Exploring the relations between light exposure, subjective sleep quality and subjective vitality in the field

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Exploring the relations between light exposure, subjective sleep quality and subjective vitality in the field

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Preface

This master thesis is a representation of my work in multilevel modelling on the topic of light exposure, subjective sleep quality, and subjective vitality. This is the last part of my master program in Human-Technology Interaction at the Eindhoven University of Technology. During my bachelor's program in Psychology & Technology I was still largely uncertain about the direction I wanted my studies to go in. I always had a desire to help people, and an interest in psychology and in technology, hence why I chose the bachelor's program. In the bachelor I followed the robotics track which gave me more programming insight, but near the end of that education I realised robotics was not quite for me. I was more interested in how people and their environments influence each other, and I found what I really wanted to study in the course on environmental psychology. I then proceeded to take more light related courses in order to learn more about light, so I could combine this with the knowledge I received in the environmental psychology course. For my internship I conducted a literature research into attention and stress restoration in the environmental psychology domain under supervision of prof. dr. ir. Yvonne de Kort and dr. ir. Kynthia Chamilothori, which confirmed for me that this is the field I want to continue my studies in. It was a small step from this realisation to the topic of my thesis.

I am truly grateful to my supervisors dr. ir. Karin Smolders and dr. ir. Juliëtte van Duijnhoven for all their imparted knowledge and guidance. I truly appreciate all the time you had (and made) weekly in order to discuss my progress and give feedback. Thank you for all the support and encouragement. I am also grateful to prof. dr. ir. Yvonne de Kort for her role as my third assessor, and for all I learnt from her and dr. ir. Kynthia Chamilothori and their time during my internship. I would also like to express my thanks to B'Elanna Vugts and Wenger Pwa with whom collaborated on the execution of the measurements and Matlab pre-processing, and to my study advisor ir. Will Kuijpers.

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Abstract

Sleeping well and having enough energy to last the day are naturally very important, though this is not always achieved. In current society it is not uncommon to sleep poorly or lack the vitality one needs. Previous research has shown a relation exists between subjective sleep quality and the light we are exposed to throughout the day, although it is not yet fully understood. Particularly, the temporal pattern and spectral composition of light exposure have not been studied often in field studies focussing on natural variations in light exposure. In the current semi-longitudinal field study, light sensors were used which also provided insights in the spectral pattern of light exposure, and as such allowed for computation of α-opic irradiance based metrics in addition to illuminance based metrics. These metrics included the daily average absolute Rates of Change, the daily Coefficients of Variation, the daily Average Irradiances and Illuminance, the daily Radiant and Luminous Exposures, and the daily Disparity Indices. In terms of self-reported measures, subjective sleep quality was assessed with the extended Consensus Sleep Diary, and subjective vitality during the wake episode was assessed with the Activation-Deactivation Adjective Check List. The aim of this research was to explore which light exposure aggregations would be best to predict subjective vitality throughout the day, and subjective sleep quality. Due to the low sample size of seven participants monitored for four days and hence low statistical power, no strong conclusions could be drawn based on the statistical analyses and the research question on subjective vitality was discarded. However, an analysis methodology aimed at the study of a multitude of variables in multilevel data could still be demonstrated. The explorative analysis performed with this methodology indicated that the daily average absolute Rates of Change in particular appear to be interesting to further explore in future research studying the association between light exposure and subsequent sleep quality with larger sample sizes and a longer sampling period.

Keywords: subjective sleep quality, field study, light exposure, α-opic irradiance, rate of change, multilevel model

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Introduction

An increasing number of people suffers from sleep disturbances and a related lack of energy or vitality throughout the day, especially during the current pandemic (Blume et al., 2020; Casagrande et al., 2021; Pinto et al., 2020). This has been shown to cause a wide range of issues, from decreased productivity to metabolic issues resulting in weight gain (Leproult & Van Cauter, 2010; Miyata et al., 2013; Rosekind et al., 2010). Often such sleep disturbances and low vitality have been implicated to relate to a lack of exposure to high light levels during the day (Hébert et al., 2002) and exposure to electric lighting after sundown, which has been found to result in later sleep and reduced sleep efficiency (Cain et al., 2020). A potential factor contributing to this is the usage of light emitting devices (e.g. smartphones) before bedtime; a meta-analysis found proof of a negative association between device use in “the sleep environment” and during bedtime and sleep quality (Carter et al., 2016). Overall, it is well recognized how important light, sleep quality, and vitality are in daily life.

Sleep quality and vitality have been shown to be positively correlated (Visser et al., 2014). This is not very surprising, considering the importance of sleep for the regulation of the central nervous system, immune system, and endocrine system (Perry et al., 2013; Worley, 2018). It follows that sleep is important for health related factors such as vitality and vice versa. While vitality is not often strictly defined in studies, it appears to be generally understood as the energy or strength necessary for a happy and productive life (Cambridge English Dictionary, 2021; Ryan & Frederick, 1997). Subjective vitality can then be understood as a measure of one’s own perception of their energy level and liveliness. Sleep quality is generally assumed to be mostly subjective, often used to simply refer to to how well someone feels they slept. However, other factors such as how often someone woke up during the night, how long it took to fall asleep, how long they slept, and how deeply they slept, generally also need to be taken into account (Buysse et al., 1989).

Both sleep quality and vitality have also been shown to correlate with exposure to light (Böhmer et al., 2021; Figueiro et al., 2017, 2019; Hubalek et al., 2010; Peeters et al., 2021; Smolders et al., 2013). The subject of this research is the relations between light exposure in the visible range of the spectrum (specifically the range from 390 – 760 nm), sleep quality, and vitality. There are several features of importance in the study of the effects of light exposure, which can be categorised as light level, spectral composition, temporal pattern (e.g. timing or duration of exposure, or light exposure

history), and spatial pattern ((Chellappa et al., 2011; Khademagha et al., 2016; Van Duijnhoven et al., 2020). These features of light exposure can affect humans in visual and non-visual, or neuro-behavioural ways. In the current field study, we will particularly focus on light level, spectral composition and the temporal pattern. Light history (as part of the temporal pattern) and the spatial pattern will not be studied in the field study part of this research due to time and material constraints.

In the literature, light level is often also referred to as intensity, illuminance, amount of light, light exposure, or sometimes irradiance[1] (e.g. Gamlin et al., 2007; Hubalek et al., 2010; Jarboe et al., 2020; Martinez-Nicolas et al., 2011; Wallace-Guy et al., 2002). The field studies reviewed in this research assess light level on the participant using a light sensor, which means that in current terminology (Comission Internationale de l'Eclairage, 2020) they assessed light level in terms of illuminance or irradiance. This will be referred to as light level to keep in line with the current terminology as described in footnote 1, regardless of the terminology used by authors of those studies to describe the light exposure feature. Light exposure is the term previously used to denote luminous exposure, or the total amount of light received in a period of time, or the light level multiplied by the duration (Comission Internationale de l'Eclairage, 2020). In the current report, light exposure is used as a more general term to refer to the exposure to light that participants experienced.

1.1 Neuro-behavioural effects of light

As stated above, light affects us in several ways, which can be divided into two main categories; image forming (IF) effects and non-image forming (NIF) effects. The IF system affords us to perceive our environment visually (Provencio & Warthen, 2012), whereas the NIF system passes information through the retino-hypothalamic tract, which influences our physiology and psychology (Boyce, 2003). This information pathway receives information from the intrinsically photosensitive retinal ganglion cells (ipRGCs) and delivers it to the suprachiasmatic nucleus (SCN) among other brain structures (Boyce, 2003). The ipRGCs are most sensitive to short wavelengths (peak sensitivity ≈ 482 nm; (Berson et al., 2002; Gamlin et al., 2007)), primarily in the blue part of the visible spectrum (Commission Internationale de l'Eclairage, 2018; Gamlin et al., 2007; Provencio & Warthen, 2012). The NIF effects can be further categorised into acute or short term effects, and circadian or phase-shifting effects.

1 Light intensity is a property of a light source which describes how much light it radiates in a particular direction, and irradiance and illuminance describe how much light a surface receives, in terms of radiometric or photometric terms respectively (Comission Internationale de l'Eclairage, 2020).

The circadian rhythm, as regulated by the biological clock (SCN) in the brain, dictates biological rhythms, such as the sleep-wake rhythm, body temperature, and metabolism. Under free-running conditions, the circadian rhythm in humans deviates from the 24h day-night cycle, and therefore requires entrainment with the day-night cycle by zeitgebers to prevent desynchronisation or misalignment between the circadian rhythm and local time (Czeisler et al., 1999). One of the primary zeitgebers is light, which can shift the phase of the circadian rhythm forward or backward. The direction of the subsequent shift depends on the timing of the exposure to light (Blume et al, 2019; Czeisler, 2013; Lack & Bootzin, 2003). High light levels closer to the subjective midnight will cause the strongest shift in circadian rhythm. Light in the subjective morning can shift the circadian rhythm forward, resulting in an earlier sleep onset, whereas light in the evening can delay the circadian rhythm, resulting in a later sleep onset (Lack & Bootzin, 2003). When light is timed right, it can therefore help the biological clock remain entrained with the day-night rhythm, but when timed incorrectly, such as through the use of artificial light after sunset, this can start to desynchronise the internal clock (Blume et al., 2019; Czeisler, 2013; Wirz-Justice, 2007).

