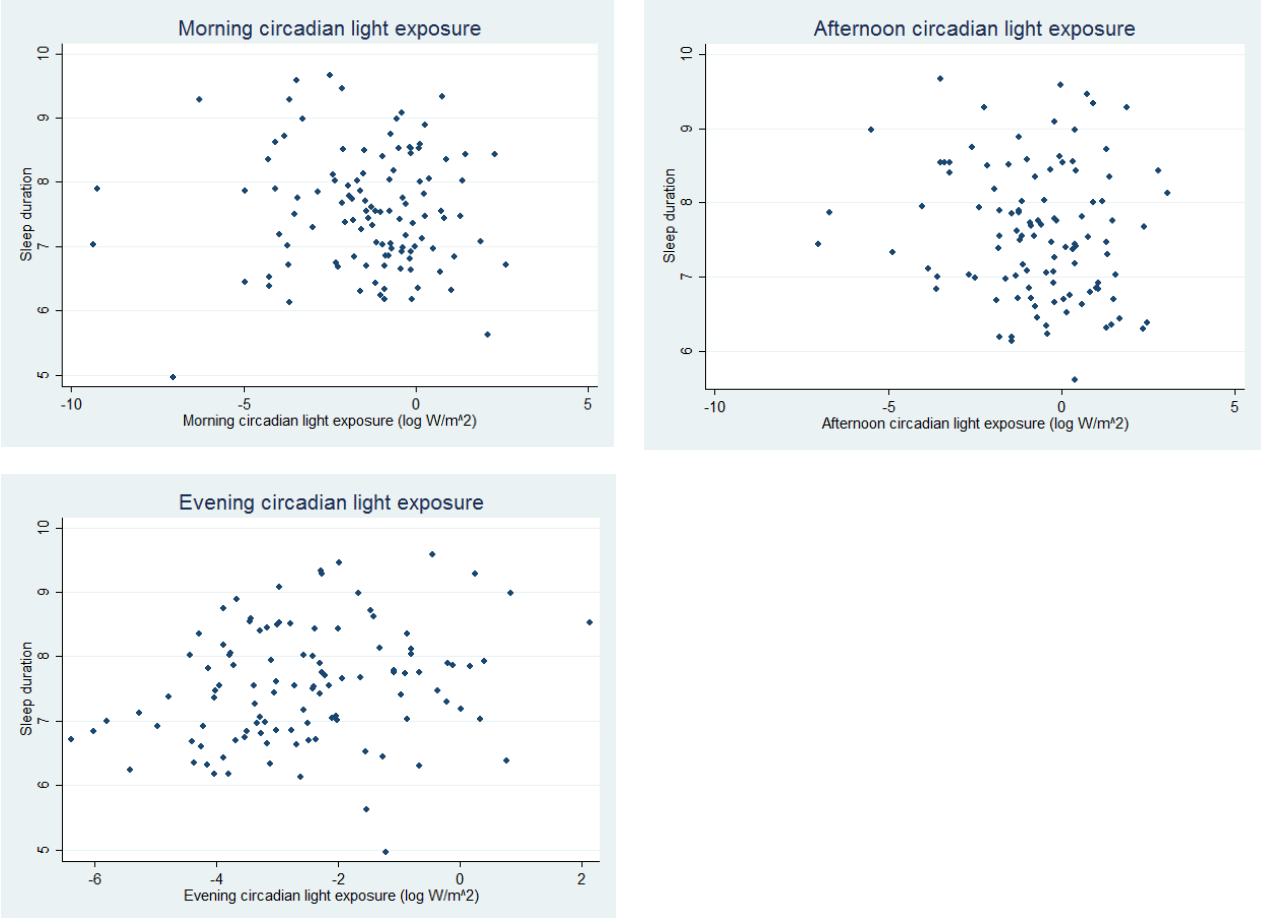


Figure 9. Scatterplots of the variation in sleep duration for prior morning, afternoon and evening circadian light exposure.

Last, separate HLM analyses were performed to investigate the relationship between midsleep and prior morning, afternoon and evening circadian light exposure (see Table 6). A trend near significance was found for the relationship between Afternoon circadian light exposure and midsleep (B = -.29, z = -1.94, p = .05). Indicating that participants who were exposed to more intense levels of circadian light in the afternoon tend to have an earlier midsleep on the upcoming night. Adding Chronotype to this model revealed that chronotype

was not a significant covariate within this model (B = .04, z = .13, p =.90). No significant relationships were found for the relationship between midsleep and Morning circadian light exposure (B = .17, z = 1.40, p = .16), and midsleep and Evening circadian light exposure (B = .13, z = 1.14, p = .25) (see Table 3). Adding Chronotype as covariates to these models revealed that chronotype was not a significant covariate for midsleep in both models (B = -.24, z = -.83, p =.41 and B = -.24, z = -.84, p = .40 respectively). Figure 10 shows the variation of midsleep for prior morning, afternoon and evening circadian light exposure.

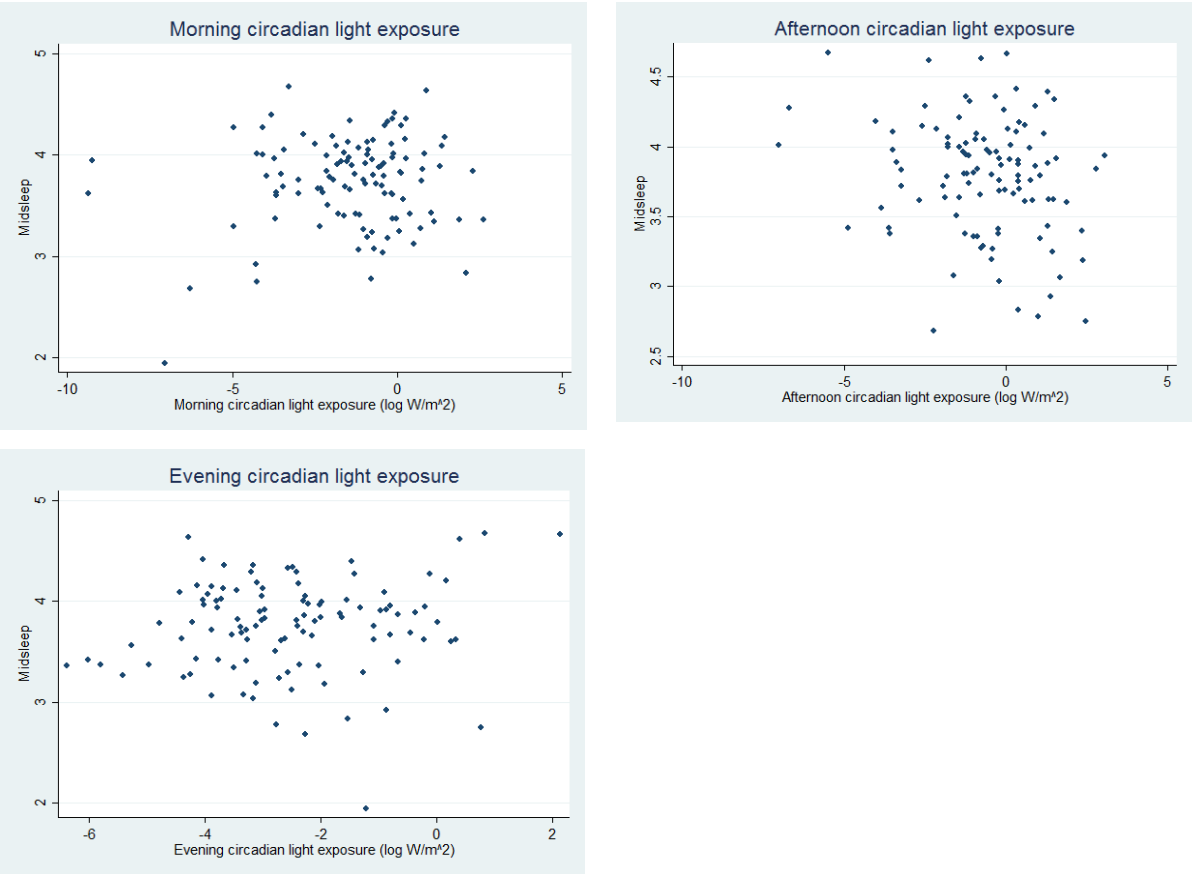


Figure 10. Variation in midsleep for prior morning, afternoon and evening circadian light exposure.

4.3. Well-being

4.3.1. Vitality

Figure 11 shows the variation of feelings of vitality over local clock time. An unconditional model of feelings of vitality reveals that 17.43 % of the variance in Feelings of vitality occurred between persons, 8.20 % of the variance occurred between days, and 74.37

% of the variance occurred between measurement occasions. Based on the scatterplot of feelings of vitality over time (Figure 11), it was suggested that feelings of vitality did vary over time of day to a polynomial or third degree function. To explore which relation would best fit the data, separate HLM analyses were performed that assessed the variation of vitality over time (see Table 7). First, a linear relationship was assessed with a HLM with Feelings of vitality as dependent variable and Time of day as independent variable [model fit: X2(1) = .45 p = .50], this revealed no significant relationship between Time of day and Feeling of vitality (B = .01, z = .67, p =.50). Second, a parabolic function of time of day was assessed with a HLM with Feelings of vitality as dependent variable and Time of day and Time of day squared as independent variables. Results revealed a significant model fit [X2(2) = 15.61, p <.01], with significant relationship between Time of day and Feelings of vitality (B = .48, z =3.74, p <.02), and Time of day squared and Feelings of vitality (B = -.02, z = -3.84, p <.01). Last, a third degree polynomial function of time of day was assessed with a HLM with Feelings of vitality as dependent variable and Time of day, Time of day squared and Time of day to the third power as independent variables. This model revealed a significant model fit [X2(3) = 37.81, p <.01], with Time of day (B = 2.08, z = 5.13, p < .01), Time of day squared (B = -.13, z = 5.13, p <.01) and Time of day to the third power (B = <.00, z = 4.70, p < .01) as significant predictors. Based on the log likelihood it was found that the third degree function fitted slightly better the prediction of feelings of vitality over time (log likelihood = -1346.86, compared to -1357.13).

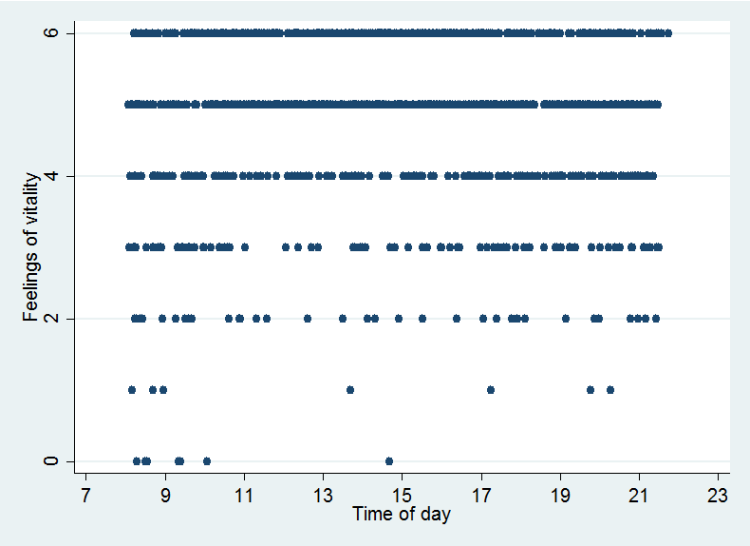


Figure 11. Variation in feelings of vitality over time.

Table 7. *Results of separate HLM's that explored the variance of vitality over time.*

	B	Z	p
Linear model			
Time of day	.01	.67	.50
Polynomial model			
Time of day	**.48**	**4.74**	**< .01**
Time of day squared	**-.02**	**-3.84**	**< .01**
Third degree function			
Time of day	**2.08**	**5.13**	**< .01**
Time of day squared	**-.13**	**-5.01**	**<.01**
Time of day to the third power	**< .00**	**4.70**	**<.01**

Note. Significant predictors are indicated in bold.

Next, we explored the relationship between Feelings of vitality and Hourly circadian light exposure (Figure 12). A HLM with Feelings of vitality as dependent variable and Hourly circadian light exposure as independent variable revealed a non-significant trend for a positive relationship between Feelings of vitality and Hourly circadian light exposure (B = .13, z = 1.84, p = .07). This suggested that participants reported higher levels of feelings of vitality when they were exposed to more intense levels of circadian light exposure one hour prior to the questionnaire.

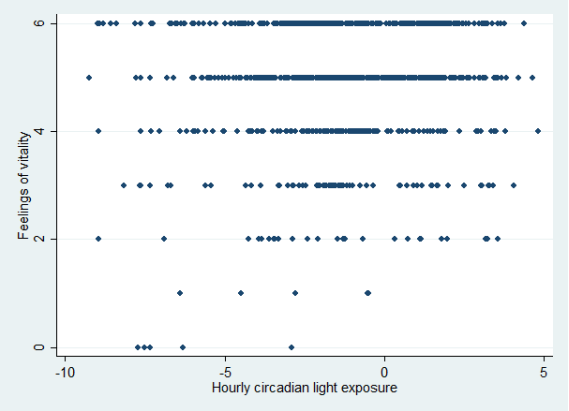


Figure 12. Variations in feelings of vitality over hourly circadian light exposure.

To investigate the effect of hourly light exposure, controlling for variations in vitality as a function of time of day, a HLM was performed with Time of day, Time of day squared, Time of day to the third power and Hourly light exposure as predictor variables. The fit of the model was significant [X2(4) = 22.71, p <.01], and the results revealed that Time of day (B = 1.44, z = 3.18, p < .01), Time of day squared (B = -.09, z = -3.16, p < .01) and Time of day to the third power (B = < .00, z = 3.05, p <.01) were significant predictors within this model. Hourly circadian light exposure was not a significant predictor (B = .09, z = 1.37, p =.17).

4.3.1.1. Covariates of feelings of vitality

It was expected that, other factors could influence feelings of vitality as well. Therefore, a HLM analysis was performed with the third-degree polynomial function of Time of day and Hourly circadian light exposure as predictors with covariates added to this model in a step wise manner. Only significant covariates were kept into the model. Note that by every addition of a covariate to the model the relation of the other predictors within the model changed. In this section, only substantial changes will be reported.

Type of activity

First, covariates that described the type of activity where participants were engaging in one hour prior to filling in the questionnaire were added to the model. Results revealed that Social interaction was a significant predictor of vitality within this model (B = .25, z = 4.22, p < .01), suggesting that participants that were engaged in more social interaction one hour prior to the questionnaire reported higher feelings of vitality. Additionally, Physical effort (B = .18, z = 3.79, p < .01) and Mental effort (B = .15, z = 3.02, p < .01) turned out to be significant covariates within the model, indicating that participants who were engaged in more physical

effort and mental effort one hour prior to filling in the questionnaire reported higher levels of feelings of vitality.

Environmental variables

Second, environmental variables were added to the model to assess whether these covariates had an influence on Feelings of vitality. First, Being with others was added to the model. Results indicated that Being with others was not a significant predictor within the model (B = -.03, z = -1.00 p =.32). Therefore, Being with others was removed from the model. Adding Being in nature to the model revealed that Being in nature was a significant predictor within the model (B = .08, z = 2.65, p <.01). These results indicated that participants that were surrounded by nature when filling in the questionnaire reported higher feelings of vitality. However, with the addition of this variable to the model, the p-value of Physical effort substantially increased (p =.09), although the correlation of Physical effort and Being in nature was small to medium (r = .36, p <.01) it was suggested that a substantial part of the variance within Physical effort and Being in nature was related within the nested structure of the model. To investigate whether this was true, a HLM with Physical effort as dependent variable and Being in nature as independent variable was performed. This revealed a significant linear relationship within the nested structure between Being in nature and Physical effort (B = .35, z = 7.33, p < .01). Therefore, Being in nature was removed from the model for further analyses. Next, Being outdoors was added as a covariate to the model. Results revealed that Being outdoors was a significant predictor within the model (B = .19, z = 2.28, p = .02), suggesting that participants that were outdoors when filling in the questionnaire reported higher levels of vitality. However, again the p-value of Physical effort substantially increased after adding this variable (p = .12). To investigate whether this was due to multicollinearity, a separate HLM with Physical effort as dependent variable and Being outdoors as independent variable was performed. Resulted indicated a significant linear relationship between Being outdoors and Physical effort (B = .77, z = 8.86, p <.01), indicating that indeed a substantial part of the variance within these two variables was related. Therefore, Being outdoors was also removed from the model for further analyses.

Sleep

Next, covariates that were related to sleep were added to the model in a step wise manner. First, Prior sleep duration was added as a covariate. Results revealed that Prior sleep duration was not a significant covariate within the model (B = .04, z = .77, p = .44). Subsequently,

General sleep quality was added to the model. Also General sleep quality was not a significant covariate within the model (B = -.14, z = -1.19, p = .24). Thereafter, Prior nap was added as a covariate to the model. Results revealed that Prior nap was a significant covariate within the model (B = -.37, z = -2.76, p < .01). This suggested that participants that took a nap one hour prior to the questionnaire reported lower feelings of vitality. Note that by adding Prior nap to the model a substantial change of the influence of Time of day (B = .77, z = 1.95, p = .05), and Physical effort (B = .10, z = 1.87, p =.06) within the model had occurred. Although the correlation between Prior nap and time of day was relatively weak (r = -.08, p <.01). It was suggested that within the nested structure and with the third degree function of time of day, these two variables could be related. Therefore a separate HLM was performed with Prior nap as dependent variable and Time of day, Time of day squared and Time of day to the third power as independent variables. This later HLM revealed that all dependent variables within this model were significantly related to Prior nap (time of day: B = -.47, z = -2.90, p <.01; Time of day squared: B = .03, z = 2.73, p <.01; Time of day to the third power: B = <-.00, z = -2.53, p = .01). The model with Prior nap as a covariate suggested also a possible correlation between Prior nap and Physical effort. Also, the correlation between Prior nap and Physical effort seemed relative low (r = -.18, p < .01). However, a separate HLM with Prior nap as independent variable and Physical effort as dependent variable revealed a significant relationship between Physical effort and Prior nap (B = -.05, z = -4.36, p < .01). Therefore, Prior nap was removed from the model as a covariate.

Personal characteristics

Then, covariates related to personal characteristics were added to the model. The addition of General Health to the model revealed that General Health was not a significant predictor for Feelings of vitality within the model (B = .05, z = .54, p = .59). Therefore, General health was removed as a covariate from the model. Additionally, Chronic fatigue was added as a covariate to the model. Results revealed that Chronic fatigue was not a significant predictor within the model (B = .07, z = .64, p =.52). Also this variable was removed from the model.

Subsequently, Trait vitality was added as a covariate to the model. Results revealed that Trait vitality was a significant predictor within the model (B = .19, z = 2.27, p =.02). This suggests that participants with a higher score on trait vitality tended to also report higher scores of feelings of vitality in the ESM-questionnaires during the sampling week.

Last, Light sensitivity and Chronotype were separately added as covariates to the model, this revealed that Light sensitivity was not a significant covariate within the model (B = -.04,

z = -.41, p =.69), neither was Chronotype (B = -.14, z =-.66, p =.51). Table 8 shows the results of the prediction model of Feelings of vitality with all significant predictors included.

Table 8. *Statistics of the final model with predictors for Feelings of vitality*

	Z	P	Standardized B
Level 1 predictor			
Time of day	**2.42**	**.02**	**.93**
Time of day squared	**-2.50**	**.01**	**-.06**
Time of day to the third power	**2.52**	**.01**	**<.00**
Hourly light exposure	.78	.43	.04
Social interaction	**2.75**	**<.01**	**.14**
Physical effort	**2.05**	**.04**	**.11**
Mental effort	**2.93**	**<.01**	**.13**
Level 3 predictor			
Trait vitality	**2.27**	**.02**	**.19**

Note. Significant predictors were indicated with bold and a trend near significance was indicated with an astrix (*).

4.3.1.2. Time-of-day dependency in relation between light and vitality

Figure 13 shows scatter plots for the relationship between hourly circadian light exposure and vitality for the morning (8:00 a.m. – 1:00 p.m.), afternoon (1:00 p.m. – 7:00 p.m.) and evening (7:00 p.m. – 10:00 p.m.). To investigate whether the relationship between hourly circadian light exposure and feelings of vitality differed for the morning, afternoon and evening measurements, separate HLM analyses were performed for the morning (8:00 a.m. – 1:00 p.m.), afternoon (1:00 p.m. – 7:00 p.m.), and evening (7:00 p.m. – 10:00 p.m.).

The relationship between Feelings of vitality and Hourly circadian light exposure in the morning was significant (B = .26, z = 2.45, p =.01) (see Table 9), suggesting that in the feelings of vitality were higher when participants were exposed to more intense circadian light during the hour prior to completing the questionnaire. The relationships between

Feelings of vitality and Hourly light exposure in the afternoon and in the evening were not significant (see Table 9).

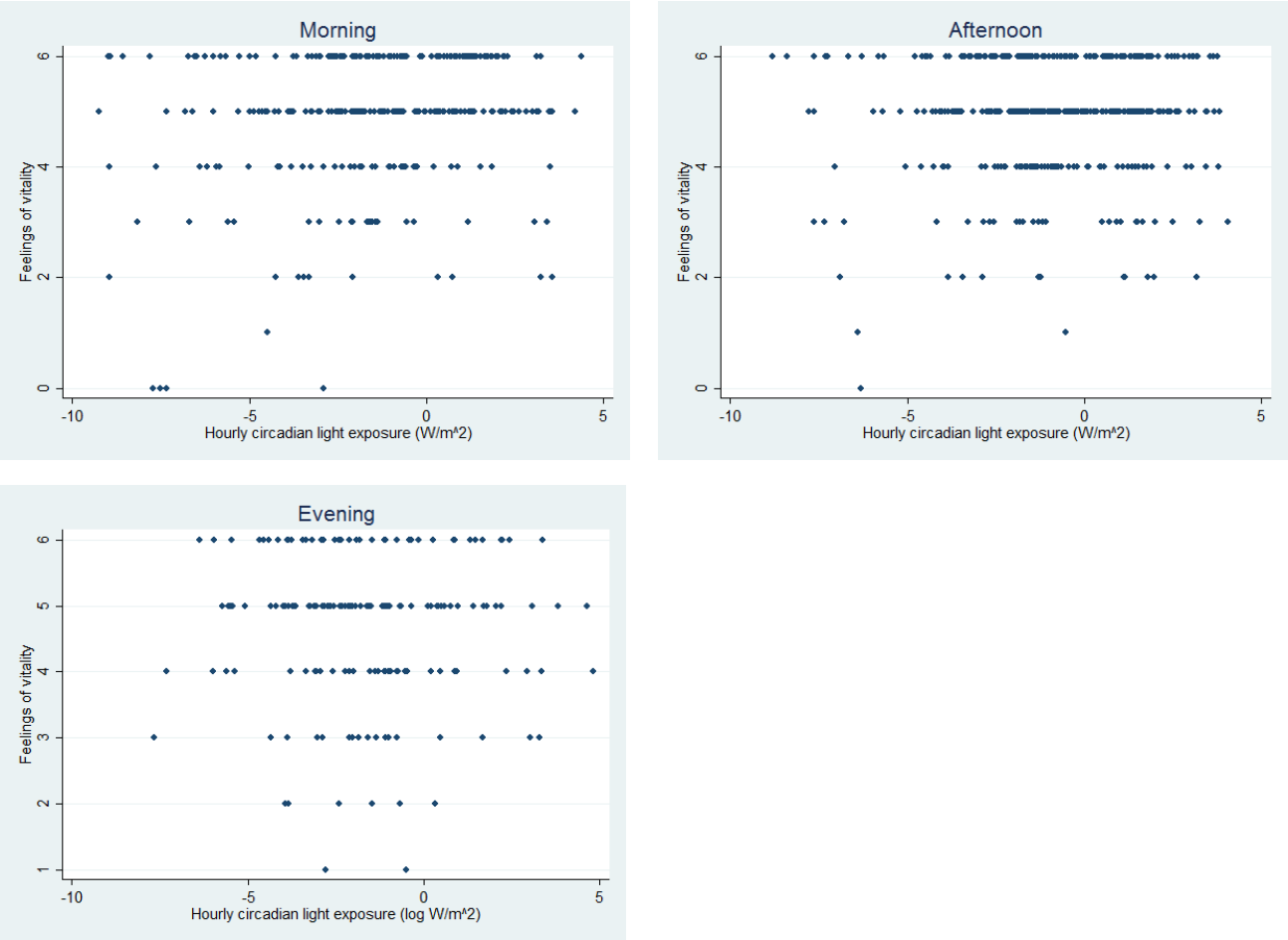


Figure 13. Scatterplots that represent the relationship between vitality and hourly circadian light exposure as a function of time of day (morning (8:00 a.m. – 1:00 p.m.), afternoon (1:00 p.m. – 7:00 p.m.) and evening (7:00 p.m. – 10:00 p.m.)) based on the raw data (without hierarchical modelling).

Table 9. *Statistics for separate HLM analyses that investigated the relationship between vitality and circadian light exposure for the morning afternoon and evening.*

Moderator	X(2)	Df	Z	P	Standardized B
Moring	**6.00**	**(1, 306)**	**2.45**	**.01**	**.26**
Afternoon	.80	(1, 443)	.89	.37	.05
Evening	.68	(1, 180)	.82	.41	.06

Note. Significant predictors are indicated in bold.

Subsequently, the analyses were ran with all covariates of the final model on feelings of vitality included (see Table 10). Results revealed that in the morning, mental effort was a significant covariate within this model (B = .24, z = 3.64, p < .01), suggesting that participants who participated in a task required a high level of concentration one hour prior to the questionnaire reported higher levels of feelings of vitality in the morning. Furthermore, a non-significant trend was found for the relationship between Physical effort and vitality (B = .13, z = 1.95, p = .05) in the morning within the model. Interestingly, no significant relationship was found between Hourly circadian light exposure and vitality in the morning within this model (B = .15, z = 1.65, p = .10), suggesting that the relationship disappeared when controlling for potential confounding variables.

A HLM of the final prediction model with afternoon circadian light exposure included suggested that participants who were engaged in social interaction one hour prior to the questionnaire in the afternoon reported higher levels of vitality (B = .18, z = 3.58, p <.01). Additionally a significant relationship between Trait vitality and Feelings of vitality was found for the afternoon (B = .26, z = 3.61, p <.01), suggesting that participants that scored high on trait vitality reported higher Feelings of vitality in the questionnaires during the afternoon. Furthermore, a trend near significance (B = .08, z = 1.93, p = .05) was found for Mental effort. This indicated that participants who were engaged in a task that required high mental effort one hour prior to the questionnaire reported higher levels of vitality in the afternoon.

Last, the model that predicted vitality for the evening suggested that none of the variables were significant predictors for feelings of vitality in the evening. However, a non-significant trend was found for Physical effort (B = .19, z = 1.96, p = .05), suggesting that participants that were engaged in more physical effort one hour prior to the questionnaire reported higher Feelings of vitality in the evening.

Table 10. Statistics for separate HLM analyses that investigated the relationship between vitality, circadian light exposure and its covariates in the morning, afternoon and evening.

	Z	Df	P	Standardized B
Morning				
Hourly circadian light	1.65	(1, 365)	.10	.15

exposure				
Social interaction	.85	(1, 453)	.39	.06
Physical effort	1.95	(1, 453)	.05*	.13
Mental effort	**3.64**	**(1, 453)**	**<.01**	**.24**
Trait vitality	1.49	(1, 19)	.14	.16
Afternoon				
Hourly circadian light exposure	.58	(1, 512)	.56	.03
Social interaction	**3.58**	**(1, 537)**	**<.01**	**.18**
Physical effort	.07	(1, 538)	.95	<.00
Mental effort	1.93	(1, 538)	.05*	.08
Trait vitality	**3.61**	**(1, 19)**	**<.01**	**.26**
Evening				
Hourly circadian light exposure	.21	(1, 180)	.83	.01
Social interaction	.13	(1, 190)	.90	.01
Physical effort	1.96	(1, 190)	.05*	.19
Mental effort	.91	(1, 190)	.36	.09
Trait vitality	1.10	(1, 19)	.27	.16

Note. Significant predictors are indicated in bold. A trend near significance was indicated with an asterix (*).

4.3.2. Mood

Figure 14 shows the variation of mood over time. An unconditional model for mood revealed that 29.24% of the variance in mood occurred between persons, 12.32% of the variance occurred between measurement days and 58.44% of the variance occurred between measurement occasions. With separate HLM analyses the fit of the mood over time was

explored. A HLM that suggested a linear function of Time of day revealed a non-significant trend for a relationship between Mood and Time of Day (B = .02, z = 1.78, p = .07). A HLM that assessed a parabolic function of Time of day revealed a significant effect of Time of day (B = .29, z = 3.08, p <.01) and Time of day squared (B = -.01, z = -3.10, p <.01). A last model that assessed a third-degree polynomial function of time of day in relation to Mood revealed that Time of day (B = 1.04, z = 2.54, p = .01), Time of day squared (B = -.06, z = -2.22, p = .03) and Time of day to the third power (B = <.00, z = 1.99, p = .05). Since the log pseudolikelihood of this latter model was slightly better compared to the log pseudolikelihood of the model that incorporated the parabolic function of time (log pseudolikelihood = -1271.32 compared to log pseudolikelihood = -1274.05) it was decided to use the third-degree polynomial function of time of day for the continuing HLM analyses.