The propensity to sleep at a certain time during the 24 hour day, as dictated by our circadian rhythm, has been named chronotype (Blume et al., 2019; Roenneberg, 2012). Chronotype can be expressed on a continuum, ranging from morningness (being an “early bird”) on one end of the scale, to eveningness (being a “lark”) on the other end of the scale. Those in the middle have an average or neutral chronotype. Dim Light Melatonin Onset (DLMO) is a previously used objectively measured marker of circadian phase (Wams et al., 2017). Throughout the subjective evening and night, the hormone melatonin is produced in the pineal gland, which causes sleepiness in subjects. This production is regulated by the circadian rhythm, but melatonin in turn also informs the internal clock about the day/night cycle and the time of year as melatonin secretion duration is related to night (or dark period) length (Reiter, 1993). This feedback loop explains in part how changing the light/dark cycle that is experienced to be different from the day/night cycle can cause the aforementioned phase-shifting effects.

Chronotype has also been shown to be related to how light affects us, the light exposure pattern one is exposed to, and sleep quality (Martin et al., 2012). Evening types have been found to experience worse sleep quality than morning or average types, more chronic fatigue, more sleepiness, more psychological distress, and as expected later sleep onset and offset. Compared to morning types, evening types were also found to experience less exposure to 100 to 500 lux in particular, and were exposed to less light in the morning and more in the evening.

As previously stated, light can induce acute or instantaneous neuro-behavioural NIF effects, which are distinct effects from the circadian or long term effects. This includes a plethora of instantaneous effects: increased alertness (based on subjective or performance task assessments; Cajochen, 2007; de Kort & Veitch, 2014; Smolders & de Kort, 2014; Souman, Tinga, et al., 2018), supression of melatonin production and therefore increased sleep onset latency and decreased sleep efficiency (Blume et al., 2019; Cain et al., 2020), mood effects (Blume et al., 2019; Jung et al., 2010; Smolders & de Kort, 2014), and increased subjective vitality (in particular during the morning and when participants feel less energetic; Smolders et al., 2013; Smolders & de Kort, 2014).

1.2 Relations between light and subjective sleep quality and subjective vitality in the literature

Böhmer et al. (2021) recently conducted a systematic literature review on the relationship between light and sleep and mental state in field studies. As further discussed in Appendix 1, their literature review was extended with an additional literature search with stricter inclusion criteria to add recent studies published since they conducted their search. The extension was specifically focussed on the relations between light and sleep quality, and light and subjective vitality. The overview of included articles in this research can be found in Appendix 1. This has information on the method including in- and exclusion criteria, and overview tables on study-specific details and results (see Tables 12, 13, and 14 of Appendix 1).

The review by Böhmer et al. (2021) included two articles on the relation between light exposure and sleep quality in the target population of the current study (students and office workers), and another was found in the search extension. The study by Hubalek et al. (2010) found that a longer exposure to high light levels was related to higher subjective sleep quality, as assessed with two newly formulated items which were not part of a (standardised) scale. However, they also found that longer exposure to blue light was related to a lower sleep quality. Hubalek and colleagues (2010) did not study the timing of when participants were exposed to high light levels in terms of illuminance or blue light, but studied aggregated values across the entire day. The study by Figueiro et al. (2017) also studied the relation between light exposure and sleep quality, but did take timing into account. They found that exposure to higher levels of circadian effective light was related to better sleep quality when participants were exposed to this during the morning and during the whole workday, as assessed with the Patient-Reported Outcomes Measurement Information System Sleep

Disturbance–Short Form 8a (PROMIS; (Cella et al., 2010)), and when participants were exposed to this during the workday and during workday mornings, as assessed with the Pittsburgh Sleep Quality Index (PSQI). The two scales differ in terms of time frame; the sleep disturbance section of the PROMIS assesses the daily sleep quality (Yu et al., 2011), whereas the PSQI (Buysse et al., 1989a) focusses on sleep quality of the past month. Peeters et al. (2021) found no statistically significant relation between subjective sleep quality and light exposure in the morning (08.30 – 12.30) or afternoon (13.00 – 17.00) when they assessed subjective sleep quality with the Karolinska Sleep Diary.

Two articles included in Böhmer's review that studied different target populations than student and office-workers also investigated the relation between light exposure and subjective sleep quality. Kripke et al. (2004) found that an increase in the mesor of light level (as assessed with an Actillume I wrist monitor) was related to better subjective sleep quality (as assessed using the subjective sleep quality subscale from their women's health initiative questionnaire) when studying postmenopausal women. Hood et al. (2004) analysed time over thresholds of 500 lux, 3000 lux, and 10000 lux (as assessed with a waistband-worn Mini Mitter 2000 Data Logger), and found that exposure to light levels at or above 3000 lux was related to better subjective sleep quality (as assessed with the PSQI) in elderly people with a mean age of 74. The results from both of these studies are in line with the results from the studies by Hubalek et al. (2010) and Figueiro et al. (2017).

The study by Sahin and Figueiro (2021) from the search extension (which can be found in Table 13 in Appendix 1) studied shift-workers in their own offices during the day and night, and measured light with a Daysimeter worn as a pendant. They found that supplemented red enriched white light and blue enriched white light was related to a better subjective sleep quality than the baseline light conditions (a horizontal light level of 28 lux, and a vertical light level of 9.5 lux, as measured in 2015), as assessed with the PSQI. There was no control group.

As can be found in Table 13 in Appendix 1, the studies by Figueiro et al. (2017), Peeters et al (2021), and Wams et al. (2017), also studied other sleep metrics generally used as markers of sleep quality. Figueiro et al. (2017) found less sleep disturbances (when assessed with the PROMIS) with increased levels of circadian effective light in the morning and during the work day, and Wams et al. (2017) found more sleep disturbances (as assessed with actigraphy) when the first exposure to a light level of 10 lux or more occurred later rather than earlier in the day. This implies that receiving more light earlier in the morning and throughout the work day could reduce sleep disturbances. Figueiro and colleagues (2017) found that shorter sleep onset latency (as assessed with actigraphy) was related to exposure to higher levels of circadian effective light. Peeters et al. (2021) measured

light in terms of illuminance rather than circadian effective light but did not find this relation, which they also assessed with actigraphy. They did find that higher supplemented light levels in the morning and lower light levels on winter afternoons was related to larger sleep onset latencies. Furthermore, Wams and colleagues (2017) found that shorter sleep duration (as assessed with polysomnography) was related to an increase in the average log transformed light level that participants received during the preceding day, and that this relation was clock-phase modulated, i.e. affected by the circadian rhythm. Peeters et al. (2021) also found a negative relation between light level and sleep duration as assessed with the Karolinska Sleep Diary for winter morning light level, but did not assess clock phase modulation and did not find this relation when they assessed sleep duration with actigraphy.

Two articles from the literature search extension studied metrics generally used in the calculation of sleep quality. Sahin and Figueiro (2021) also found that red enriched white light and blue enriched white light reduced self-reported sleep disturbances as compared to the participants' baselines, as assessed with the PSQI. Estevan et al. (2021) found that a ten times higher average light level throughout the previous day was associated with a 32 minutes earlier sleep onset, and an 18 minutes longer sleep duration. The results of these two articles are in line with those found by Figueiro et al. (2017). Estevan et al. (2021) also found that a sleep offset delay of an hour was related to a 22.7% decrease in average light level during the previous day, 18 minutes shorter exposure to 500 lux or higher during the previous day, and a 20 minute delay in the first exposure to 500 lux or more during the previous day.

In addition to the relation between light exposure and sleep quality, a few studies investigated the relation between light exposure and vitality. Each of the three studies (one from the review by Böhmer et al. (2020), two from the extension) that studied the relation between light exposure and subjective vitality used a different scale to measure subjective vitality. The studies by Smolders et al. (2013) and Figueiro et al. (2019) both found that higher light levels were related to increased subjective vitality. The former measured vitality using the Activation-Deactivation Adjective Checklist (Thayer, 1989) and assessed light level in terms of the logarithm of illuminance and time above threshold, whereas the latter used the Subjective Vitality Scale (Ryan & Frederick, 1997) and assessed light in terms of the Circadian Stimulus (Rea & Figueiro, 2016; Rea et al., 2010). Furthermore, Smolders and colleagues (2013) found that this relationship was less strong in autumn and winter, and during the morning, whereas Peeters et al. (2021) found the opposite when they assessed vitality with a single unstandardised question pertaining to vitality, and light level in terms of the logarithm of illuminance. They found that a higher light level during the morning in spring

was associated with lower subjective vitality, and did not find any significant relations in winter.