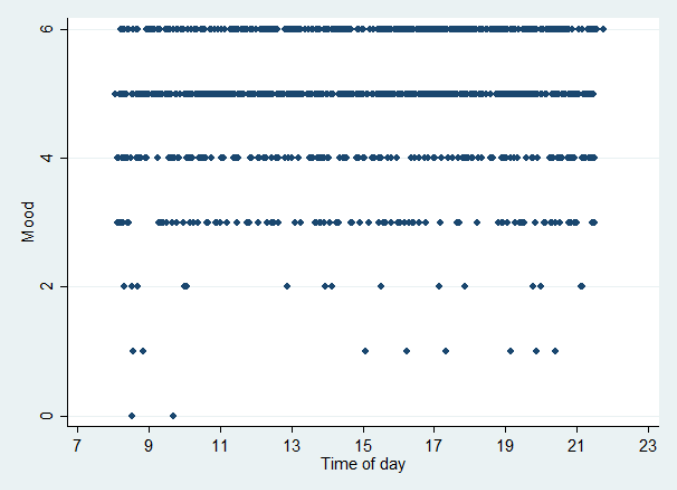


Figure 14. Variation of mood over time of day

Figure 15 shows the variation of mood over circadian light exposure levels. A HLM with Mood as dependent variable and Hourly circadian light exposure ad independent variable revealed that Hourly circadian light exposure was a significant predictor for Mood (B = .12, z = 2.97, p <.01). This suggested that participants that were exposed to more intense levels of circadian light exposure the hour prior to filling in the questionnaire reported better mood.

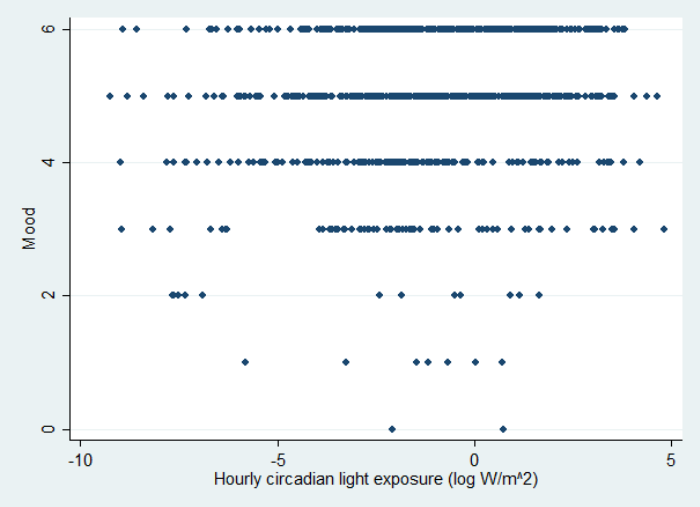


Figure 15. Variation of mood over circadian light exposure levels.

To investigate whether hourly light exposure was still a significant predictor for mood when controlling for time-of-day dependent variations in mood, a HLM was performed with Time of day, Time of day squared, Time of day to the third power and Hourly light exposure as predictor variables. This revealed that Time of day (B = .69, z = 1.55, p = .12), Time of day squared (B = -.04, z = -1.43, p = .15) and Time of day to the third power (B = <.00, z = 1.30, p = .19) were no significant predictors within this model. In contrast, Hourly circadian light exposure was a significant predictor (B = .10, z = 2.38, p = .02). It was possible that the increase in the p-values of the time-related variables was due to a moderate to high correlation between the third-degree polynomial function and hourly circadian light exposure. As assessed earlier in dataset 1, this was indeed the case. However, since we are interested in the combination of these two variables and the influence of the covariates on mood, it was decided to keep both, the third degree polynomial function of time of day and hourly circadian light exposure within the model.

4.3.2.1. Covariates of mood

Also for mood it was suggested that activities, different environments, sleep behavior and personal characteristics could affect mood as well as the relationship between Hourly circadian light exposure and mood. To explore whether this was the case, covariates were added in a step wise manner to a HLM with Mood as dependent variable and Time of day, Time of day squared, Time of day to the third power, and Hourly circadian light exposure as independent variables. Note that by every addition of a covariate to the model the relation of

the other predictors within the model changed. In this section, only substantial changes will be reported.

Activities

First, Social interaction was added as a covariate to the model. This revealed that Social interaction was a significant predictor for mood (B = .21, z = .4.38, p < .01), indicating that the more social interaction the participants had engaged in one hour prior to answering the questionnaire, the more positive they assessed their mood. Adding Physical activity (B = .06, z = 1.36, p = .17) revealed that physical activity was not a significant predictor of mood. Therefore, Physical activity was removed from the model. Subsequently, Mental effort was added as a covariate to the model. This revealed that Mental effort was not a significant predictor of mood (B = .05, z = .95, p = .34). Mental effort was removed as a covariate from the model.

Environmental variables

Adding Being with others as a covariate to the model revealed that Being with others was a significant predictor within the model (B = .06, z = 2.52, p = .01). This indicated that participants that were surrounded by others when filling in the questionnaire reported a more positive mood. The addition of Being in nature as a covariate to the model revealed that Being in nature was also a significant predictor within the model (B = .06, z = 2.65, p <.01). This suggested that the more participants were surrounded by nature when filling in the questionnaire, the more positive mood they reported. Note that it was not possible to add Being outdoors as a covariate to this model, due to the moderate to high correlation that was found between Being in nature and Being outdoors (r = .66, p < .01). To explore whether Being outdoors was a significant predictor for Feelings of vitality, Being in nature was temporarily removed from the model and Being outdoors was added as a covariate. This HLM with Feelings of vitality as dependent variable and Time of day, Time of day squared, Time of day to the third power, Hourly circadian light exposure, Social interaction, Being with others and Being outdoors as independent variables revealed that Being outdoors was a significant predictor within this model (B = .17, z = 2.39, p = .02), indicating that participants that were outdoors when filling in the questionnaire reported a more positive mood.

To avoid the problem of multicollinearity within the model Being outdoors was removed from the model and only Being in nature was only added as a covariate for further analyses.

Sleep

Next, Prior sleep duration was added as a covariate to the model. Results revealed that prior sleep duration was not a significant predictor of mood (B = .05, z = .99, p = .32), and was therefore removed from the model. Additionally, General sleep quality was added to the model. Also general sleep quality was not a significant predictor within the model (B = -.07, z = -.57, p = .57) and was therefore removed from the model. Subsequently, Prior nap was added as a covariate. Results revealed that Prior nap was a significant covariate within this model (B = -.24, z = -2.26, p =.02), suggesting that participants that took a nap one hour prior the filling in the questionnaire reported more negative mood.

Personal characteristics

Last, personal characteristics were added in a step wise manner to the model to investigate their influence on mood. First, General health was added as a covariate to the model. This revealed that General health was not a significant predictor for mood within the model (B = .01, z = .12, p = .90). Next, General health was removed from the model and Chronic fatigue was added as a covariate. This model revealed that Chronic fatigue was also not a significant predictor for mood within the model (B = .10, z = .74, p =.46). Again, the insignificant covariate was removed from the model. Adding Trait vitality to the model revealed a significant relationship between Trait vitality and Mood (B = .23, z = 2.45, p =.01), indicating that participants with a high score on trait vitality reported more positive mood during the sampling week. Adding Sensitivity to light revealed that this was not a significant predictor for mood within the model (B = -.13, z = -.87, p = .38), neither was Chronotype (B = -.21, z = -.83, p =.41). Table 11 shows the statistics of the prediction model of mood with all significant covariates included.

Table 11. *Statistics of predictors for mood.*

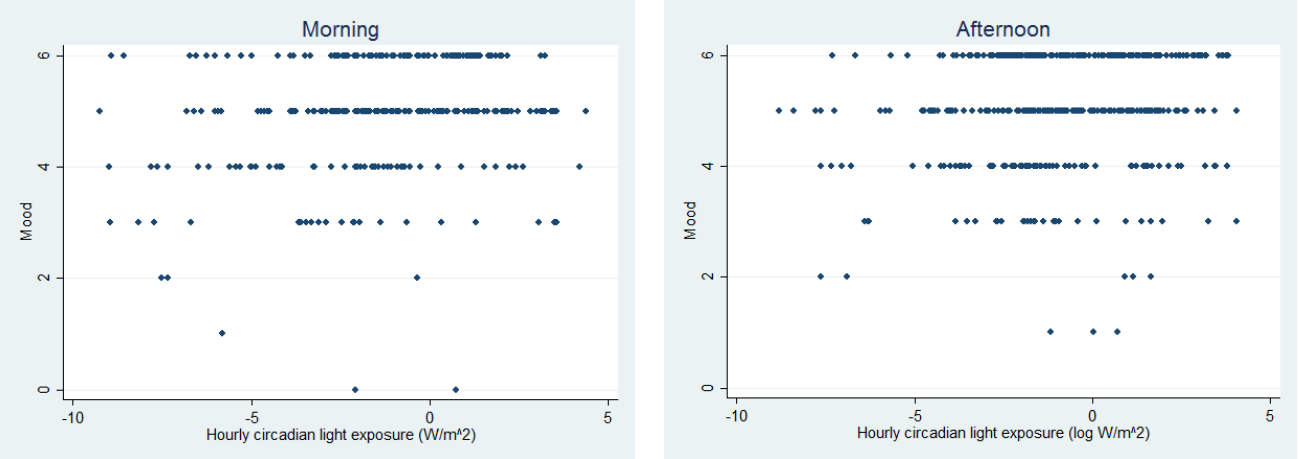
	Z	DF	P	Standardized B
Time of day	.88	(1, 1043)	.38	.37
Time of day squared	-.84	(1, 1043)	.40	-.02
Time of day to the third power	.80	(1, 1043)	.43	<.00
Hourly	1.75	(1, 932)	.08*	.06

circadian light exposure				
Social interaction	**3.40**	**(1, 1041)**	**<.01**	**.17**
Being in nature	**2.63**	**(1, 1043)**	**<.01**	**.06**
Being with others	**2.63**	**(1, 1042)**	**<.01**	**.14**
Prior nap	**-2.26**	**(1, 1042)**	**.02**	**-.24**
Trait vitality	**2.45**	**(1, 19)**	**.01**	**.23**

Note. Significant predictors are indicated in bold, and a trend near significance is indicated with a star (*)

4.3.2.2. Time-of-day dependency in relation between light and mood

Figure 16 shows scatterplots for the relationship between Hourly circadian irradiance and mood for the morning (8:00 a.m. – 1:00 p.m.), afternoon (1:00 p.m. – 7:00 p.m.) and evening (8:00 p.m. – 10:00 p.m.). Separate HLM analyses were conducted to investigate the relationship between mood and Hourly circadian light exposure in the morning, afternoon and evening separately. Results indicated that Hourly circadian light exposure in the morning (B = .21, z = 2.62, p < .01) and afternoon (B =.10, z = 2.91, p <.01) were positively related to positive mood, whereas light exposure in the evening was not significantly related to mood (B = .01, z = .07, p =.95) (see Table 12).



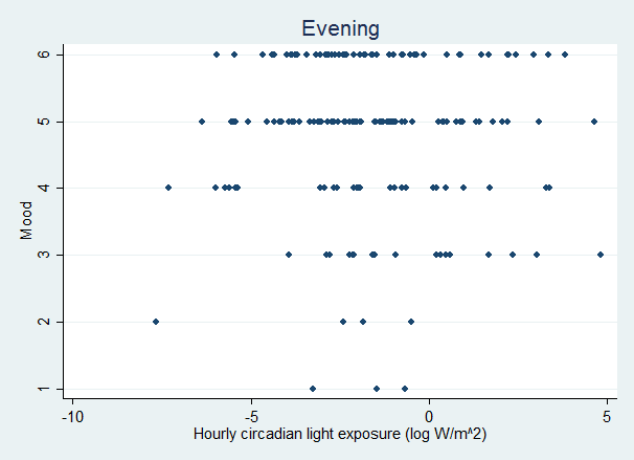


Figure 16. Scatterplot representing the relationship for mood and hourly circadian irradiance in the morning (8:00 a.m. – 1:00 p.m.), afternoon (1:00 p.m. – 7:00 p.m.) and evening (7:00 p.m. – 10:00 p.m.)

Table 12. *Statistics for separate HLM analyses that investigated the relationship between mood and circadian light exposure for the morning afternoon and evening.*

Moderator	X(2)	Df	Z	P	Standardized B
Moring	**6.68**	**(1, 307)**	**2.62**	**<.01**	**.21**
Afternoon	**8.49**	**(1, 442)**	**2.91**	**<.01**	**.10**
Evening	<.00	(1, 180)	.07	.95	.01

Note. Significant predictors are indicated in bold.

Subsequently, similar analyses were performed with all covariates of the final model of mood included (see Table 13). The HLM for the morning revealed that, when controlling for potential confounding variables, the relationship between Hourly circadian light exposure and mood in the morning became less profound (B = .15, z = 1.84, p = .07). Additionally, Social interaction (B = .15, z = 2.13, p = .03), Being in nature (B =.09, z = 2.58, p =.01) and Trait vitality (B =.21, z = 2.43, p = .02) were found to be significant predictors for mood in the morning. This indicated that participants that were engaged in social interaction one hour prior to the questionnaires reported better mood in the morning. Also participants that were surrounded by nature when filling in the questionnaire and participants that scored high on trait vitality reported a more positive mood in the morning.

A HLM for the afternoon revealed that Social interaction (B = .13, z = 2.85, p <.01), Being with others (B = .09, z = 2.21, p < .03), Prior nap (B = -.46, z= -2.05, p =.04), and Trait

vitality (B = .27, z = 2.83, p <.01) were significant predictors for mood in the afternoon. This suggested that participants that were engaged in social interaction the hour prior to filling in the questionnaire reported better mood in the afternoon. Also, participants that were surrounded by others when filling in the questionnaire reported better mood. Furthermore, these results suggest that participants that took a nap the hour prior to filling in the questionnaire reported more negative mood and participants with a high trait vitality reported more positive mood during the afternoon. Note that the relationship between Hourly circadian light exposure and mood in the afternoon became less profound when controlling for potential confounding variables: A non-significant positive trend was found (B = .07, z = 1.89, p =.06).

Finally, a HLM for the evening was performed. No significant predictors were found within this model. However, Trait vitality revealed a non-significant trend for a positive relationship between Trait vitality and Mood in the evening (B= .23, z = 1.85, p = .06).