Although the results for the studies investigating the relation of light exposure with subjective sleep quality and subjective vitality reviewed above are somewhat mixed, there appears to be a trend towards a positive relation between light exposure during the (work) day and sleep quality and vitality; higher light levels and longer durations of light exposure appear to be related to higher sleep quality and vitality. Part of the variety in results might be explained by the lack of standardisation in terms of methodology, measurement tools, and assessment timescales, as was also commented on by Münch et al. (2020). Furthermore, no direct replication studies were found.

Böhmer et al. (2020) deemed the evidence for a relation between light and sleep, and light and mental health to be conflicting to limited. They too found that some studies did find relations, with both positive and negative relations reported, but others reported no statistically significant relation. Most studies had very low participant numbers and therefore often lacked statistical power (Böhmer et al., 2021). Often, no sensitivity or power analysis was reported. Additionally, light exposure was often assessed at wrist-level, which can introduce additional sizeable inaccuracies of up to 27% (Aarts et al., 2017; Böhmer et al., 2021). Münch et al. (2020) came to similar conclusions after a multidisciplinary workshop on the role of daylight for humans in general. They also identified the uncertainty that still exists with regards to the requirements with regards to light level, spectral composition, and temporal pattern in order to function best, both mentally and physically, and avoid health risks due to under or over exposure to light. Some information on this is available from laboratory studies, but these are highly controlled and generally use electric lighting rather than daylight for more control over experimental conditions.

The review above shows previous research has mostly been concerned with average light levels and their durations. Therefore, in order to give advice on light exposure patterns and the relation between such patterns and subjective sleep quality and subjective vitality, more research is required into other features of light exposure.

1.3 Previously used light aggregations in the literature

The articles that were reviewed by Böhmer et al (2021) and the articles from the literature search extension described in Appendix 1 used a variety of light aggregations (these researches studied more outcome measures than subjective sleep quality and subjective vitality discussed above). An overview of the light aggregations which were studied in the aforementioned literature can be seen

below in Table 1. The associated formulas can be found in Table 23 in Appendix 1.

Table 1: Overview of the light aggregations used in the literature.

Light Feature	Light Aggregation	Article(s) in which it was studied
Light level	Average Illuminance	Araki et al., 2012; Beale et al., 2017; Boubekri et al., 2014; Crowley et al., 2015; Estevan et al., 2021; Figueiro et al., 2019; Grandner et al., 2006; Hoaki et al., 2010; Hubalek et al., 2010; Koller et al., 1993; Martinez-Nicolas et al., 2011; Peeters et al., 2021; Sahin & Figueiro, 2021; Smolders et al., 2013; Wallace-Guy et al., 2002; Wams et al., 2017; Wang et al., 2003
	Maximum Illuminance	Wams et al., 2017
	Fitted cosine mesor (mean)	Espiritu et al., 1994; Grandner et al., 2006; Jean-Louis, Kripke, Cohen, et al., 2005; Jean-Louis, Kripke, Elliott, et al., 2005; Kripke et al., 2004
	Fitted cosine amplitude (height from peak to mesor)	Espiritu et al., 1994; Grandner et al., 2006; Jean-Louis, Kripke, Cohen, et al., 2005; Jean-Louis, Kripke, Elliott, et al., 2005; Koller et al., 1993; Kripke et al., 2004; Van Der Maren et al., 2018
Light level, spectral pattern	Vis-nonvis	Hubalek et al., 2010
	Circadian Light	Figueiro & Rea, 2014
	Circadian Stimulus	Figueiro et al., 2019; Figueiro et al., 2017; Itzhacki et al., 2019; Sahin & Figueiro, 2021
Light level, temporal pattern	Time above Threshold	Aan Het Rot et al., 2008; Asai et al., 2018; Estevan et al., 2021; Hood et al., 2004; Hubalek et al., 2010; Smolders et al., 2013
	Percentual Time above Threshold	Espiritu et al., 1994
	Weighted Illumination	Espiritu et al., 1994
	Luminous Exposure	Hubalek et al., 2010
	Light quality index	Martinez-Nicolas et al., 2011
	Hourly percentage of daily mean illuminance respective of DLMO	Van der Maren et al., 2018
Temporal pattern	Fitted cosine acrophase (period length)	Espiritu et al., 1994; Grandner et al., 2006; Jean-Louis, Kripke, Cohen, et al., 2005; Jean-Louis, Kripke, Elliott, et al., 2005; Koller et al., 1993; Kripke et al., 2004
	First and last >10 lux exposures	Wams et al., 2017
	Rate of Change	Martinez-Nicolas et al., 2011

1.3.1 Light level

Table 1 shows that light level has been taken into account quite often; average illuminance was studied in 15 articles out of 29 (Araki et al., 2012; Beale et al., 2017; Boubekri et al., 2014; Crowley et al., 2015; Figueiro et al., 2019; Grandner et al., 2006; Hoaki et al., 2010; Koller et al., 1993; Martinez-Nicolas et al., 2011; Peeters et al., 2021; Sahin & Figueiro, 2021; Smolders et al., 2013;

Wallace-Guy et al., 2002; Wams et al., 2017; Wang et al., 2003). Average illuminance has also been studied five times in the form of the cosine mesor modelled on the light/dark cycle found in illuminance measures (Espiritu et al., 1994; Grandner et al., 2006; Jean-Louis, Kripke, Cohen, et al., 2005; Jean-Louis, Kripke, Elliott, et al., 2005; Kripke et al., 2004). Maximum illuminance was studied once by Wams et al. (2017. This is comparable to the amplitude of a cosine function model based on measured data, which was studied seven times (Espiritu et al., 1994; Grandner et al., 2006; Jean-Louis, Kripke, Cohen, et al., 2005; Jean-Louis, Kripke, Elliott, et al., 2005; Koller et al., 1993; Kripke et al., 2004; Van Der Maren et al., 2018).

1.3.2 Spectral composition

While light level has frequently been taken into account, the spectral distribution of light has been taken into account quite little, and often only partially. This was in the form of vis-nonvis (Hubalek et al., 2010), Circadian Light (Figueiro & Rea, 2014), and Circadian Stimulus (Figueiro et al., 2019; Figueiro et al., 2017; Itzhacki et al., 2019; Sahin & Figueiro, 2021). Vis-nonvis is the difference between light level in terms of illuminance and the blue part of the illuminance, and as such does not take the full spectrum into account. Circadian Light is intended to take the spectral sensitivity of photo-transduction circuits in the retina into account, whereas the Circadian Stimulus transforms Circadian Light in such a way that it also reflects the operating characteristics of the photo-transduction circuits, from threshold to saturation (Rea & Figueiro, 2016; Rea et al., 2010; Sahin & Figueiro, 2021). This is at least in part based on hypothesised relations between light, the pineal gland, and melatonin suppression, and the opposition between blue and yellow light pathways in the eyes. It consequentially has a strong focus on melatonin suppression which does not necessarily relate directly to other non-image forming responses (Houser & Esposito, 2021; Rahman et al., 2018).

Fully taking the spectrum of light into account is important for reproducibility due to the way light is perceived by our non-visual system; metameric equivalence occurs when two lighting sources send out light with different spectral compositions, which are perceived by our visual system as the same and can be represented by the same chromaticity coordinates, correlated colour temperature (CCT), and light level. These metameric equivalent light sources can, however, have different irradiances at different parts of the spectrum (such as more irradiance in the blue part of the spectrum), and therefore initiate differing non-visual effects. This, and small sample sizes could explain differences between research results in the studies reviewed above (Böhmer et al., 2021), along with other differences such as chosen outcome measures and temporal pattern of light

exposure (Souman, Borra, et al., 2018; Souman, Tinga, et al., 2018; Vetter et al., 2021). It also shows why light level and CCT cannot accurately describe the spectrum data, as these are based on visual perception, and therefore cannot account for metamerism.

Several other iterations of metrics which do take the spectrum of light into account have been developed. Lucas et al. (2014) developed metrics which take the five photoreceptors into account using the light source specific efficacy of luminous radiation of each photoreceptor. These metrics were not SI compliant (Houser & Esposito, 2021), however, and were followed up by the next iteration by Ámundadóttir (2016). Her photo-receptor specific equivalent daylight illuminances implemented spectral sensitivity curves, which she used to calculate relative spectral effectiveness factors.

The current standard by the CIE (Commission Internationale de l'Eclairage, 2018), the α-opic irradiances, are SI compliant and will be used for this research to aid in their standardisation. The "α" in the name can be replaced by each of the photoreceptor types; S-cone-opic for the short cones which are most sensitive to blue light, M-cone-opic for the medium cones which are most sensitive to green light, L-cone-opic for the long cones which are most sensitive to red light, rhodopic for the rods which contain the photopigment rhodopsin, and melanopic for the ipRGC's which contain the photopigment melanopsin. In order to calculate the α-opic irradiances, they used a specific sensitivity curve for each photoreceptor in the same way that the sensitivity curve for the eye, V(λ) is used to calculate illuminance. The sensitivities of the photoreceptors incorporate more information on the spectrum than V(λ), as it relates the spectrum to the information our eye actually receives and relays to the brain beyond the visual perception of colour. Therefore, using these α-opic irradiances is more suitable than using the CCT and chromaticity coordinates as these α-opic irradiances can take the differences between metamerically equivalent light spectra, and between the spectral sensitivity of the photoreceptors, into account. As can be seen in Table 3, research studying these α-opic irradiances in the field appears to not have been performed previously.