Table 13. *Statistics for separate HLM analyses that investigated the relationship between mood, circadian light exposure and its covariates for the morning, afternoon and evening.*

	Z	Df	P	Standardized B
Morning				
Hourly circadian light exposure	1.84	(1, 308)	.07*	.15
Social interaction	**2.13**	**(1, 382)**	**.03**	**.15**
Being in nature	**2.58**	**(1, 382)**	**.01**	**.09**
Being with others	1.67	(1, 382)	.10	.08
Prior nap	-.90	(1, 382)	.37	-.25
Trait vitality	**2.43**	**(1, 19)**	**.02**	**.21**
Afternoon				
Hourly circadian light exposure	1.89	(1, 443)	.06*	.07

Social interaction	**2.85**	**(1, 467)**	**<.01**	**.13**
Being in nature	1.15	(1, 469)	.25	.03
Being with others	**2.21**	**(1, 468)**	**.03**	**.09**
Prior nap	**-2.05**	**(1, 469)**	**.04**	**-.46**
Trait vitality	**2.99**	**(1, 19)**	**<.01**	**.27**
Evening				
Hourly circadian light exposure	-.71	(1, 180)	.48	-.05
Social interaction	.69	(1, 190)	.49	-.06
Being in nature	1.07	(1, 190)	.29	.09
Being with others	1.52	(1, 190)	.13	.10
Prior nap	.49	(1, 190)	.63	.07
Trait vitality	1.85	(1, 19)	.06*	.23

Note. Significant predictors are indicated in bold. Insignificant trends were indicated with an asterix (*).

5. Discussion

The current study investigated light exposure patterns as well as the influence of daily light exposure on markers of well-being and sleep (timing and quality) in elderly (mean age = 71.18 years, *SD* = 3.71). In order to explore this research question, a field study was performed in which sleep, vitality, mood and light exposure were measured by means of an experience sampling method (ESM) and wearable sensors (i.e., lightloggers and actiwatches) during seven sequential days among elderly. Data was analyzed by means of hierarchical modelling.

For the analyses two datasets were used. Analyses on light exposure patterns and sleep were conducted with dataset 1. This dataset contained the average light exposure levels (log transferred) per hour (24-h per day), the average light exposure levels (log transformed; per

day per participant) for the morning (7:00 a.m. – 1:00 p.m.), afternoon (1:00 p.m. – 7:00 p.m.) and evening (7:00 p.m. – 11:59 p.m.) and all variables related to sleep. For the analyses that explored the light patterns in elderly all light exposure measures during the 24-h day were taken into account. For the analyses on sleep, only the light exposure levels during the day (7:00 a.m. – 11:59 p.m.) were used. Dataset 2 contained the variables that were related to the ESM questionnaire (e.g., vitality and mood) and the average light exposure levels (log transformed) of the hours prior to the assessments of the ESM questions. Notice that a random sampling method between 8:00 a.m. and 10:00 p.m. was used for the ESM questionnaires. For the analyses that investigated the effect of light exposure at different parts of the day filter variables were used for the morning (8:00 a.m. – 1:00 p.m.), afternoon (1:00 p.m. – 7:00 p.m.) and evening (7:00 p.m. – 10:00 p.m.).

The current study was a replication of the study by Smolders et al. (2013), who investigated the effect of daytime light exposure on feelings of vitality in a (relative) young sample (mean age = 25, *SD* = 8.1). Therefore, results with regard to light patterns and the relation between light patterns and vitality of the current study will be compared with the study of Smolders et al. (2013). However, it should be noted that there is no one-to-one correspondence between both studies. First, measurement periods differed. Smolders et al. (2013) measured light exposure and vitality during three sequential days between 8:00 a.m. and 8:00 p.m., whereas in our study measures took place at seven sequential days between 8:00 a.m. and 10:00 p.m. Furthermore, the devices that measured light exposure differed. Smolders et al. (2013) used a Daysimeter (worn at eye level), whereas our study used light loggers. Additionally, the data collection for the study of Smolders et al. (2013) was distributed over a year (all seasons), whereas our study only assessed data during spring. Therefore, one should be cautious by interpreting the comparisons between these two studies.

Overall, the results revealed structural time-of-day dependent variations in light exposure patterns. Additionally, results suggest that light exposure has an effect on the well-being and sleep of elderly in real life, and that the timing of exposure to more intense light plays an important role in the magnitude of the correlational strength.

5.1. Light patterns of elderly

Results revealed a structural variation of light exposure as a function of time of day. Average irradiance levels were found to be lowest in the evening (7:00 p.m. – 23:59 p.m.) and highest in the afternoon (1:00 p.m. – 7:00 p.m.). Furthermore, average illuminance levels were found

to be more intense in the elderly sample of the current study compared to the younger sample of Smolders et al. (2013).

5.1.1. Variations in light exposure

Particularly intra-individual variations in hourly light exposure were found in the current study. More specifically, most of the variance in hourly light exposure occurred within participants on an hour-to-hour basis. In contrast, when looking at the average light exposure at different parts of the day, light exposure in the morning and evening showed particularly inter-individual differences and to a lesser extent day-to-day variations. Although these differences between inter-individual variations and day-to-day variations in the morning were relatively small, the differences in the evening were quite large.

5.1.1.1. Elderly vs. younger individuals

The current study found similar variations in hourly light exposure (particularly within person variations) with regard to hourly light exposure as Smolders et al. (2013). However, these hourly measures of light exposure for the younger sample in Smolders et al. (2013) were only assessed between 8:00 a.m. and 8:00 p.m., instead of during the 24-h day. Therefore, one should be cautious by comparing these results, and more research is needed to discover whether the same variations in hourly light exposure occur between younger and elderly individuals. Follow-up analyses with the dataset of the current study that only assess the variations in hourly light exposure between 8:00 a.m. and 8:00 p.m. could enable a better comparison between the two studies. However, there would still be no one-to-one correspondence due to the different light measures that were used and the fact that we measured only in one season while the measurements performed in Smolders et al. (2013) occurred throughout the year. Therefore, it is suggested that more research is needed that assesses inter- and intra-individual variations in hourly light exposure between younger and elderly individuals within the same studies.

5.1.1.2. Variations in light exposure at different parts of the day

A possible explanation for finding of particularly inter-individual differences in the morning and evening is that we defined the different parts of the day based on local clock-time instead of internal time (e.g., time since midsleep). Therefore, it is possible that for the measurements in the morning, as well as in the evening, some of the participants were asleep while others were awake, causing large differences between light exposure levels at those times between

individuals. Furthermore, it could be that the differences between individuals were larger in the evening compared to the morning and afternoon due to the relatively sunny days for the time of the year during the sampling period, leading to people spending more time outside.

5.1.2. Average light exposure levels

Average light exposure levels were found to be relatively high compared to the light exposure levels that were reported in the study of Smolders et al. (2013). Additionally, in the current study differences in the average light exposure levels between the morning, afternoon and evening were found. Average light exposure levels were lowest in the evening and highest in the afternoon.

5.1.2.1. Elderly vs. younger individuals

Light exposure levels were relatively high compared to the light exposure patterns of a younger sample assessed by Smolders et al. (2013). They reported a median illuminance level (log transformed) of 2.87 lux during spring. In contrast, the median of the photopic light exposure levels during the day (log transformed) of the current study was 5.55 lux. Notice that these medians were measured with different intervals: Smolders et al. (2013) measured photopic light between 8:00 a.m. and 8:00 p.m. and the interval for daily photopic light exposure in the current study was between 7:00 a.m. and 11:59 p.m.

This finding of relative high photopic light exposure levels among elderly is in line with a study of Scheuermaier et al. (2010), who compared light exposure patterns between younger individuals (mean age = 23.41, *SD* = 4.57) and elderly individuals (mean age = 66.01, *SD* = 5.83) across all seasons. They found that healthy independently living elderly were exposed to significantly more intense levels of light compared to the younger individuals for all seasons.

Yet, other findings of illuminance levels monitored in studies that assessed light exposure in elderly contradict the current findings. For example Nioi et al. (2017), who measured light exposure levels at the wrist, found that elderly individuals (age range = 72 – 99 years; mean age and SD were not reported) living in care homes in Scotland spent very short durations of time outdoors, resulting in relatively low illuminance levels, particularly during the winter (i.e., a mean illuminance of 466 lux in summer and 65 lux in winter).

A possible explanation of why we found more intense illuminance levels compared to studies that assessed illuminance levels in younger individuals, as well as elderly individuals, is that the elderly in our sample were healthy and lived independently. It is suggested that this

group of elderly was able to go more outdoors compared to elderly living in care houses. Furthermore, because the elderly in our sample were all retired, it is possible that they had more opportunities to go outside during the day compared to the participants of the study of Smolders et al. (2013) who had to be more indoors due to work or study obligations.

Overall, there are few studies conducted that compared light patterns between age groups. All comparisons that were made in the current study are made between studies with different research paradigms. These comparisons indicated that indeed, a difference is expected in the light patterns between age groups. However, one should be cautions with the interpretation of these comparisons. Especially with regard to the different measurement methods that were used. A study of Aarts, van Duijnhoven, Aries and Rosemann (2017) revealed that measurement devices can show very different output values in the same circumstances. Furthermore, the location of where the measurement device is worn (e.g., at wrist or near the eye) matters with regard to the precision of the output value (Aarts et al., 2017). Therefore, more research is required to explore the relationship between light exposure patterns and age groups.

5.2. Light and sleep

In the current study we did not find any significant effects between the average light exposure during the day (7:00 a.m. – 23:59 p.m.) and sleep (quality and timing). However, the average light exposure at different parts of the day did influence sleep. More specifically, exposure to more intense circadian light in the morning (7:00 a.m. – 1:00 p.m.) was associated with better subjective sleep quality, while exposure to more intense circadian light exposure in the evening (7:00 p.m. – 23:59 p.m.) was associated with an increase in sleep duration.

5.2.1. The effect of average daily light exposure on sleep

No significant relationship was found between the average light exposure during the day and sleep (quality and timing). Similar to these results Ichimori et al. (2015), who investigated the relationship between daily illuminance levels and subjective sleep quality among Japanese elderly (mean age = 82.8, *SD* = 5.3) who required care in winter time, did not find any significant relations between light exposure during the day and sleep quality. Notice that light exposure during the day was differently measured compared to the current study. Ichimori et al. (2015) measured illuminance levels with several illuminance loggers that were located in

the living room of each participant, near the pillow on which the participant slept and on the rooftop of a nearby research facility.

In contrast to these results, a study of Hubalek et al. (2010), that investigated the relationship between light exposure during the day and sleep quality in 23 participants (mean age = 38.5, *SD* = 10.6) revealed a positive significant relationship between light exposure during the day and sleep quality of the following night, indicating that exposure to more intense light was associated with a higher sleep quality.

Additionally, a study of Hood, Bruck, and Kennedy (2004), who investigated the relationship between light (measured with a Mini Mitter 2000 Data Logger, near the eye) and nighttime sleep quality in healthy aged people (mean age = 74.18, age range = 65 – 85 year, SD was not reported), found that light exposure above 3000 lux, which can be considered as very bright light, was significantly associated with objective sleep quality of the upcoming night, suggesting that light exposure above 3000 lux increased sleep quality.

These results could indicate that elderly need more light compared to younger people. However, more evidence needs to be gathered to explore this suggestion. To our knowledge there are no studies that investigated the relationship between the average light exposure during the day and sleep timing.

5.2.2. The relation between light exposure at different time spans of the day and sleep

To our knowledge, this is the first field study that explored the effect of light at specific time spans of the day on subjective sleep quality, sleep duration and midsleep in the field. Therefore, the effect of morning, afternoon and evening light in everyday lives, on indicators for sleep quality and sleep timing are still relatively unknown.

The interpretation of our results with regard to the average light exposure at different parts of the day is rather complex. Based on earlier studies that assessed the effect of bright light exposure on sleep timing in the late afternoon to the early evening (Ancoli-Israel & Cooke, 2005; Benloucif et al., 2006), one would expect that light exposure in the evening would cause a phase delay. In our data this would mean that midsleep would increase as a response to the exposure to more intense average circadian light levels in the evening. However, we did not find a significant relationship between the average light exposure in the evening and midsleep. In contrast, we did find an association between an increase in circadian irradiance levels in the evening and an increase in sleep duration. A possible explanation for this comes from a study of Lack and Wright (1993). They investigated the effect of bright light simulations (2500 lux) from 8:00 p.m. to midnight on two sequential days with nine

participants that suffered from insomnia (mean age = 53.4 years, SD was not reported). Their study revealed a phase delay assessed with melatonin and core body temperature. However, only the wake times were affected by these bright light simulations, resulting in an increase in average sleep duration of approximately one hour. It is possible that in the current study also only the wake times were affected by the phase delaying response to more intense light exposure levels in the evening. However, follow-up analyses of the current dataset are required for sleep timing in terms of sleep onset and sleep offset to investigate whether the positive association between light exposure in the evening and sleep duration can be explained by this.

Additionally, earlier studies that assessed the relationship between bright light exposure in the late night and early morning and sleep (Borbély et al., 2016; Benloucif et al., 2006) suggested that bright light exposure during the morning is related to a phase advance in the sleep-wake rhythm. Although we did find a positive relationship between morning circadian irradiance levels and subjective sleep quality, we did not find any relationship between morning circadian irradiance levels and midsleep. It is possible that we did not find any significant effects on the relationship between light exposure at different time spans and midsleep due to the season (i.e., spring) wherein our study took place. A study of Owen and Arendt (1992) suggests that shifts in our circadian rhythm are much stronger during seasons with a short photoperiod (e.g., winter) compared to seasons with a long photoperiod (e.g., summer and spring). Since the current study was assessed during spring it is possible that a phase shift was not found in the current study, but could be found in a study that is conducted during the winter.

Overall, it seems that our results are quite counterintuitive. Based on earlier research it could be suggested that the circadian clock, which plays a crucial role in the regulation of sleep, is most sensitive to light exposure in the morning and evening. Indeed, in the current study, significant associations were found between light exposure and sleep for morning and evening exposure. However, these associations were not very consistent within the study nor always in line with earlier literature.

A possible confounding factor that should be taken into account when interpreting these results is the effect of physical activity. Benloucif et al. (2006) found a positive correlation between morning exercise and sleep quality and between evening exercise and sleep quality. Additionally, Nioi et al. (2017) found that daytime physical activity level was positively associated with sleep efficiency. Because the current study used local clock-time for the different time spans, it could be suggested that participants that received more intense levels

of light exposure in the morning were awake and indeed active, while participants that were asleep were exposed to very low levels of light exposure and were not active. To control for this confounding effect it is suggested for future research to use internal time (i.e., time since midsleep) to create these different time spans instead of local clock time.

Additionally, it should be taken into account that some differences between the objective and subjective sleep data of the current study were found. Further investigation revealed that the Actiware software only calculated one sleep episode, which can be problematic for the sleep pattern of elderly that is characterized by a decrease of the deeper levels of sleep and therefore associated with a disturbed sleeping pattern (i.e., an increase of awakenings during the night; Ancoli-Israel & Cooke, 2005). Indeed, after visual inspection of the actograms that were created by the Actiware software, it became clear that the sleeping patterns of our sample was characterized by awakenings during the night and restless sleep. It could be that this influenced our results. For example, when people sleep restlessly during the night it is possible that they stay in bed for a longer duration of time compared to people that had a good night of sleep, to make up for their disturbed sleep during the night.

In sum, little is known about the underlying mechanisms regarding sleep quality and sleep duration and their relation to light exposure. Some earlier studies did explore the relationship between photopic light exposure (over the time span of a day) and sleep quality and found mixed results (e.g., Ichimori et al., 2015; Hubalek et al., 2010). However, the current study reveals that despite no relationship was found over the course of a day, associations between light exposure and sleep were found at specific times of the day. To compare results of different studies and the effect of light at different times of the day on sleep it is recommended to use the internal time instead of local clock time. Furthermore, for future research it is important to take the disturbed sleeping patterns of elderly into account, and use a measure for objective sleep data that is tuned to the elderly population.

5.3. Light and vitality

Results of the current study revealed structural time-of-day dependent variations in feelings of vitality. No associations were found between light exposure (one hour prior to the assessment of feelings of vitality) and feelings of vitality in the current sample. When looking at the influence of light exposure at specific parts of the day, it was found that light exposure was a significant predictor for feelings of vitality in the morning (8:00 a.m. – 1:00 p.m.).

5.3.1. Associations between light exposure and vitality

Similar to the findings of Smolders et al. (2013) variations in feelings of vitality did occur mainly between measurement occasions and were smallest between days. In contrast to Smolders et al. (2013), no significant association was found between light exposure (over the course of day) and feelings of vitality in the current sample. Besides the study of Smolders et al. (2013), laboratory studies that assessed the effect of daytime light exposure on vitality in relative young samples did also find a significant acute activating effects of exposure to a higher amount of light on subjective vitality and sleepiness. For example, a study of Smolders et al. (2012) assessed the effect of bright light (1000 lx vs. 200 at the eye) on – among others – subjective vitality and sleepiness with a (relative) young sample (mean age = 22, *SD* = 4.0) during regular working hours. Their findings showed that 1-h exposure to more intense light induced higher levels of vitality and lower subjective sleepiness. Furthermore, a laboratory study of Phipps-Nelson et al. (2003) assessed the effect of bright light exposure (1000 lx vs. < 5 lx) in the afternoon on levels of sleepiness in younger individuals (mean age = 25.3, age range = 18 – 35 years, SD was not reported) after sleep restriction during the prior night. Results of this study also showed a significant effect of exposure to bright light exposure on subjective sleepiness, indicating that an increase in daytime bright light exposure was associated with lower levels of sleepiness.

A possible reason for the difference between our findings and the earlier findings in relative young samples is that elderly are less sensitive to light exposure levels regarding their feelings of vitality compared to the younger individuals, as was indicated earlier by Daneault et al. (2016). They conducted a neuroimaging study that investigated the brain responses to blue monochromatic light in younger (mean age = 22.8, *SD* = 4) and elderly individuals (mean age = 61, *SD* = 4.4) and found that the brain areas related to the NIF effects of light had a decreased response in elderly individuals compared to younger individuals, whereas the brain areas that were related to the IF pathway reacted similarly in elderly and younger individuals. However, more research is needed to discover whether indeed there is a causal relationship between a decreased response of vitality and light exposure in elderly.

It should be noted that in the current study the relationship between light exposure and vitality was only measured during spring. Based on results of Huiberts et al. (2017) it is expected that the effects of light exposure on vitality are probably larger during the winter, as was also suggested by Smolders et al. (2013). Therefore, it is possible that there is an association between light exposure and feelings of vitality in elderly, although not observed in the current study.

5.3.2. The association between light exposure at different times of the day and vitality

Light exposure turned out to be a significant predictor for feelings of vitality during the morning in the elderly sample of the current study. This was in line with results of Smolders et al. (2013), who also found a significant relationship between morning light exposure and feelings of vitality. A study that assessed subjective alertness among young participants (mean age = 22.5 years, *SD* = 1.1) found that 2-h bright light exposure in the morning (5:00 a.m. – 7:00 a.m.) was positively associated with subjective alertness (Clodoré et al., 1990), suggesting that acute alerting effect do occur in response to bright light exposure in the morning. In contrast to the study of Smolders et al. (2013) we also investigated the effect of evening light on feelings of vitality. No significant effects were found.

5.3.3. Possible confounds in the relationship between light exposure and vitality

Social interaction, physical effort, mental effort, trait vitality, being outdoors, being in nature and prior napping were significantly and positive related to feelings of vitality. Similar to our results, Smolders et al. (2013) found that social interaction and physical effort were positively associated with vitality. Mental effort, trait vitality, being outdoors and being in nature were not found to be significant predictors of feelings of vitality in the study of Smolders et al. (2013). Moreover, we found that the strength of the prediction of the confounding factors on feelings of vitality differed between the morning, afternoon and evening.

These mixed findings for possible confounds for the relationship between light exposure and vitality suggest that it is possible that these confounds vary between age groups and times of the day. More research is needed to elaborate on these results.

5.4. Light and mood

A positive relationship between light exposure and mood was found in the current study, suggesting that an increase in light exposure was associated with an increase in positive mood. When looking at the effect of light exposure and different time spans of the day, results revealed that an increase in circadian irradiance levels in the morning, as well as the afternoon was associated with an increase in positive mood.

5.4.1. Light exposure (over the time span of a day) and mood

The finding of the association between circadian irradiance levels and mood was in line with earlier studies that found a significant and positive relationship between bright light exposure and mood in mildly seasoned people (mean age = 31 years, *SD* = 8; Aan het Rot et al., 2008) and healthy adults working in an office environment (mean age = 41.2 years, *SD* = 9.0; Patronen & Lonngvist, 2000). It can be suggested that findings of the current study show that light can also play an important role in mood regulations of elderly. However, it should be noted that results of earlier studies on the effect of light exposure on mood are mixed. For example a study of Genhart et al. (1993), that assessed the effect of bright light on mood (2500 lux; for 2.5-h during the morning and 2.5-h during the evening) revealed that bright light was negatively associated with positive mood in elderly woman (mean age = 79 years, *SD* = 8.05). Moreover, Hubalek et al. (2010) did not find any significant effects of light exposure on mood among office employees (mean age = 38.5, *SD* = 10.6). Therefore, more research is required to investigate whether there is indeed a relationship between light exposure and mood in the elderly population.

5.4.2. Light exposure at different time spans of the day and mood

When looking at the effect of light exposure and different time spans of the day, the current study revealed that light exposure was significantly related to positive mood in the morning. This is in line with earlier studies that revealed the antidepressant effect of morning bright light therapy (Lewy et al., 1987; Terman, Terman, Lo & Cooper, 2001).

Besides a significant association between light exposure and mood in the morning we also found a positive and significant relationship between light exposure and mood in the afternoon, indicating that more intense light was associated with better mood in the afternoon.

A study of Avery et al. (2001) seems to support our findings. They investigated the effect of morning and afternoon bright light treatment (2500 lux; for two weeks) in thirty subsyndromal seasonal affective disorder patients (age range = 26 – 52) at their workplace, and found that both, morning and afternoon bright light significantly improved mood.

5.4.3. Possible confounds in the relationship between light exposure and mood in elderly

Findings of the current study suggested that other factors within the daily lives of the elderly sample did affect the relationship between light exposure on mood. More specifically, when we added possible confounding factors such as social interaction, being with others and trait vitality the association between light exposure and mood became less profound. A study of

Grandner et al. (2006), who investigated the effect of light exposure in older woman (mean age = 67.68, *SD* = 7.86), supports this finding. They revealed a positive relationship between light exposure, especially in the morning, and social functioning, and emphasized the importance of the mediating effect of social function on the relationship between light exposure and mood. Although we did not test for a possible mediation, it may be possible that this mediating effect does exist. Therefore, it is suggested that future research should take these possible confounds and mediators into account.

5.5. Strengths and limitations

A strength of the current study was that light exposure, sleep and markers of well-being were measured during a relative long period of time (i.e., seven days). Also, these measurements took place 24-h a day, which enabled us to investigate habitual light patterns over the 24-h sleep-wake cycle in the everyday life of elderly. In other words, inherent to field studies, the ecological validity of the current study was high.

Another strength of the current study was the use of the random sampling method for the ESM questionnaires. The advantage of a random sampling is that it decreases the chance of reactivity in an ESM study. Despite the random sampling method, the response rate to the ESM questionnaires was very high (95.71%)

Compared to Smolders et al. (2013), the current study had an advantage with regard to social jetlag. Smolders et al. (2013) asked their participants to fill in their ESM questionnaire every hour from 8:00 a.m. to 8:00 p.m., which caused participants that normally woke up later than 8:00 a.m. having to wake up earlier than they were used to. In the current study, on the contrary, the participants were not asked to wake up earlier than they were used to due to the random sampling that was used.

It should be noted that the sample size (n = 20) was only sufficient to detect medium to large effects in the current study. Due to the nested structure of the data the number of measures that were taken into account were relatively large for the analyses regarding mood and vitality, however, with regard to sleep only one measurement per day was used, which reduced the power of these analyses. Moreover, the power of the analyses with regard to specific time spans is smaller compared to analyses that take into account all measurements during the day. Especially the power of the analyses for well-being that were done for evening light exposure was relatively low compared to the morning and afternoon analyses,

because of the limited number light measurements during the evening. This should be kept in mind when interpreting the results in terms of statistical significance.

It is possible that our sample was slightly biased. Part of the participants were recruited at the sport center of Eindhoven University of Technology, therefore it is possible that these participants were more active compared to elderly that do not exercise regularly. However, since this group consists of only thirty percent of the total sample, it is expected that this did not influence the data considerably. Furthermore, when looking at the overall vitality scores of the elderly sample, it seems that the current sample consisted in general of relatively vital elderly. Therefore, it should be noted that it is possible that this sample is not representative for the entire elderly population. Additionally, due to the use of smartphones, Actiwatches and light loggers, it could be that only elderly who were interested in new technologies or at least were not afraid of new technologies, participated in the study.

The current study had an explorative character. Due to the correlational nature of the study, causal relationships cannot be established as the variables were only observed and were not experimentally controlled or manipulated. However, the light measures that were associated with the measurements of sleep and well-being did all precede the dependent measures (e.g., sleep, mood and vitality). Therefore it can be argued that the results do allow to some extend for causal relationships. Moreover, inherent to field studies, which are characterized by a decreased control over potential confounding variables, it is possible that other covariates that were not measured within the current study influenced the relationship between light exposure and sleep, vitality and mood.

5.6. Future research

In the current study, local clock time was used to investigate the daily patterns of light, sleep, vitality, and mood, and to investigate the relationship of light exposure on sleep and well-being at different time spans. Specifically local clock time was chosen to enable the comparison of our results with earlier studies that investigated daily patterns of light and relationships between light exposure and sleep and well-being in younger individuals, such as the study by Smolders et al. (2013). However, the use of local clock time also meant including light measurements in the morning and evening while participants were asleep. It could be argued that this affected the results, because these light levels were very low and therefore influenced the overall light exposure levels of the morning and evening measurements. Additionally, with the use of local clock time we did not take into account the

different sleep-wake rhythms between individuals, which could have influenced our results. Moreover, with regard to the sleep analyses, by using local clock time we did not take into account the natural sleeping patterns of participants that were represented by chronotype. Future research is needed that uses internal time instead of local clock time to explore whether the same effects hold for the relationship between light exposure, well-being and sleep at various parts of the day. Furthermore, it should be noted that the intervals that were used for the analyses of the effect of light exposure at different time spans were rather arbitrary and relatively large. Therefore, future research could look at smaller intervals that are tuned to individuals or could use different weight factors for light exposure during the day.

During the current study we discovered that the objective sleep data of the actiwatches did not always match the subjective sleep data that was obtained by the sleep diaries. Therefore, it is important to take this into account during future research and potentially use an algorithm that is tuned to the elderly population.

Last, not all measured variables were analyzed in the current study. For example, subjective alertness and tension were also measured with the ESM. For future research, the current dataset could be used to explore more patterns in the data with respect to these variables. Furthermore, the current study used two datasets: one for daily light exposure and the sleep variables, and one for the experience sampling data and the light exposure data of one hour prior to the questionnaires of the ESM. For future research it could be interesting to combine these datasets and to explore for example the mediating effect of sleep timing on feelings of vitality.

5.7. Applications for findings of the current study

Although more research is needed to quantify our results, the current study suggests that light exposure at specific time spans of the day is able to support well-being and sleep in elderly. Our research shows that more intense circadian irradiance levels in the morning are beneficial for feelings of vitality, mood and subjective sleep quality in elderly individuals. Subsequently, more intense levels of light in the afternoon seem to improve mood in elderly individuals as well. Moreover, our study suggests that more intense light levels in the evening affect sleep duration. However, more research is needed for this latter finding to determine whether increased light exposure in the evening is beneficial or disadvantageous for the overall sleep timing and quality of elderly. Nevertheless, the current findings can be used

prevent sleep problems in elderly and to support their well-being. For example, light settings within their homes could be adjusted in such a way that more intense light levels are presented in the morning and afternoon. Moreover, these light settings could even be personalized to their own sleep-wake rhythm to optimize the results on their well-being and sleep. Besides, these personalized light settings within their homes, it could also be considered to encourage elderly to go more outside to receive more intense light exposure levels. Earlier research suggests that daylight illuminance can reach up to 100 000 lux, whereas indoor lights in living rooms are typically between 50 and 200 lux (Turner & Mainster, 2008). Technology could be used to encourage elderly to go outdoors, for example by using a smartphone application that reminds and steers them at specific times of the day to go outside.

5.8. Conclusion

The current study contributes to a better understanding of the influence of light exposure on well-being and sleep in the everyday life of healthy independently living elderly. It has yielded new insights in the light exposure patterns of elderly, and explored which times were best to support well-being and sleep with light interventions in elderly. Light patterns of daily light exposure were explored and compared with the study of Smolders et al. (2013). These comparisons indicated similar variations in light exposure patterns between the elderly individuals of the current study and the younger sample in Smolders et al. (2013). Furthermore, comparisons indicated that the elderly of the current study were, on average, exposed to more intense light settings during the day compared to younger sample. However, since the studies that we compared used different research paradigms, more research is required to establish these indications.

Additionally, the connection between light exposure patterns and sleep behavior in the current study was investigated. Results suggested a relation between light exposure in the morning and evening, and sleep behavior of elderly individuals. However, the relationships that were found between morning and evening light exposure, and sleep behavior were somewhat counterintuitive. Therefore, more research is required to explore these relations more pronouncedly, for example by focusing on internal time instead of local clock time and explore also other markers for sleep timing.

Subsequently, a relationship between light exposure and vitality in the morning was found for elderly in the current study, similar to Smolders et al. (2013). However, the current study

indicated that the relationship between light exposure and vitality during the day was less profound in the elderly sample of the current study compared to the younger sample in Smolders et al. (2013).