1.3.3 Temporal pattern

The importance of studying the temporal pattern of light exposure can be illustrated quite clearly with the study by Chang et al. (2012). In this study, they found a non-linear relationship between duration and light level with regards to non-visual effects, such that shorter exposures at a higher light level had a greater effect for each minute of exposure. Duration and light level are often studied together in the form of time above threshold (TaT). As can be seen in Table 1 above, multiple researches used TaT (Aan Het Rot et al., 2008; Asai et al., 2018; Hood et al., 2004;

Hubalek et al., 2010; Smolders et al., 2013). Espiritu (1994) used a percentual TaT in which the TaT was divided by the total measurement period of 48 hours. TaT was also used by Martinez-Nicolas et al. (2011) in their light quality index, which is the normalised difference between the TaT of less than 10 lux and the TaT of more than 500 lux; and by Espiritu et al. (1994) in their weighted illumination, which normalises TaT by dividing it by the light level it corresponds to.

An alternative to TAT which takes all light levels and their durations into account, is luminous exposure, which is the integral of light exposure, or the area under the light over time graph (Adams & Essex, 2018a; Comission International de l'Eclairage, 2020). This metric was previously used by Hubalek et al. (2010). Duration of the entire light/dark period was studied five times (Espiritu et al., 1994; Grandner et al., 2006; Jean-Louis, Kripke, Cohen, et al., 2005; Jean-Louis, Kripke, Elliott, et al., 2005; Koller et al., 1993; Kripke et al., 2004) in the form of the acrophase, i.e. the period length of the cosine of the light/dark cycle, modelled on light level measurements.

Reid et al. (2014) developed the mean light timing above threshold metric (MLiT), which reflects the average timing of TaT. It therefore aims to combine light level and timing of light exposure into one aggregate measure. However, MLiT inherently aggregates the light exposure data in such a way, that when TaT is timed mostly during the morning and evening, this will yield the same MLiT as the situation in which most of the TaT occurs at noon, as the timing is averaged. Therefore, this is not yet a full solution, because it does not allow one to distinguish between all different timings, i.e. temporal light profiles, due to this averaging. This shortcoming was also pointed out by Peeters and colleagues (2022). Even though the metric is therefore not perfect, Reid et al. (2014) were able to use it successfully to find support for a relation between light and BMI. This metric was also successfully used by (Peeters et al., 2022)[2] when combined with TaT to examine the interaction of these two metrics. This interaction was found to yield the most consistent parameter estimates across seasons, which led to the conclusion that a complex interaction of light level, timing, and duration was required when studying the effects of light exposure on sleep onset, midpoint, and duration. They found timing to be of influence on the direction of an effect between light exposure and sleep metrics; during spring, earlier light exposure was related to longer and earlier sleep, whereas this effect was reversed for winter light exposure during which later light was found to have this effect. This may be because later timed light exposures reduce sensitivity to light exposure in the evening, which would have positive effects on sleep in winter. In spring the reverse could

2 This study is briefly mentioned rather than fully incorporated into the literature review as it was published later than the last literature search performed for this research.

occur, implying that earlier light in the morning would have a stronger effect, as people would likely be exposed to more light during the day already and would therefore already be less sensitive to light in the evening.

As seen in Table 1 above, Wams et al. (2017) accounted for timing by analysing the first and last times that participants were exposed to light levels greater than 10 lux. Taking such metrics into account requires sensors that are accurate in the low light level ranges. Van der Maren et al. (2018) studied timing and light level by dividing the day up into hours based on the individuals' circadian rhythm, and subsequently mean-centring the hourly light level data. Timing was also often taken into account by splitting up the data into several timeslots (e.g. Aan Het Rot et al., 2008; Martinez-Nicolas et al., 2011; Peeters et al., 2021; Smolders et al., 2012), as can be seen in Table 12 of the appendix.

A metric often used to describe to describe variability in a sample is the standard deviation. A variant of this, the coefficient of variation, or relative standard deviation (Brown, 1998), is an option that would allow for better comparability between studies. Prior research on the relations between sleep quality and light exposure and vitality and light exposure appears have studied neither the standard deviation nor the relative standard deviation in their analyses (see Table 3).

To include the speed at which light level changes, rather than only the variability, the rate of change (also known as slope) can be considered. This is the difference in light level between two time points, divided by the difference in time (Adams & Essex, 2018b). The issue with this aggregation, is that it does not describe all differences across the trajectory; if the light level varies strongly between three time points, but the direction of this variation is opposed between timepoints one and two, and two and three, then the rate of change would be either zero or smaller than the actual change in this timeframe leading to an incorrect conclusion. One solution which was previously researched can be seen in Table 1; the larger scale cosine periodicity which is related to the day-night cycle (Espiritu et al., 1994; Grandner et al., 2006; Jean-Louis, Kripke, Cohen, et al., 2005; Jean-Louis, Kripke, Elliott, et al., 2005; Koller et al., 1993; Kripke et al., 2004; Van Der Maren et al., 2018), although this disregards the smaller scale variability in favour of the larger scale cosine pattern. Another solution which still allows one to study the smaller scale changes, would be by using the average of the absolute rates of change.

An alternative to the coefficient of variation and the rate of change is the consecutive disparity index. This is a variability index aimed at taking the chronological order of observations into account (Fernández-Martínez et al., 2018; Martín-Vide, 1986). Fernández-Martínez et al. (2018) therefore advise its use in the study of temporal variability in field studies after comparing it

to the coefficient of variation and proportional variability indices. This metric has previously been used in sleep research by Kompier and colleagues (2022)[2], who found that an increase in the consecutive disparity index was significantly related to a decrease in sleep onset and an increase in sleep duration.

1.4 Rationale and research question

The overall trend in the review, was that exposure to higher light levels and longer durations of light exposure appear to be related to higher sleep quality and vitality. Even though there was a clear focus on light level assessments, the literature overview also demonstrated that new insights are being incorporated; for example, with regards to the spectrum of light, a first step was made with the introductions of Vis-nonvis, circadian light, and circadian stimulus. However, as seen from the literature overview, the α-opic irradiances which are intended to be the current standard have not yet been used for analyses relating to person-based monitoring in field studies, largely due to the previous state of wearable technology.

A further lack of (utilised) aggregation metrics becomes apparent from the literature, not only on the topic of the spectral pattern, but also on the topic of the temporal pattern. In terms of temporal pattern, most focus has been on aggregations concerned with duration of light exposure at specific light levels.

Furthermore, studies generally used only one (or few) light related predictors, while a multitude would be required to capture a majority of information of the temporal and spectral distributions of light exposure, as the aggregations introduced so far only cover particular aspects of these patterns. Because the spectral composition and temporal pattern have not been fully explored, there is still much to learn about the relations between these light exposure features and sleep quality and vitality.

This has led to the following research questions: “Which set of light exposure quantifications are best to predict subjective sleep quality?” and “Which set of light exposure quantifications are best to predict subjective vitality throughout the day?”[3]. These two outcome measures were chosen because previous research revealed promising albeit mixed results when researching the relationship between these two concepts and light exposure (Figueiro et al., 2017; Figueiro et al., 2019; Hubalek et al., 2010; Peeters et al., 2021; Smolders et al., 2013). The current research will

3 Due to changes in methodology discussed in the method, this research question will not be studied further in this research.

consist of an exploratory pilot study, proposing a data-driven analysis methodology with the aim of extracting the most prominent features predicting sleep quality. It was hypothesised that a combination of Melanopic metrics representing multiple aspects of light exposure would be most effective at predicting subjective vitality throughout the day and subjective sleep quality, with a potential role for L-cone opic metrics in the prediction of subjective vitality and subjective sleep quality considering the research by Figueiro and Pedler (2020) and Sahin and Figueiro (2021) demonstrating alerting but non-melatonin-suppressing effects of red light in manipulated field studies[4].

4 Figueiro and Pedler (2020) did not measure light exposure in this study but supplemented red and blue light using glasses; hence it was not included in the literature review.

Method

The sections below describe the original plan for the study, which was executed as such for three weeks with five participants in total. One of these participants dropped out after the intake briefing. However, due to challenges with recruitment in part due to the COVID-19 pandemic, changes were made to the experiment during its execution. These changes will be described in their relevant sections.

2.1 Design

This field study was performed in the semi-longitudinal format of seven days. The aim of this study was to assess the associations between light exposure and momentary vitality throughout the day, and between daily light exposure and subsequent sleep quality. To this end, participants wore wearable spectroradiometers as a pendant to measure the spectral power distribution of light they were exposed to, and filled out morning diaries, daily logbooks, and experience sampling questionnaires (8 times a day at random moments, with at least 30 minutes between questionnaires). This research was conducted in collaboration with other researchers, therefore more questionnaires were filled out than required for this specific study. Variables that were measured for the other studies will not be analysed in this research, but will also be listed below for completeness.

After the changes due to the recruitment problems, the field study was performed in the format of four full days, five nights, and an additional fifth morning. Additionally, the relations between light exposure and momentary vitality throughout the day could no longer be explored. Payment for all participants remained the same, to ensure that the changes were fair to participants for whom the changes took place during their measurement period. These participants were allowed to change to the new methodology during their measurement period.

2.2 Participants

Participants were recruited from the JSF participant database from Eindhoven University of Technology in addition to office workers and students recruited through convenience sampling. The last version of the invitation letter is included in Appendix 4. The following inclusion criteria applied; participants had to:

- be 18 years or older
- not be diagnosed with a chronic sleeping problem or self-reported sleep problems/regular sleep disturbances;
- not experience regular factors that (may) wake them up during the night;
- not use (prescription) drugs or sleep medication;
- work or study at least four days a week for six hours each work day;
- work at least roughly half the time from home during the measurement period;
- drink no more than five caffeinated beverages a day, and have none after five pm; and
- drink no more than two portions of alcohol on nights before free days and no alcohol at all before work days.

Due to the difficulties with participant recruitment, the following criteria were lifted which resulted in the participation of 11 more participants:

- no experience of regular factors that (may) wake them up during the night;
- drink no more than five caffeinated beverages a day, and have none after five pm; and
- drink no more than two portions of alcohol on nights before free days and no alcohol at all before work days.

Participants concluded their eligibility to participate based on these criteria themselves, therefore the researchers were not informed about the reasons for which they were ineligible to participate.

Because this research was exploratory, an a priori sensitivity analysis based on feasibility was performed to determine the smallest effect size that could reliably be detected with 33 participants (based on three sampling weeks with 11 wearable spectrometers), a required power of 0.90, and an α of 0.05. According to the sensitivity analysis, a study with these parameters should be able to detect a parameter estimate of 0.35 with an estimated power of 97%, a parameter estimate of 0.30 with a power of 93% and a parameter estimate of 0.25 with a power of 80%.

In total, 16 participants, of which nine were students, participated in the research (4 female, 11 male, 0 other, 1 preferred not to say), with a mean age of 31.13 (range: 19 – 62, *SD* = 15.28). Participants had on average a chronotype of 4.46 (range: 2.88 – 6.38, *SD* = 1.15, therefore not including any extreme chronotypes (Kühnle, 2006)), an average SF-12 physical score of -1.30

(range: -10.77 – 5.31, *SD* = 4.76), and an average PSQI score of 4.67 (range: 2 – 7, *SD* = 1.50, which indicates the inclusion of poor sleepers with a score of PSQI > 5 (Buysse et al., 1989b)). One additional participant took part in a briefing, but declined participation afterwards.

During the data cleaning phase of this research it became apparent that students had not participated conscientiously. They generally did not report whether they wore the spectroradiometer or not, making it impossible to distinguish between whether the data was from when the sensor was worn or not. The office workers' logbooks made it apparent that it was quite common for participants to start wearing the spectroradiometers up to roughly an hour after they indicated waking up, and to stop wearing the device up to roughly an hour before actually going to sleep. Therefore, the uncertainty as to when student participants wore the device added a lot of noise to the data. Moreover, they were often missing multiple consecutive days of data, likely because they forgot to download the data from the spectroradiometer in time before it was overwritten. For these reasons, it was decided to only use the data from office workers.

This reduced the dataset to 7 participants (2 female, 5 male, 0 other, 0 preferred not to say), with a mean age of 44.43 (range: 26 – 62, *SD* = 14.62). Two of the seven office workers participated in accordance with the original methodology. Participants had on average a chronotype of 3.93 (range: 2.88 – 6.38, *SD* = 1.29, therefore not including any extreme chronotypes (Kühnle, 2006)), and an average PSQI score of 4 (range: 3 – 7, *SD* = 1.41, which indicates the inclusion of poor sleepers with a score of PSQI > 5).

2.3 Measures

2.3.1 Intake questionnaire

The intake questionnaire started with demographic questions on age and gender. After the demographic questions, the ultra-short Munich Chronotype Questionnaire (µMCTQ; Ghotbi et al., 2019) of 6 items was employed to assess participant's chronotype using questions about their sleep timing and wake timing habits during work and work-free days. The Pittsburgh Sleep Quality Index (PSQI; (Buysse et al., 1989a)) of 24 items asking participants about their subjective sleep quality, sleep latency, sleep duration, habitual sleep efficiency, sleep disturbances, medication usage, and daytime functioning in the past month was employed to assess general past sleep quality. The 27-item Light Exposure Behaviour Assessment (LEBA; Siraji et al., 2021) was used to ask participants about their light exposure-related behaviours during the last four weeks; blue-light filter usage, natural light exposure, smart device usage, light related bed time habits, and electrical light usage at

home, on five-point Likert scales ranging from 1 = never to 5 = always. The 12 item Short Form Survey (SF-12; Ware et al., 1996) was included to assess the impact of physical and mental health on the participants' daily life, including one question on vitality. Lastly, the participants were asked to answer ten questions about their main workplace at home and their main workplace outside their home (e.g. office or university). These workplace related questions can be found in Appendix 2.[5]

2.3.2 Morning diary

In the morning the participants filled in the extended Consensus Sleep Diary (CSD-M; Carney et al., 2012) consisting of 21 items to assess their sleep timing, sleep duration during the night, their subjective sleep quality, as well as sleep medicine use, alcohol, and caffeine intake on the previous day. An item on whether they woke up by an alarm was also included. [6] For this study, only the question on subjective sleep quality on a likert scale from *1 (very poor)* to *5 (very good)* was used.

2.3.3 Experience sampling questionnaire

The experience sampling questionnaire assessed participants' mental state. Firstly with the sub-scales Energy (to assess subjective vitality; 5 items) and Tension (to assess subjective stress; 5 items) from Thayer's (1989) Activation-Deactivation Adjective Check List (AD ACL). These items were presented with a four-point Likert scale format, ranging from *1 = definitely do not feel* to 4 = *definitely feel*. Two separate items in the same format were added to this, one to assess Happiness and one to assess Sadness. Lastly, sleepiness was assessed with the 1-item Karolinska Sleepiness Scale (KSS; Shahid et al., 2011) on a 9 point Likert scale ranging from *1 = extremely alert* to *10 extremely sleepy – fighting sleep*.

Due to difficulties with recruitment the experience sampling questionnaire was removed from the study completely, in order to lower participant burden. Therefore, the Cronbach's α's of these scales was not reported, and the small amount of data that was gathered with the experience sampling questionnaire before it's removal was not analysed.

2.3.4 Logbook

Throughout the day, participants reported their total screen time, which workplaces they worked at

5 From these questionnaires only the µMCTQ and PSQI were used (as demographics data in the previous section)
6 In the current analysis, only the subjective sleep quality item from the CSD-M was analysed.

during that day, their total work and study time, and filled out a modified version of the Harvard Light Exposure Assessment (H-LEA; Bajaj et al., 2011) in which participants indicated for each hour of the day how much of that hour was spent indoors (in minutes) and to which of four light source types they were exposed to most (daylight only, electric light only, daylight and electric light, no light source) and whether they used an extra desk lamp or not. Participants were also asked to indicate when and for how long they were not wearing the wearable spectrometer, for example when showering. When preferred by participants this was initially done on paper throughout the day after which they received a reminder in the evening to digitise their logbook, rather than filling it in digitally throughout the dat. [7]

2.3.5 Wearable spectroradiometer

Eleven wearable spectroradiometers (nanoλ XL-500H BLE; Nanolambda, 2020) were available, ten with a measurement range from 390 nm to 760 nm, one with a measurement range from 340 nm to 1010 nm. These devices were worn at chest height as a pendant, and were set to take a measurement every 30 seconds. Participants were required to download their data to the provided smartphone twice a day, once after waking up, and once before going to bed). The linearity and directionality indices of the sensors can be found in Appendix 3. The linearity indices were used to calculate calibration factors with which to correct the data from the wearable spectroradiometers.

An overview of light aggregations based on the data recorded by the wearable spectroradiometers which were used for this research will be given below. Some of these have not been used in the literature discussed in the above sections. The formulas of the aggregations discussed below can be found in Table 23 in the appendix.

2.3.5.1 Light level and spectral pattern

As mentioned above in section 1.4, the CIE has decided that in order to take the spectrum of light into account, the α-opic irradiances are currently the best metric. These were therefore used in addition to illuminance values for the purposes of this research, in order to calculate the other light aggregates. This allowed for the study of the spectrum of light in terms of photo-receptor sensitivities, while also allowing for comparison between studies that did not study the spectrum of light. Light level and spectral pattern were aggregated into the daily average α-opic irradiances and

7 No logbook data was analysed in this research, other than for the facilitation of determining when the spectroradiometers were worn or not.

illuminances, and the radiant and luminous exposure using data of when the wearable spectroradiometer was worn between waking and falling asleep. The period length of each daily average differed therefore between participants and each day.