Last, the current study investigated which time spans of the day (morning, afternoon and evening) where best to support elderly with light interventions in order to improve their well-being and sleep quality. Results of the current study suggested that especially light in the morning was beneficial to improve both, well-being (vitality and mood), and sleep quality. Also, it was suggested that light interventions in the afternoon would improve mood as well.

Overall, the current study contributed to a better understanding of the connection between light exposure during the day and well-being and sleep in elderly. Although, more research is needed, results of the current study seem promising with regard to the potential beneficial effect of light (interventions) for well-being and sleep in elderly.

6. References:

aan het Rot, M., Moskowitz, D.S., & Young, S.N. (2008). Exposure to bright light is associated

with positive social interaction and good mood over short time periods: A naturalistic study in mildly seasonal people. *Journal of Psychiatric Research, 42,* 311 - 319.

Aarts, M. P., van Duijnhoven, J., Aries, M. B., & Rosemann, A. L. (2017). Performance of personally worn dosimeters to study non-image forming effects of light: Assessment methods. *Building and Environment, 117*, 60-72. doi: 10.1016/j.buildenv.2017.03.002

Åkerstedt, T. & Gillberg, M. (1990). Subjective and Objective Sleepiness in the Active Individual. *International Journal Of Neuroscience, 52*(1-2), 29-37. http://dx.doi.org/10.3109/00207459008994241

Ancoli-Israel, S., & Cooke, J.R. (2005). Prevelance and comorbidity of insomnia and effect on functioning in elderly populations. *Journal of the American Gereatrics Society, 53*(7). S264 - S271.

Ancoli-Israel, S., Ayalon, L., & Salzman C. (2008). Review: Sleep in the elderly: Normal variations and common sleep disorders. *Harvard Review Psychiatry, 16*(5). 279-286.

Avery, D. H., Kizer, D., Bolte, M. A., & Hellekson, C. (2001). Bright light therapy of subsyndromal seasonal affective disorder in the workplace: morning vs. afternoon exposure. *Acta Psychiatrica Scandinavica, 103*(4), 267-274.

Barker, F.M. & Brainard, G.C. (1991). *The direction of spectral transmittance of the excised human lens as a function of age*, FDA 785345 0090 RA, US Food and Drug Administration: Washington DC.

Benloucif, S., Green K., Hermite-Balériaux, M.L., Weintraub S., Wolfe L.F., & Zee P.C. (2006). Responsiveness of the aging circadian clock to light. *Neurobiology of Aging, 27*. 1870-1879.

Beurkens, A. J. H. M., Bültmann, U., Kant, I., Vercoulen, J. H. M. M., Bleijenberg, G., & Swaen, G. M. H. (2000). Fatigue among working people: Validity of a questionnaire measure. *Occupational and Environmental Medicine, 57*, 353 – 357, doi: 10.1136/oem.57.5.353.

Bjorvatn, B., Stangenes, K., Øyane, N., Forberg, K., Lowden, A., Holsten, F., & Åkerstedt, T. (2007). Randomized placebo-controlled field study of the effects of bright light and melatonin in adaptation to night work. *Scandinavian journal of work, environment & health*, 204-214.

Borbély, A.A., Daan, S., Wirz-Justice, A., & Deboer, T. (2016). The two-process model of sleep regulation: a reappraisal. *Journal of Sleep Research, 25*, 131-143.

Brainard, G. C., Hanifin, J. P., Greeson, J. M., Byrne, B., Glickman, G., Gerner, E., & Rollag, M. D. (2001). Action spectrum for melatonin regulation in humans: evidence for a novel circadian photoreceptor. *Journal of Neuroscience, 21*(16), 6405-6412.

Broadbent, D. E., Cooper, P. F., FitzGerald, P., & Parkes, K. R. (1982). The cognitive

failures questionnaire (CFQ) and its correlates. *British journal of clinical psychology, 21*(1), 1-16.

Buysse, D. J., Reynolds, C. F., Monk, T. H., Berman, S. R., & Kupfer, D. J. (1989). The Pittsburgh Sleep Quality Index: A new instrument for psychiatric practice and research. *Psychiatry Research, 28,* 193 - 213.

Cajochen, C. (2007). Alerting effects of light. Sleep Medicine Reviews, 11. 453-464.

Cajochen, C., Zeitzer, J.M., Czeisler, C.A., & Dijk, D. (2000). Dose-response relationship for light intensity and ocular and electroencephalographic correlates of human alertness. *Behavioural Brain Research, 115,* 75-83.

Cajochen, C., Münch, M., Kobialka, S., Kräuchi, K., Steiner, R., Oelhafen, P., Orgül, S. & Wirz-Justice, A. (2005). High sensitivity of human melatonin, alertness, thermoregulation, and heart rate to short wavelength light. *J Clin Endocrinol Metab, 90*(1), 1311 – 1316.

Chellappa, S.L. & Cajochen, C. (2010). *The circadian clock and the homeostatic hourglass: Two timepieces controlling sleep and wakefulness*. In A. Urs (Ed.), The circadian clock (pp. 195 - 228). New York, NY: Springer.

Clodoré, M., Foret, J., Benoit, O., Touitou, Y., Aguirre, A., Bourard, G., & Touitou, C. (1990).

Psychophysiological effects of early morning bright light exposure in young adults. *Psychoneuroendocrinology, 15*(2), 193 – 205.

Czeisler, C.A., Shanahan, T.L., Klerman, E.B., Martens, H., Brotman, D.J., Emens, J.S., Klein,

T., & Rizzo, J.F. (1995). Suppression of melatonin secretion in some blind patients by exposure to bright light. *N Engl J Med., 332,* 6 – 11.

Daneault, V., Dumont, M., Massé, É., Vandewalle, G., & Carrier, J. (2016). Light-sensitive brain pathways and aging. *Journal of Physiological Anthropology, 35*(9), doi: 10.1186/s40101-016-0091-9

Dijk, D. & Archer, S.N. (2010). PERIOD3, circadian phenotypes, and sleep homeostasis. *Sleep*

Medicine Review, 14(3), 151 – 160.

Dittmar, M. (2001). Changing colour preferences with ageing: A comparative study on younger

and older native Germans aged 19-90 years. *Gerontology, 47,* 219 – 226.

Echt, K.V. (2002). Designing Web-Based Health Information for Older Adults: Visual

Considerations and Design Directives. In Morrell, R.W. (Ed.) *Older Adults, Health Information and the World Wide Web* (pp. 73-74). Mahwah, New Jersey: Lawrence Erlbaum Associates.

Foley, D.J., Monjan, A.A., Brown, S.L., Simonsick, E.M., Wallace, R.B. & Blazer, D.G. (1995). Sleep complaints among elderly persons: An epidemiological study of three communities. *Sleep, 18*(6), 425 – 432.

Folstein, M. F., Folstein, S. E., & McHugh, P. R. (1975). "Mini-mental state": a practical method for grading the cognitive state of patients for the clinician. *Journal of psychiatric research, 12*(3), 189-198.

Gabel, V., Maire, M., Reichert, C. F., Chellappa, S. L., Schmidt, C., Hommes, V. Viola, A.U. & Cajochen, C. (2013). Effects of artificial dawn and morning blue light on daytime cognitive performance, well-being, cortisol and melatonin levels. *Chronobiology international, 30*(8), 988-997.

Gasio, P.F., Kräuchi, K., Cajochen, C., van Someren, E., Amrhein, I., Pache, M., Savaskan, E.,

Wirz-Justice, A. (2003). Dawn–dusk simulation light therapy of disturbed circadian rest–activity cycles in demented elderly. *Experimental Gerontology, 38,* 207–216.

Genhart, M. J., Kelly, K. A., Coursey, R. D., Datiles, M., & Rosenthal, N. E. (1993). Effects of bright light on mood in normal elderly women. *Psychiatry research*, *47*(1), 87-97.

Giménez, M.C., Beersma, D.G.M., Bollen, P., van der Linden, M.L. & Gordijn, M.C.M. (2014). Effects of a chronic reduction of short-wavelength light input on melatonin and sleep patterns in humans: Evidence for adaptation. *Chronobiology International.* doi: 10.3109/07420528.2014.893242

Gradisar, M., Dohnt, H., Gardner, G., Paine, S., Starkey, K., Menne, A., ... & Trenowden, S. (2011). A randomized controlled trial of cognitive-behavior therapy plus bright light therapy for adolescent delayed sleep phase disorder. *Sleep, 34*(12), 1671-1680.

Grandner, M.A., Kripke D.F., & Langer, R. D. (2006). Light exposure is related to social and emotional functioning and to quality of life in older woman. *Psychiatry Research, 143,* 35-42.

Herljevic, M., Middleton, B., Thapan, K. & Skene, D.J. (2005). Light induced melatonin suppression Age-related reduction in response to short wavelength light. *Experimental Gerontology, 40,* 237-242.

Hood, B., Bruck, D., & Kennedy, G. (2004). Determinants of sleep quality in the healthy

aged: the role of physical, psychological, circadian and naturalistic light variables. *Age and Ageing*, *33*, 159 – 165. doi: 10.1093/ageing/afh051

Hubalek, S., Brink, M., & Schierz, C. (2010). Office workers' daily exposure to light and its influence on sleep quality and mood. *Lighting Research and Technology*, *42*, 33-50.

Huiberts, L.M., Smolders, K.C.H.J. & de Kort, Y.A.W. (2015). Shining light on memory: Effects of bright light on working memory performance. *Behavioral brain research, 294,* 234 – 245.

Huiberts, L.M., Smolders, K.C.H.J. & de Kort, Y.A.W. (2016). Non-image forming effects of illuminance level: Exploring parallel effects on physiological arousal and task performance. *Physiology & Biology, 16*, 129 – 139.

Huiberts, L. M., Smolders, K. C. H. J., & De Kort, Y. A. W. (2017). Seasonal and time-of-day variations in acute non-image forming effects of illuminance level on performance, physiology, and subjective well-being. *Chronobiology international*, 1-18.

Ichimori, A.,Tsukasaki, K., & Koyama E. (2015). Illuminance, subjective sleep quality, and psychosomatic health in elderly individuals requiring care: A survey of Japan's Hokuriku region in winter. *Journal of Community Health Nursing, 32*, 104-114.

Kaida, K., Takahashi, M. & Otsuka, Y. (2007). A short nap and natural bright light exposure improve positive mood status. *Industrial Health, 45*, 301 – 308.

Knez, I., & Kers, C. (2000). Effects of indoor lighting, gender, and age on mood and cognitive

performance. *Environment and Behavior*, *32*(6). 817-831.

Kretschmer, V., Schmidt, K-H., & Griefahn, B. (2012). Bright light effects on working memory, sustained attention and concentration of elderly night shift workers. *Lighting Res. Technol. 44*. 316 – 333.

Kuijsters, A., Redi, J., de Ruijter, B., & Heynderikx, I. (2015). Lighting to make you feel better:

Improving the mood of elderly people with affective ambiences. *Plos ONE, 10*(7), doi: 10.1371/journal.pone.013273

Kuijsters, A., Redi, J., de Ruijter, B., Seuntiëns, P., & Heynderikx, I. (2015). Affective ambiences created with lighting for older people. *Lighting Research and Technology, 47*, 859-875.

Lack, L., & Wright, H. (1993). The effect of evening bright light in delaying the circadian rhythm and lengthening the sleep of early morning awakening insomniacs. *Sleep, 16*(5), 436 – 443.

LeGates, T.A., Fernandez, D.C., & Hattar, S. (2014). Light as a central modulator of circadian

rhythms, sleep and affect. *Nat. Rev. Neurosci., 15*(7), 443 – 454.

Lewy, A. J., Sack, R. L., Miller, L. S., & Hoban, T. M. (1987). Antidepressant and circadian phase-shifting effects of light. *Science*, *235*, 352-354.

Lockley, S.W., Brainard, G.C., Czeisler, C.A. (2003). High sensitivity of the human circadian melatonin rhythm to resetting by short wavelength light. *J Clin Endocrinol Metab, 88*(9). 4502-4505.

Lockley, S. W., Evans, E. E., Scheer, F. A., Brainard, G. C., Czeisler, C. A., & Aeschbach, D.

(2006). Short-wavelength sensitivity for the direct effects of light on alertness, vigilance, and the waking electroencephalogram in humans. *Sleep, 29*(2), 161-168.

Lowden, A., Åkerstedt, T. & Wibom, R. (2004). Suppression of sleepiness and melatonin by bright light exposure during breaks in night work. *Journal of sleep research, 13*(1), 37 – 43.

Lucas, R. J., Peirson, S. N., Berson, D. M., Brown, T. M., Cooper, H. M., Czeisler, C. A., Figueiro, M.G., Gamlin, P.D., Lockley, S.W., O'Hagan, J.B., Price, L.L.A., Provencio, I., Skene, D.J. & Brainard, G.C. (2014). Measuring and using light in the melanopsin age. *Trends in neurosciences, 37*(1), 1-9.

Mackenbach, J., 2010, 'Ziekte in Nederland', Elsevier Gezondheidzorg, Amsterdam.

Mather, G. (2009). *Foundations of sensation and perception* (2e ed.). Hove, United Kingdom:

Psychology Press.

Monk, T.H. (2005). Aging human circadian rhythms: Conventional wisdom may not alway be

right. *Journal of biological rhythms, 20*(4), 366-374.

Najjar, R.P., Chiquet, C., Teikari, P., Comut, P., Claustrat, B., Denis, P., Cooper, H.M., & Gronfier, C. (2014). Ageing of non-visual spectral sensitivity to light in humans: Compensatory mechanisms? *PLos ONE, 9*(1). 10.1371/journal.pone.0085837

Nioi, A., Roe, J., Gow, A., McNair, D., & Aspinall, P. (2017). Seasonal differences in light exposure and the associations with health and well-being in older adults living: An explorative study. *Health Environments Research & Design Journal, 0*(00), 1-16.

Obayashi, K., Saeki, K., Iwamoto, J., Ikada, Y., & Kurumatani, N. (2013). Exposure to light at

night and risk of depression in the elderly. *Journal of Affective Disorders, 151*, 331-336.

Owen, J., & Arendt, J. (1992). Melatonin suppression in human subjects by bright and dim light in Antarctica: time and season-dependent effects. *Neuroscience letters*, *137*(2), 181-184.

Phipps-Nelson, J., Redman, J. R., Dijk, D. J., & Rajaratnam, S. M. (2003). Daytime exposure to bright light, as compared to dim light, decreases sleepiness and improves psychomotor vigilance performance. *Sleep, 26*(6), 695-700.

Patronen, T., & Lönnqvist, J. (2000). Bright light improves vitality and alleviates distress in healthy people. *Journal of Affective Disorders, 57*, 55-61.

Postma, I.R., Bouma, A., Ankersmit, I.F., & Zeeman, G.G. (2014). Neurocognitive functioning following preeclampsia and eclampsia: a long-term follow-up study. *American Journal of Obstetrics & Gynecology, 211*(1), e1 – 9.