2.3.5.2 Temporal pattern

For the study of the temporal pattern, this study used several aggregations based on the α-opic irradiances; the average rate of change, the coefficient of variation, and the consecutive disparity index. The average rate of change was calculated using the absolute rates of change between each measurement, because even though the direction of change was lost in these absolute values, the average magnitudes of change were correct as negative and positive slopes would no longer cancel each other out. Due to the consecutive disparity index' focus on the temporal aspect of the data, values of zero would have been problematic as they would not have returned a value due to a log transform and a potential division by zero. For this reason, Fernández-Martínez et al. (2018) followed the advise of Gaston and McArdle (1994) and added 0.01 times the mean to both the current and next measurement values. This version of the consecutive disparity index was also used in this study.

2.4 Procedure

The current study was allocated a measurement period of roughly three weeks, roughly one week after the transition from summer to winter time in November of 2021. Participants started their participation on their "day 0" with a briefing on the study, during which they were explained what was expected of them. During this meeting they filled in the informed consent form and the data handling form. Participants then received a wearable spectrometer and a smartphone, and after signing the aforementioned forms they installed the Metricwire app (Metricwire, 2021) used to send reminders throughout the day. They had four options for the times during which the reminders would be sent; between 07.00 and 21.00, between 08.00 and 22.00, between 09.00 and 23.00, or between 10.00 and 00.00. If they did not have a roommate or bedpartner they filled in the intake questionnaire during this briefing session, else they filled it in at home. The experiment then lasted for seven consecutive days.

During each of the seven measurement days, participants started their day by filling in the morning questionnaire, and ended their day by digitising the pen and paper logbook they kept throughout the day in case they used the back-up paper version. Participants were instructed to wear

the wearable spectroradiometers while awake, and at all times on top of their clothes at chest height (unless they had to protect it from water). During the night, they were instructed to place the uncovered spectrometer on their nightstand next to their bed. Eight times per day at random moments with at least 30 minutes in between, they were prompted with a push-notification on their smartphone to fill in the experience sampling questionnaire. Questionnaires remained accessible for 30 minutes before being closed, to prevent participants from filling them in later than instructed, in order to limit the introduction of bias. Participants were instructed to hand in the wearable spectrometer and smartphone on day eight. Day eight was then day zero for the next group of participants.

After the methodological changes, the study started on a Sunday night for all participants. They started the light measurements that Sunday night, but the questionnaires started the following morning. Their participation ended on Friday morning after the morning diary. Because the experience sampling questionnaire was dropped, they no longer had to choose a time frame for reminders, and did not receive push-notifications for the experience sampling questionnaires. The study ran from the 22nd of November 2021 to the 7th of January 2022.

2.5 Statistics

2.5.1 Pre-processing

The first step of pre-processing was performed by hand in a spreadsheet program, which consisted of marking the light exposure data in terms of whether the device was worn or not worn. The second step of pre-processing was performed in Matlab R2021b Update 2 (specifically the 64-bit Linux version; The Math Works Inc, 2021). This step consisted of reading in and organising the spectrum data of each participant of each day, correcting the spectrum data with the absolute correction factors, and transforming the spectrum data to α-opic irradiance metrics, which were in turn used to calculate the proposed measures (mean α-opic irradiance, coefficient of variation, luminous exposure, consecutive disparity index, and average rate of change. This was done using the formula's found in Table 23 of the appendix).

Because the following analysis was concerned with aggregations across the full day, measurement days with gaps larger than two hours in their irradiance data were regarded as missing. This was chosen as a measure against more extreme measurements having a larger influence on the aggregations in participants with more missing data. To help with transforming the

irradiance data to more normal distributions, it was logarithmically transformed in order to deal with potential large light level differences, for example between indoor and outdoor light exposure. This was done after calculating the daily consecutive Disparity indices, as the calculation of these already includes a logarithmic transformation. Furthermore, in order to focus on studying the differences between participants, make sure all predictors are on the same scale, and have parameter estimates reflect effect sizes, the data was standardised per participant (i.e. cluster based standardisation).

2.5.2 Assumption testing

Cluster-based standardisation[8] and assumption testing for the multilevel regressions were performed in R version 4.4.1 (R Core Team, 2021), which is an open source language and environment for statistics. The assumption tests were performed in two steps. Firstly the data of all variables was tested for normality (the daily mean α-opic irradiances, daily coefficient of variation, daily luminous exposure, daily consecutive disparity index, daily average rate of change, subjective vitality, and subjective sleep quality), with the Shapiro-Wilk test. (the shapiro.test function in R) If variables were not found to be normally distributed, an attempt was made to correctively transform them to a more normal distribution with the transformTukey() function in the R rcompanion package (Mangiafico, 2021).

The second step of the assumption testing was performed after modelling the data as described below in section 2.4.3 Statistical analyses below, taking the nested structure of the data into account. These assumptions were homogeneity of variance, normality of residuals, and linearity of the α-opic irradiances and subjective sleep quality and subjective vitality. At this stage, outliers were also assessed in terms of leverage points, outliers on the residuals, and Cook's distance. After the second step of assumption testing, analyses were performed with and without outliers. Both versions were reported; the version without outliers in the main text of the results section, the version with outliers in Appendix 5. The ggplot2 package (Wickham, 2016) was used to for scatter plots with regression lines used to visually inspect linearity, in addition to heatmaps of the variables chosen after hierarchical multilevel modelling. Normality of residuals was tested with the Shapiro-Wilk test, heteroscedasticity was tested with the leveneTest function from the car package (Fox & Weisberg, 2018), and multicollinearity was tested with the vif function from the car R package. A variance inflation score of higher than five was considered an indication of significant

8 Cluster-based standardisation was performed by subtracting the participant based average from their respective observations, and dividing this by the respective participant based standard deviation.

multicollinearity due to the small sample size, and this was used as a manual first feature selection step as the next automated step partly depended on variance. Pearson's correlations between model predictors were post estimated with the summary command from R's lmerTest package (Kuznetsova et al., 2017).

Assumptions for subjective vitality were not tested, as this data was not measured for the majority of the participants.

2.5.3 Statistical analyses

The explorative analyses were performed in two steps. In the first step, twelve multilevel regressions were performed to determine which combinations of light aggregations were successful at describing the relationship between light and the two outcome variables (subjective vitality and subjective sleep quality). More specifically, this entailed the execution of multilevel regressions with the R package lme4 (Bates et al., 2015) focussed on each of the five photoreceptors or illuminance, consisting of the five aggregates associated with the specific photoreceptor or illuminance focussed on in that analysis, for each of the two outcome variables. The second step consisted of two multilevel hierarchical regressions (one for subjective vitality and one for subjective sleep quality) using the step function from R's lmerTest package (Kuznetsova et al., 2017), which was a process of backwards feature selection focussed on Akaike's Information Criterion aimed at investigating which predictors best described the relation between the light exposure based predictors and the two outcome variables, and whether the multilevel structure contributed to a better model. The variables included in these regressions, all based on all five of the α-opic irradiances and illuminance were:

- daily Average α-opic Irradiances,
- daily Coefficients of Variation,
- daily Radiant or Luminous Exposures,
- daily Consecutive Disparity Indices,
- and daily average absolute Rates of Change.

Analyses for subjective vitality were not performed, as this data was not measured for the majority of the participants as they participated under the altered methodology. Therefore, only six multilevel regressions were performed rather than twelve, and only one multilevel hierarchical regression rather than two.

Results

Out of the four sampling days, three of the morning diaries and three days of light exposure measurements were missing. It is important to note, however, that two of the seven office workers participated in accordance with the original methodology. They therefore participated consecutively from Wednesday morning to Wednesday morning rather than consecutively from Sunday evening to Friday morning, and therefore their Wednesday data does not consecutively follow their Tuesday data. Because of this, week days were not ordered sequentially in the visualisations below, in order to prevent the implication of full consecutiveness for all participants.

The dataset included 28 daily observations, of which 23 were complete. Standardisation caused four more missing variables, however, as one participant had no variation in subjective sleep quality. Therefore, the dataset consisted of a total of 19 useable daily observations. Table 2 and Figure 1 below show that for many of the variables normality was not supported.