Purves, D., Augustine, G. J., Fitzpatrick, D., Katz, L. C., LaMantia, A., McNamara, J. O., & Williams, S. M. (2001). *Neuroscience* (2nd ed.). Sunderland (MA), United Kingdom: Sinauer Associates.

Pinchasov, B. B., Shurgaja, A. M., Grischin, O. V., & Putilov, A. A. (2000). Mood and energy regulation in seasonal and non-seasonal depression before and after midday treatment with physical exercise or bright light. *Psychiatry research*, *94*(1), 29-42.

Reichert, C. F., Maire, M., Schmidt, C., & Cajochen, C. (2016). Sleep-wake regulation and its impact on working memory performance: the role of adenosine. *Biology, 5*(1), 11, doi: 10.3390/biology5010011.

Revell, V.L., Arendt, J., Fogg, L.F. & Skene, D.J. (2006). Alerting effects of light are sensitive to very short wavelengths. *Neuroscience Letters*. doi:10.1016/j.neulet.2006.01.032

Riemersma-Van Der Lek, R. F., Swaab, D. F., Twisk, J., Hol, E. M., Hoogendijk, W. J., & Van Someren, E. J. (2008). Effect of bright light and melatonin on cognitive and noncognitive function in elderly residents of group care facilities: a randomized controlled trial. *Jama, 299*(22), 2642-2655.

Rijksinstituut voor Volksgezondheid en Milieu. (n.d.). Totale zorguitgaven 2011 - 2030.

Retrieved August 5, 2017, from http://www.eengezondernederland.nl/Trends_in_de_toekomst/Zorg/Zorguitgaven

Roenneberg, T., Kuehne, T., Pramstaller, P. P., Ricken, J., Havel, M., Guth, A., et al. (2004). A marker for the end of adolescence. *Current Biology, 14,* 1038 - 1039. http://dx.doi.org/10.1016/j.cub.2004.11.039.

Roenneberg, T., Wirz-Justice, A., & Merrow, M. (2003). Life between clocks: Daily temporal patterns of human chronotypes. *Journal of Biological Rhythms, 18*, 80 - 90. doi: /10.1177/0748730402239679.

Ryan, R. M., & Frederick, C. (1997). On energy, personality, and health: Subjective vitality as a dynamic reflection of well-being. *Journal of personality*, *65*(3), 529-565.

Scheuermaier, K., Laffan, A. M., & Duffy, J. F. (2010). Light exposure patterns in healthy older and young adults. *Journal of biological rhythms*, *25*(2), 113-122.

Smolders, K. C. H. J. (2013). *Daytime light exposure: effects and preferences Eindhoven: Technische Universiteit Eindhoven*. doi: 10.6100/IR762825

Smolders, K.C.H.J., de Kort, Y.A.W. & Cluitmans, P.J.M. (2012). A higher illuminance induces alertness even during office hours: Findings on subjective measures, task performance and heart rate measures. *Physiology & Behavior, 107,* 7-16.

Smolders, K.C.H.J., de Kort, Y.A.W., & van den Berg, S.M. (2013). Daytime light exposure and feelings of vitality: Results of a field study during regular weekdays. *Journal of Environmental Psychology, 36*. 270 - 279.

Terman, J. S., Terman, M., Lo, E. S., & Cooper, T. B. (2001). Circadian time of morning light administration and therapeutic response in winter depression. *Archives of general psychiatry*, *58*(1), 69-75.

Turner, P.L., & Mainster, M.A. (2008). Circadian photoreception: ageing and the eye's important role in systemic health. *Britisch Journal of Ophthalmology, 92*(11). 1439 - 1444.

Van Someren, E.J.W. (2000). Circadian and sleep disturbances in the elderly. *Experimental Gerontology, 35,* 1229 – 1237.

Van Someren, E. J., Kessler, A., Mirmiran, M., & Swaab, D. F. (1997). Indirect bright light improves circadian rest-activity rhythm disturbances in demented patients. *Biological psychiatry, 41*(9), 955-963.

Van der Zee, K. I., Sanderman, R., Heyink, J. W., & de Haes, H. (1996). Psychometric qualities of the RAND 36-Item health survey 1.0: A multidimensional measure of general health status. *International Journal of Behavioral Medicine, 3*, 104 - 122.

Van Duin, C., & Stoeldraijer, L. (2012). Bevolkingsprognose 2012-2060: Langer leven, langer werken (Centraal Bureau voor de Statistiek, Den Haag/Heerlen). Retrieved from https://www.cbs.nl/NR/rdonlyres/DB34C87D-823D-49B4-AE3A-A3DE66CDCB1A/0/2012bevolkingprognoselangerlevenlangerwerken.pdf

Veitch, J. A., & McColl, S. L. (1995). Modulation of fluorescent light: Flicker rate and light source effects on visual performance and visual comfort. *Lighting Research and Technology, 27*, 243-256.

Wittman, M., Dinich, J., Merrow, M., & Roenneberg, T. (2006). Social jetlag: Misalignment of biological and social time. *Chronobiology International, 23*(1&2), 497 – 509.

Yang Y., Thompson, K., Burns S.A. (2002). Pupil location under mesopic, photopic, and pharmacologically dilated conditions. *Invest Ophthalmol Vis Sci, 43*, 2508 – 12.

Zeitzer, J. M., Dijk, D. J., Kronauer, R. E., Brown, E. N., & Czeisler, C. A. (2000). Sensitivity of the human circadian pacemaker to nocturnal light: melatonin phase resetting and suppression. *The Journal of physiology, 526*(3), 695-702.

Zorg voor Beter. (2017, April 22). Cijfers: vergrijzing en toenemende zorg. Retrieved from http://www.zorgvoorbeter.nl/ouderenzorg/hervorming-zorg-cijfers-vergrijzing.html

7. Appendices

Appendix 1.

Vragenlijst over uw ogen (m.b.t. onderzoek licht en slaap)

Wat is uw naam (voornaam + achternaam)?

Draagt u een bril of lenzen?
[Ja/nee]

Indien ja: Welke sterkte hebben uw brilglazen / uw lenzen?
Draagt u geen bril of lenzen? Dan kunt u deze vraag overslaan

Heeft u uw ogen laten laseren?
[Ja/nee]

Heeft u in het verleden een oogziekte gehad?
[Ja/nee]

Indien ja, welke oogziekte heeft u in het verleden gehad?
Indien u geen oogziekte heeft gehad kunt u deze vraag overslaan

Pagina 2: Huidige staat van het oog
Vul voor de onderstaande symptomen in of u hier de afgelopen maand last van heeft gehad:

Lijdt u op dit moment aan een (gediagnosticeerde) oogziekte?
[Ja/nee]

Indien ja, aan welke oogziekte lijdt u?
Wanneer u niet lijdt aan een oogziekte kunt u deze vraag overslaan.
[…]

Brandende ogen
Helemaal niet – Extreem veel (schaal: 1-5)

Jeukende ogen
Helemaal niet – Extreem veel (schaal: 1-5)

Zanderig gevoel in de ogen
Helemaal niet – Extreem veel (schaal: 1-5)

Pijn aan de ogen
Helemaal niet – Extreem veel (schaal: 1-5)

Gevoeligheid voor licht
Helemaal niet – Extreem veel (schaal: 1-5)

Rode ogen
Helemaal niet – Extreem veel (schaal: 1-5)

Tranende ogen
Helemaal niet – Extreem veel (schaal: 1-5)

Droge ogen
Helemaal niet – Extreem veel (schaal: 1-5)

Vertekend beeld
Dit wordt bijvoorbeeld gekenmerkt door rechte lijnen die krom worden en vlakken oppervlakten lijken een beetje op te bollen.
Helemaal niet – Extreem veel (schaal: 1-5)

Moeite met het zien van contrast
Kleuren worden vager. Het is voor u lastig om een wit vel op een witte tafel op te merken en/of gekleurde letters op een gekleurde achtergrond zijn voor u moeilijk te lezen.
Helemaal niet – Extreem veel (schaal: 1-5)

Huidige staat van het oog
In de volgende vragen ziet u steeds een afbeelding met daarbij een omschrijving. We zouden er graag achter komen of uw zicht vergelijkbaar is met een van deze afbeeldingen. Het kan zijn dat u het beeld herkent maar dat het niet exact overeenkomt. In dat geval kunt u in het tekstvlak nog een aantekening zetten met een toelichting.

Afbeelding 1

Onderstaande afbeelding kenmerkt zich door zicht waarbij u wazig en/of minder contrast ziet (zelfs als uw zicht gecorrigeerd is met een bril/lenzen/laser). Verder kan het zijn dat, wanneer u met één oog kijkt, u dubbel ziet of schaduwbeeld ziet. Geef hieronder aan of dit kenmerkend is voor uw zicht:
[Ja/nee/other]

Afbeelding 2

Onderstaande afbeelding kenmerkt zich door vermindering van het zicht en het zien van wazige vlekken. Verder kan het voorkomen dat onderdelen of details voor u lastig te zien en/of te onderscheiden zijn. Vaak wordt dit omschreven als een soort koker-visie, het centrum van het gezichtsveld blijft scherp maar aan de zijkanten wordt het zicht wazig of mist u details. Geef hieronder aan of dit kenmerkend is voor uw zicht:
[Ja/nee/other]

Afbeelding 3

Onderstaande afbeelding kenmerkt zich door verlies van zicht in het centrum van het gezichtsveld. Het kan lastig voor u zijn om uw ogen scherp te stellen op een bepaald punt. De gezichtssterkte gaat heel snel achteruit en het dragen van een bril lost het probleem niet op. Geef hieronder aan of dit kenmerkend is voor uw zicht:
[Ja/nee/other]

Afbeelding 4

Onderstaande afbeelding kenmerkt zich door vlekken op het gezichtsveld en/of verlies van zicht op delen van het gezichtsveld. Geef hieronder aan of dit kenmerkend is voor uw zicht: [Ja/nee/other]

Appendix B.

Wat is uw geslacht? O man O vrouw

Wat is uw leeftijd? ……

Geef per stelling aan in welke mate deze voor u *in het algemeen* van toepassing is.

	Helemaal geen	Weinig	Nogal	Veel	Erg veel
Hoeveel problemen hebt u met uw ogen bij blootstelling aan fel licht?	O	O	O	O	O
Hoeveel last hebt u van hoofdpijn bij blootstelling aan fel licht?	O	O	O	O	O
Hebt u last van nachtblindheid	O	O	O	O	O
Gebruikt u een zonnebril omdat het licht te fel is?	O	O	O	O	O

	Helemaal niet juist			Beetje juist			Zeer juist
Ik voel me levendig en vitaal.	O	O	O	O	O	O	O
Ik voel me niet erg energiek.	O	O	O	O	O	O	O
Soms bruis ik van de energie.	O	O	O	O	O	O	O
Ik zit vol energie en levenslust.	O	O	O	O	O	O	O
Ik kijk uit naar elke nieuwe dag.	O	O	O	O	O	O	O
Ik voel me bijna altijd alert en wakker.	O	O	O	O	O	O	O
Ik voel me energiek.	O	O	O	O	O	O	O

Wat vind u over het algemeen van uw gezondheid?

Uitstekend	Zeer goed	Goed	Matig	Slecht
O	O	O	O	O

	Volkomen juist	Grotendeels juist	Weet ik niet	Grotendeels onjuist	Volkomen onjuist
Ik lijk makkelijker ziek te worden dan andere mensen	O	O	O	O	O
Ik ben net zo gezond als andere mensen die ik ken	O	O	O	O	O
Ik verwacht dat mijn gezondheid op korte termijn achteruit zal gaan	O	O	O	O	O
Mijn gezondheid is uitstekend	O	O	O	O	O

Geef voor iedere stelling aan of deze wel of niet voor u van toepassing was gedurende de laatste twee weken.

	Ja, dat klopt						Nee, dat klopt niet
Ik voel me fit	O	O	O	O	O	O	O
Ik zit vol activiteit	O	O	O	O	O	O	O
Nadenken kost me moeite	O	O	O	O	O	O	O
Lichamelijk voel ik me uitgeput	O	O	O	O	O	O	O
Ik heb zin om allerlei leuke dingen te gaan doen	O	O	O	O	O	O	O
Ik voel me moe	O	O	O	O	O	O	O
Ik vind dat ik veel doe op een dag	O	O	O	O	O	O	O

	Ja, dat klopt						Nee, dat klopt niet
Als ik ergens mee bezig ben, kan ik mijn gedachten er goed bijhouden	O	O	O	O	O	O	O
Ik voel me slap	O	O	O	O	O	O	O
Ik vind dat ik weinig doe op een	O	O	O	O	O	O	O

dag							
Ik kan me goed concentreren	O	O	O	O	O	O	O
Ik voel me uitgerust	O	O	O	O	O	O	O
Het kost me moeite ergens mijn aandacht bij te houden	O	O	O	O	O	O	O
Lichamelijk voel ik me in een slechte conditie	O	O	O	O	O	O	O
Ik zit vol plannen	O	O	O	O	O	O	O
Ik ben gauw moe	O	O	O	O	O	O	O
Er komt weinig uit mijn handen	O	O	O	O	O	O	O
De zin om dingen te ondernemen ontbreekt mij	O	O	O	O	O	O	O
Mijn gedachten dwalen gemakkelijk af	O	O	O	O	O	O	O
Lichamelijk voel ik me in een uitstekende conditie	O	O	O	O	O	O	O
	Ja, dat klopt						Nee, dat klopt niet

De volgende vragen hebben betrekking op uw slaapgewoonten tijdens de afgelopen maand. De antwoorden zouden een zo nauwkeurig mogelijke weergave moeten zijn van de meerderheid van de dagen en nachten in de afgelopen maand.

Hoe laat ging u 's avonds gewoonlijk naar bed gedurende de afgelopen maand?

Gebruikelijke bedtijd: ..... : ……...

Hoeveel minuten duurde het de afgelopen maand gewoonlijk elke nacht voordat u in slaap viel?

Aantal minuten: ……...

Hoe laat stond u de afgelopen maand 's ochtends gewoonlijk op?

Gebruikelijk tijdstip van opstaan: ..... : ……...

Hoeveel uren hebt u de afgelopen maand 's nachts daadwerkelijk geslapen? (Dat aantal kan verschillen van het aantal uur dat u in bed doorgebracht hebt.)

Aantal uren slaap per nacht: .....

Hoe vaak had u de afgelopen maand moeite met slapen omdat u:

	Niet gedurende afgelopen maand	Minder dan 1 keer per week	1 of 2 keer per week	3 keer per week of vaker
niet binnen 30 minuten kon slapen	O	O	O	O
midden in de nacht of 's ochtends vroeg wakker werd	O	O	O	O
op moest staan om naar het toilet te gaan	O	O	O	O
niet comfortabel kon ademen	O	O	O	O
hard snurkte of hoestte	O	O	O	O
het te koud had	O	O	O	O
het te warm had	O	O	O	O
nare dromen had	O	O	O	O
pijn had	O	O	O	O

Hoe zou u over het algemeen uw slaapkwaliteit gedurende de afgelopen maand beoordelen?