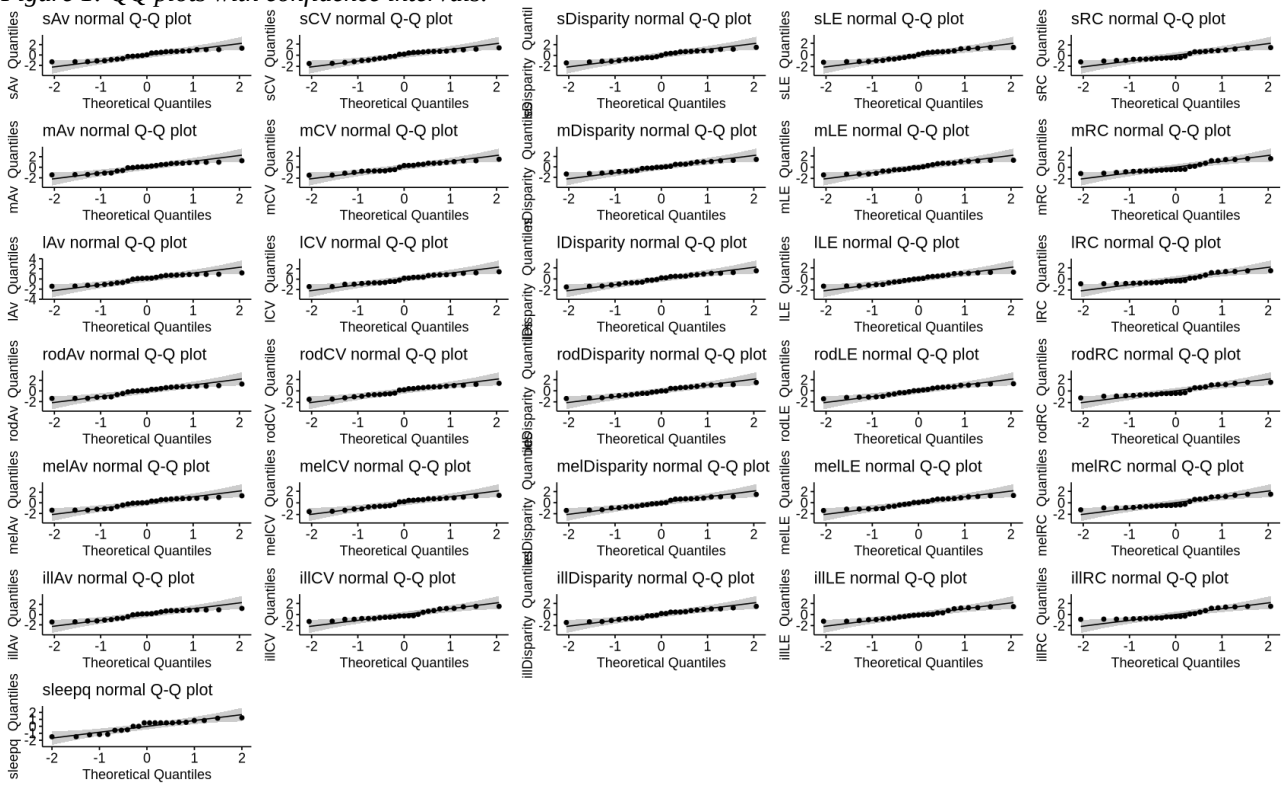
Table 2: Shapiro-Wilk test results. [9]

Name	*W*	*p-value*	Name (contintued)	*W*	*p-value*
sAv	0.92	0.042	rodCV	0.93	**0.109**
sCV	0.93	**0.078**	rodDisparity	**0.95**	**0.253**
sDisparity	0.94	**0.160**	rodLE	0.94	**0.135**
sLE	0.92	**0.050**	rodRC	0.88	0.007
sRC	0.89	0.011	melAv	0.91	0.029
mAv	0.91	0.024	melCV	0.93	**0.076**
mCV	0.94	**0.147**	melDisparity	0.94	**0.167**
mDisparity	**0.95**	**0.249**	melLE	0.93	**0.112**
mLE	0.93	**0.105**	melRC	0.88	0.008
mRC	0.86	0.003	illAv	0.90	0.017
lAv	0.90	0.018	illCV	0.91	0.033
lCV	0.94	**0.193**	illDisparity	**0.95**	**0.309**
lDisparity	**0.95**	**0.300**	illLE	0.92	**0.066**
lLE	0.92	**0.062**	illRC	0.83	0.001
lRC	0.83	0.001	sleepq	0.89	0.020
rodAv	0.91	0.028			

Note. $W \geq 0.95$ and $p \geq 0.05$ are marked in bold.

9 s: S-cone-opic, m: M-cone-opic, l: L-cone-opic, rod: Rhodopic, mel: Melanopic, ill: illuminance, Av: daily average irradiance or illuminance, CV: daily Coefficent of Variation, Disparity: daily consecutive Disparity index, LE: Luminous or Radiant Exposure, RC: daily average absolute Rate of Change, sleepq: subjective sleep quality.

Figure 1: QQ plots with confidence intervals. [10]



Transformation of the data was attempted in such a way that all variables with the same aggregation method would be transformed to (more) normal distributions with the same formula. However, for the not yet normally distributed variables transformation to a normal distribution was either not possible, or other variables of the same type would become less normally distributed. For example, in the case of the daily average absolute Rates of Change, the Rhodopic and Melanopic based versions could have been transformed to a more normal distribution by multiplying them by -1 and taking the reciprocal value, but this transformation would have caused the others to become significantly less normally distributed than they already were. Therefore, it was decided to not perform this transformation. Table 3 shows the descriptive statistics of the predictors and outcome variable. The means are all 0 as a result of the cluster-based standardisation.

10 s: S-cone-opic, m: M-cone-opic, l: L-cone-opic, rod: Rhodopic, mel: Melanopic, ill: illuminance, Av: daily average irradiance or illuminance, CV: daily Coefficent of Variation, Disparity: daily consecutive Disparity index, LE: Luminous or Radiant Exposure, RC: daily average absolute Rate of Change, sleepq: subjective sleep quality.

Table 3: Descriptive statistics of the predictors and dependant variable after cluster-based standardisation. [11]

Name	*mean*	*sd*	*minimum*	*maximum*	Name (continued)	*mean*	*sd*	*minimum*	*maximum*
sAv	0.00	0.87	-1.32	1.31	rodCV	0.00	0.87	-1.50	1.34
sCV	0.00	0.87	-1.50	1.33	rodDisparity	0.00	0.87	-1.40	1.50
sDisparity	0.00	0.87	-1.41	1.49	rodLE	0.00	0.87	-1.46	1.28
sLE	0.00	0.87	-1.26	1.28	rodRC	0.00	0.87	-1.21	1.50
sRC	0.00	0.87	-1.20	1.50	melAv	0.00	0.87	-1.40	1.32
mAv	0.00	0.87	-1.44	1.24	melCV	0.00	0.87	-1.50	1.29
mCV	0.00	0.87	-1.48	1.42	melDisparity	0.00	0.87	-1.41	1.49
mDisparity	0.00	0.87	-1.37	1.43	melLE	0.00	0.87	-1.43	1.30
mLE	0.00	0.87	-1.39	1.24	melRC	0.00	0.87	-1.23	1.50
mRC	0.00	0.87	-1.08	1.49	illAv	0.00	0.87	-1.45	1.20
lAv	0.00	0.87	-1.44	1.20	illCV	0.00	0.87	-1.26	1.47
lCV	0.00	0.87	-1.44	1.45	illDisparity	0.00	0.87	-1.45	1.47
lDisparity	0.00	0.87	-1.46	1.47	illLE	0.00	0.87	-1.22	1.42
lLE	0.00	0.87	-1.31	1.22	illRC	0.00	0.87	-0.88	1.49
lRC	0.00	0.87	-0.87	1.48	sleepq	0.00	0.87	-1.50	1.22
rodAv	0.00	0.87	-1.41	1.30					

The analysis which included outliers can be found in Appendix 5. The decision was made to report the analyses both with and without outliers in full due to the small sample size, as well as to further illustrate the differences the removal of outliers could make. Outlier analysis was performed using the z-scores of the individual variables, and the post estimations after the execution of the final model of the analysis with outliers found in Appendix 4 in terms of leverage points, residuals, and Cook's distances. The z-scores based outlier analysis found no outliers. No leverage points or outliers on the residuals were found, but two outliers were found using Cook's distances. The outliers and missing observations together added up to 11 unusable daily observations out of 28, or 17 useable daily observations.

When performing the six multilevel regressions for the separate photoreceptors and illuminance based aggregations without the outliers, multicolinearity was found in the data for the daily M-cone-opic and L-cone-opic Average Irradiances and Radiant Exposures as their VIF scores were higher than five (see Table 4). This variance inflation was reflected in the Pearson correlation between the M-cone-opic daily Average Irradiance and the daily Radiant Exposure (r = -0.80), and between the L-cone-opic daily Average Irradiance and the daily Radiant Exposure (r = -0.79).

11 s: S-cone-opic, m: M-cone-opic, l: L-cone-opic, rod: Rhodopic, mel: Melanopic, ill: illuminance, Av: daily average irradiance or illuminance, CV: daily Coefficent of Variation, Disparity: daily consecutive Disparity index, LE: Luminous or Radiant Exposure, RC: daily average absolute Rate of Change, sleepq: subjective sleep quality.

These correlations were calculated without taking a multilevel structure into account, as the random intercepts were not statistically significant. Excluding the predictors with the highest VIF score (the daily M-cone-opic and L-cone-opic Average Irradiance) from the analyses resulted in lower VIF scores (see Table 5). Therefore, only the regression estimates of models with these variables excluded will be reported below in Table 6. As can be seen in Table 6, only the daily average absolute Rates of Change appear to be significant predictors of subjective sleep quality. The degrees of freedom vary between predictors in the L-cone model as a result of tiny differences in intercept in this multilevel model.