- O Erg goed
- O Redelijk goed
- O Redelijk slecht
- O Erg slecht

Hoe vaak hebt u de afgelopen maand medicijnen in (al dan niet voorgeschreven) gebruikt om beter te slapen?

- O Niet tijdens de afgelopen maand
- O Minder dan 1 keer per week
- O 1 of 2 keer per week
- O 3 keer per week of vaker

Hoe vaak had u het de afgelopen maand moeilijk met wakker blijven tijdens het autorijden, het eten of het deelnemen aan een sociale activiteit?

- O Niet tijdens de afgelopen maand
- O Minder dan 1 keer per week
- O 1 of 2 keer per week
- O 3 keer per week of vaker

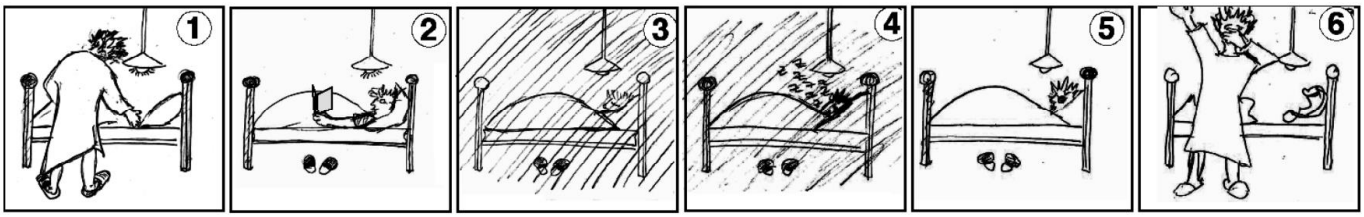
In welke mate was het tijdens de afgelopen maand voor u een probleem om voldoende enthousiasme op te brengen om iets te doen?

O Niet tijdens de afgelopen maand
O Minder dan 1 keer per week
O 1 of 2 keer per week
O 3 keer per week of vaker

De volgende vragen hebben betrekking op uw slaapgewoonten tijdens de afgelopen maand. We vragen naar dagen met verplichtingen die uw slaappatroon kunnen beïnvloeden en dagen zonder verplichtingen die uw slaappatroon kunnen beïnvloeden. Beantwoord de vragen op basis van uw beeld van een standaard week.

Ik heb een regelmatig schema (dit geldt ook voor huisvrouwen of huismannen)

O Ja
Aantal dagen waarop ik verplichtingen heb in een week:
1 O 2 O 3 O 4 O 5 O 6 O 7 O
O Nee



Bij onderstaande vragen wordt verwezen naar de afbeeldingen hierboven. Gebruik voor uw antwoorden alstublieft de 24-uur schaal (bijvoorbeeld: 23.00 uur in plaats van 11 uur).

<u>Dagen met verplichtingen</u>

Afbeelding 1: Ik ga naar bed om ……..:……..uur.
Afbeelding 2: Sommige mensen blijven een tijdje wakker wanneer ze in bed liggen.
Afbeelding 3: Ik ben klaar om te gaan slapen om ……..:…….. uur.
Afbeelding 4: Ik heb ……. minuten nodig om in slaap te vallen.
Afbeelding 5: Ik word wakker om ……..:…….. uur.
Afbeelding 6: Na ……. minuten sta ik op.
Ik gebruik een wekker op dagen met verplichtingen:

O Ja
O Nee
Indien 'Ja': Regelmatig sta ik op VOORDAT de wekker afgaat:
O Ja
O Nee

<u>Dagen zonder verplichtingen</u>

Afbeelding 1: Ik ga naar bed om ……..:…….. uur.
Afbeelding 2: Sommige mensen blijven een tijdje wakker wanneer ze in bed liggen.
Afbeelding 3: Ik ben klaar om te gaan slapen om ……..:…….. uur.
Afbeelding 4: Ik heb ……. minuten nodig om in slaap te vallen.
Afbeelding 5: Ik word wakker om ……..:…….. uur.
Afbeelding 6: Na ……. minuten sta ik op.

Ik word wakker (afbeelding 5) door mijn wekker:

O Ja
O Nee

Er zijn bepaalde redenen waarom ik niet vrij kan kiezen wanneer ik naar bed ga en opsta op dagen zonder verplichtingen:

O Ja
O Nee

Indien 'Ja': De reden hiervoor is/zijn:

O Kind(eren)/huisdier(en)
O Hobbies
O Anders, bijvoorbeeld:

……

Appendix C

Example of one day of the sleep diary.

Dag 1

De volgende vragen gaan over de slaaptijden en de kwaliteit van slaap van de afgelopen nacht.

Tijd waarop u naar bed ging: …… : ……

Tijd waarop u wakker werd: …… : ……

Lengte van uw slaap: …… uur en …… minuten

Hoe lang heeft u er over gedaan om in slaap te vallen? …… uur en …… minuten

Aantal keren dat u wakker bent geworden: ……

Hoe heeft u geslapen?

Erg slecht				Erg goed
O	O	O	O	O

Uitgerust gevoel na het wakker worden:

Helemaal niet				Volledig
O	O	O	O	O

Kalme slaap:

Erg rusteloos				Erg kalm
O	O	O	O	O

Geslapen tot de tijd waarop u wakker wilde worden:

Veel te vroeg wakker geworden				Ja
O	O	O	O	O

Het gemak van wakker worden:

Erg moeilijk				Erg makkelijk
O	O	O	O	O

Het gemak van in slaap vallen:

Erg moeilijk				Erg makkelijk
O	O	O	O	O

Appendix D.

Description of factor analysis for the creation of the variable Subjective sleep quality.

Subjective sleep quality was measured with six items that were assessed with the sleep diaries. A factor analysis was conducted to check whether these items measured indeed the same concept. Because every item was assessed seven times per participant, a filter variable for Daynumber (i.e., day 4) was used to avoid multicollinearity.

To check whether a factor analysis was possible with all six variables the correlation between the variables was checked. A correlation matrix (see Table i) revealed reasonable factorability of all variables (i.e., all variables were correlated with at least one other variable with a correlation of 0.3 or higher). All assumptions were met (i.e., sample size, linearity and factorability) except for the assumption that all variables are normally distributed. With the explorative nature of the factor analysis in mind, we found it reasonable to continue. Subsequently we checked for outliers. No significant outliers were found in the data.

A principle component analysis was used for the factor analysis. Six factors were computed. Only the first two factors had an eigenvalue of > 1.0 (i.e., 2.96 and 1.21) these explained 49.40% and 20.09% respectively.

Based on the factor loadings of the variables, and the large difference between the eigen values of both factors, it was decided that only the first factor would be used to continue the factor analyses.

All variables had a factor loading >.4 on the first factor. Therefore it was decided to use all six items to create the variable for Subjective sleep quality. Lastly, we checked whether the same factor loadings would hold for the same analyses with a filter variable of another day. These analyses revealed that the exact factor loadings differed between days, though the same items loaded highly on the first factor for all days. Therefore it was decided to create the variable Subjective sleep quality based on the mean of all six items.

Table i. Correlation matrix of items that assessed sleep quality

	Good sleep	Full rest	Calm sleep	Woke on time	Ease of waking up	Ease of falling asleep
Good sleep	1.0000					
Full rest	0.6469	1.0000				
Calm sleep	0.7514	0.6223	1.0000			
Woke on time	0.3294	0.3366	0.1942	1.0000		
Ease of waking up	0.5457	0.6455	0.4625	0.3647	1.0000	
Ease of falling asleep	0.6513	0.5418	0.4813	0.2465	0.4778	1.0000

Appendix E.1.

Pearson's correlation table to investigate correlation for the models for Subjective sleep quality, Sleep duration and Midsleep.

Table ii. *Results of with all independent variables that were used in the analyses for Dataset 1.*

	Chronotype
Hourly circadian irradiance	-.0141
Morning circadian irradiance	-.0052
Afternoon circadian irradiance	.3712
Evening circadian irradiance	-.0256

	Time of day
Hourly circadian irradiance	-.1157

Appendix E.2.

Table iii. *Results of the assumption tests for Dataset 1.*

	Normality of residuals	Homoscedasticity	Linearity
Hourly circadian irradiance			
Time of day + time of day squared + time of day to the third power	Accepted	Accepted	Accepted
Subjective sleep quality			
Hourly circadian irradiance	Not accepted	Accepted	Accepted
+ chronotype	Not accepted	Not accepted	accepted
Morning circadian irradiance	Not accepted	Accepted	Accepted
+ chronotype	Not accepted	Not accepted	Accepted
Afternoon circadian irradiance	Not accepted	Accepted	Accepted
+ chronotype	Not accepted	Not accepted	Accepted
Evening circadian irradiance	Not accepted	Accepted	Accepted
+ chronotype	Not accepted	Not accepted	Accepted
Sleep duration (dependent variable)			
Hourly circadian irradiance	Not accepted	Accepted	Accepted
+ chronotype	Not accepted	Not accepted	Accepted
Morning circadian irradiance	Not accepted	Accepted	Accepted
+ chronotype	Not accepted	Not accepted	Accepted
Afternoon circadian irradiance	Not accepted	Accepted	Accepted

+ chronotype	Not accepted	Accepted	Accepted
Evening circadian irradiance	Not accepted	Accepted	Accepted
+ chronotype	Not accepted	Not accepted	Accepted
Midsleep			
Hourly circadian irradiance	Not accepted	Accepted	Accepted
+ chronotype	Not accepted	Not accepted	Accepted
Morning circadian irradiance	Not accepted	Not accepted	Accepted
+ chronotype	Not accepted	Not accepted	Accepted
Afternoon circadian irradiance	Not accepted	Accepted	Accepted
+ chronotype	Not accepted	Accepted	Accepted
Evening circadian irradiance	Not accepted	Not accepted	Accepted
+ chronotype	Not accepted	Accepted	Accepted

Appendix F.1.

Table iv. *Pearson's correlation table (part 1) of all independent variables for dataset 2.*

	Time of day	Hourly circadian light exposure	Being outdoors	Prior sleep duration	General health	General sleep quality	Chronotype
Time of day	1.0000						
Hourly circadian light exposure	0.0299	1.0000					
Being outdoors	-0.0263	0.2556	1.0000				
Prior sleep duration	0.0113	-0.0805	0.0045	1.0000			
General health	-0.0061	-0.0121	0.0747	0.2761	1.0000		
General sleep quality	0.0134	-0.1957	-0.0712	0.2044	0.0225	1.0000	
Chronotype	0.0116	-0.0380	0.0037	0.2304	0.5918	0.2582	1.0000
Light sensitivity	0.0051	-0.0827	-0.0559	0.2647	0.0538	0.0220	-0.2184
Physical effort	-0.0100	0.1633	0.3186	0.0755	0.1395	-0.0228	0.1396
Mental effort	0.0541	0.1011	0.1028	0.0510	-0.0590	0.0545	0.1688
Social effort	0.1427	0.0966	0.1714	0.1756	0.1481	0.0753	0.2340
Prior nap	-0.0834	-0.0985	-0.0147	-0.0324	-0.0711	-0.0282	-0.0496
Being in nature	-0.0037	0.2328	0.6589	-0.0146	0.0809	-0.1099	0.0371
Trait vitality	-0.0143	-0.0133	0.0312	0.2075	0.4034	0.1043	0.5840
Being with others	0.0152	0.1029	-0.0146	-0.0074	-0.1377	-0.0079	-0.0374

Table v. *Pearson's correlation table (part 2) of all independent variables for dataset 2.*

	Sensitivity to light	Physical effort	Mental effort	Social interaction	Prior nap	Being in nature	Trait vitality	Being with others
Sensitivity to light	1.0000							
Physical effort	0.0634	1.0000						
Mental effort	0.0738	0.5831	1.0000					
Social	0.0947	0.4846	0.4888	1.0000				

interaction								
Prior nap	-0.0299	-0.1808	-0.1956	-0.1502	1.0000			
Being in nature	-0.0300	0.3614	0.2013	0.2114	-0.0809	1.0000		
Trait vitality	-0.0004	0.0205	-0.0220	0.1121	-0.0207	-0.1125	1.0000	
Being with others	-0.1102	0.0931	0.1253	0.3224	-0.0143	0.0659	0.0027	1.0000

Appendix F.2.

Table vi. *Results of the assumption tests for dataset 2.*

	Normality of residuals	Homoscedasticity	Linearity
Vitality			
Time of day + Time of day squared + Time of day to the third power	Not accepted	Not accepted	Accepted
+ Hourly circadian light exposure	not accepted	Not accepted	accepted
+ Social interaction	Not accepted	Not accepted	Accepted
+ Physical effort	Not accepted	Not accepted	Accepted
+ Mental effort	Not accepted	Not accepted	Accepted
+ Being with others	Not accepted	Not accepted	Accepted
+ Being in nature	Not accepted	Not accepted	Accepted
+ Being outdoors	Not accepted	Not accepted	Accepted
+ Prior sleep duration	Not accepted	Not accepted	Accepted
+ General sleep quality	Not accepted	Not accepted	Accepted
+ Chronic fatigue	Not accepted	Not accepted	Accepted
+ Trait vitality	Not accepted	Not accepted	Accepted
+ Light sensitivity	Not accepted	Not accepted	Accepted
+ Chronotype	Not accepted	Not accepted	Accepted
Vitality			
Morning circadian light	Not accepted	Not accepted	Accepted

exposure			
Afternoon circadian light exposure	Not accepted	Not accepted	Accepted
Evening circadian light exposure	Not accepted	Accepted	Accepted
Mood			
Time of day + Time of day squared + Time of day to the third power	Not accepted	Not accepted	Accepted
Hourly circadian light exposure	Not accepted	Not accepted	Accepted
+ social interaction	Not accepted	Not accepted	Accepted
+ physical effort	Not accepted	Not accepted	Accepted
+ mental effort	Not accepted	Not accepted	Accepted
+ Being with others	Not accepted	Accepted	Accepted
+ Being in nature	Not accepted	Not accepted	Accepted
+ Being outdoors	Not accepted	Not accepted	Accepted
+ Prior sleep duration	Not accepted	Not accepted	Accepted
+ General sleep quality	Not accepted	Not accepted	Accepted
+ Chronic fatigue	Not accepted	Not accepted	Accepted
+ Trait vitality	Not accepted	Not accepted	Accepted
+ chronotype	Not accepted	Not accepted	Accepted
Mood			
Morning circadian light exposure	Not accepted	Accepted	Accepted
Afternoon circadian light exposure	Not accepted	Accepted	Accepted
Evening circadian light exposure	Not accepted	Accepted	Accepted