Table 4: Variance inflation factor scores for the separate models without outliers after cluster-based standardisation. [12]

prefix	Av	CV	Disparity	LE	RC
s	3.55	1.24	1.24	2.70	1.47
m	**5.14**	1.64	1.37	3.18	1.66
l	**6.06**	1.91	1.46	3.40	1.83
rod	4.70	1.44	1.31	3.15	1.67
mel	4.44	1.36	1.31	3.08	1.66
ill	2.52	1.38	1.37	1.88	1.92

Note. VIF ≥ 5 is marked in bold. One row represents one model corresponding to a cluster of variables relating to one specific photoreceptor or illuminance (see the prefix column).

Table 5: Variance inflation factor scores for the separate models without outliers after cluster-based standardisation and after removing variance inflating aggregates. [12]

prefix	Av	CV	Disparity	LE	RC
s	3.55	1.24	1.24	2.70	1.47
m	-	1.06	1.13	1.13	1.11
l	-	1.17	1.28	1.30	1.36
rod	4.70	1.44	1.31	3.15	1.67
mel	4.44	1.36	1.31	3.08	1.66
ill	2.52	1.38	1.37	1.88	1.92

Note. One row represents one model corresponding to a cluster of variables relating to one specific photoreceptor or illuminance (see the prefix column).

12 s: S-cone-opic, m: M-cone-opic, l: L-cone-opic, rod: Rhodopic, mel: Melanopic, ill: illuminance, Av: daily average irradiance or illuminance, CV: daily Coefficent of Variation, Disparity: daily consecutive Disparity index, LE: Luminous or Radiant Exposure, RC: daily average absolute Rate of Change, sleepq: subjective sleep quality.

Table 6: Regression estimates for the separate models without outliers after cluster-based standardisation. [13]

Model	*Degrees of Freedom*	Name	*Estimate*	*Standard Error*	*p-value*
S-cone	11	Intercept	0.19	0.16	0.270
		sAv	-0.21	0.32	0.530
		sCV	0.05	0.22	0.814
		sDisparity	-0.13	0.20	0.521
		sLE	0.35	0.28	0.236
		sRC	-0.61	0.21	**0.014**
M-cone	12	Intercept	0.18	0.14	0.220
		mCV	0.07	0.17	0.695
		mDisparity	-0.21	0.18	0.278
		mLE	0.07	0.17	0.690
		mRC	-0.63	0.16	**0.002**
L-cone	4.38	Intercept	0.19	0.14	0.240
	8.55	lCV	0.08	0.17	0.646
	11.19	lDisparity	-0.36	0.20	0.097
	10.54	lLE	-0.01	0.19	0.941
	10.12	lRC	-0.70	0.17	**0.002**
Rod	11	Intercept	0.17	0.16	0.310
		rodAv	-0.10	0.38	0.789
		rodCV	0.05	0.23	0.831
		rodDisparity	-0.08	0.21	0.720
		rodLE	0.23	0.30	0.462
		rodRC	-0.60	0.22	**0.020**
ipRGC	11	Intercept	0.17	0.16	0.330
		melAv	-0.10	0.37	0.791
		melCV	0.07	0.23	0.762
		melDisparity	-0.06	0.21	0.789
		melLE	0.26	0.31	0.421
		melRC	-0.58	0.23	**0.025**
Illuminance	11	Intercept	0.22	0.13	0.120
		illAv	0.09	0.23	0.715
		illCV	-0.03	0.19	0.862
		illDisparity	-0.27	0.19	0.184
		illLE	-0.31	0.20	0.147
		illRC	-0.71	0.19	**0.004**

Note. The degrees of freedom are listed once if every predictor in that model had the same number, but listed for every predictor in case they differed. $P \leq 0.05$ is marked in bold. Random intercepts were not statistically significant.

13 s: S-cone-opic, m: M-cone-opic, l: L-cone-opic, rod: Rhodopic, mel: Melanopic, ill: illuminance, Av: daily average irradiance or illuminance, CV: daily Coefficent of Variation, Disparity: daily consecutive Disparity index, LE: Luminous or Radiant Exposure, RC: daily average absolute Rate of Change, sleepq: subjective sleep quality.

A subsequent stepwise feature selection, or hierarchical multilevel regression step was performed for each of the models with aggregations corresponding to a single photoreceptor or illuminance. The regression estimates of this step can be found in Table 7. These models showed no significant differences in intercept between participants, as the multilevel structures were rejected by the automated feature selection. As can be seen in Table 8, all models have support for homogeneous variances, and all models have support for normally distributed residuals. Therefore the regression assumptions hold for all models. The daily average Rates of Change appeared to be significant negative predictors of subjective sleep quality in their respective models, with medium effect sizes. Figure 2 shows scatter plots with the regression lines of the models, and due to their great visual similarity high multicollinearity would be expected if they were to be combined into one model. Figure 3 shows heat maps of the variables in these models, visually representing their distributions per day and participant. The heat map for subjective sleep quality shows that there was very little variance in this variable.

Table 7: Regression estimates for the separate models after hierarchical modelling without outliers after cluster-based standardisation. [14]

Model	*Degrees of Freedom*	Name	*Estimate*	*Standard Error*	*p-value*
S-cone	15	Intercept	0.14	0.15	0.340
		sRC	-0.52	0.17	**0.007**
M-cone	15	Intercept	0.16	0.13	0.230
		mRC	-0.60	0.15	**0.001**
L-cone	15	Intercept	0.16	0.14	0.250
		lRC	-0.58	0.15	**0.002**
Rod	15	Intercept	0.15	0.14	0.290
		rodRC	-0.55	0.16	**0.003**
ipRGC	15	Intercept	0.15	0.14	0.310
		melRC	-0.53	0.16	**0.005**
Illuminance	15	Intercept	0.16	0.13	0.240
		illRC	-0.58	0.15	**0.002**

Note. P < 0.05 is marked in bold.

14 s: S-cone-opic, m: M-cone-opic, l: L-cone-opic, rod: Rhodopic, mel: Melanopic, ill: illuminance, Av: daily average irradiance or illuminance, CV: daily Coefficent of Variation, Disparity: daily consecutive Disparity index, LE: Luminous or Radiant Exposure, RC: daily average absolute Rate of Change, sleepq: subjective sleep quality.

Figure 2: Scatterplots and regression lines of the variables in their respective photoreceptor or illuminance specific models without outliers after cluster-based standardisation.

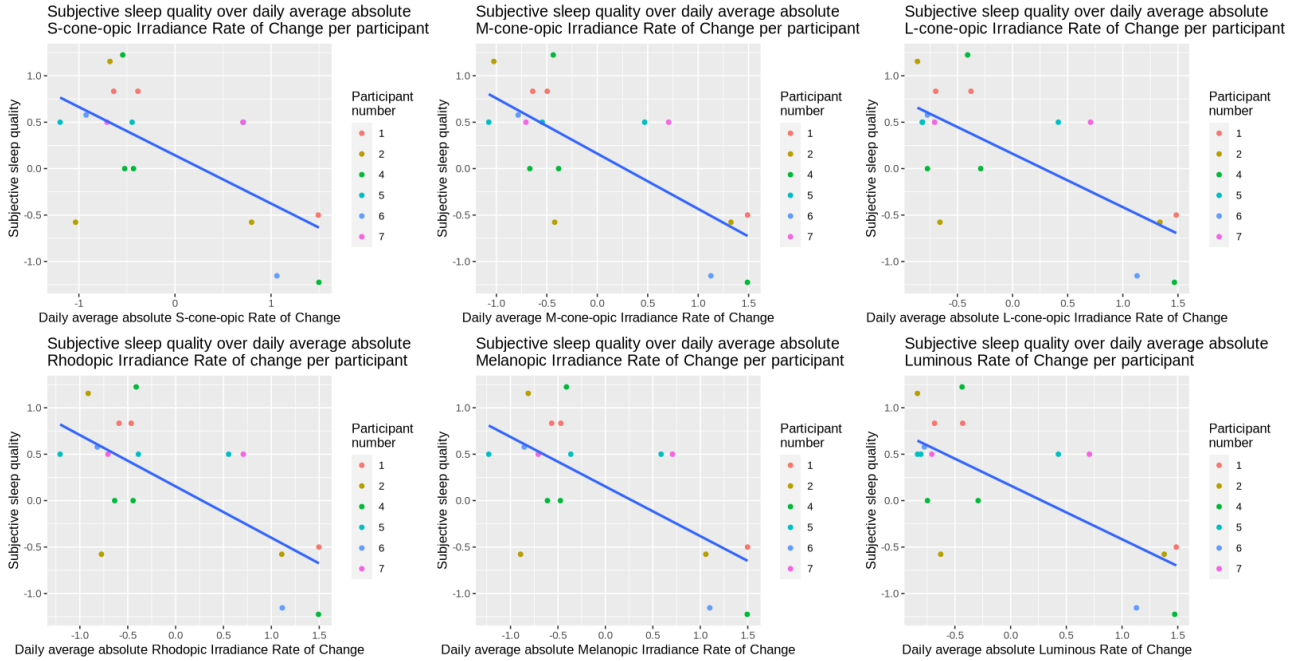
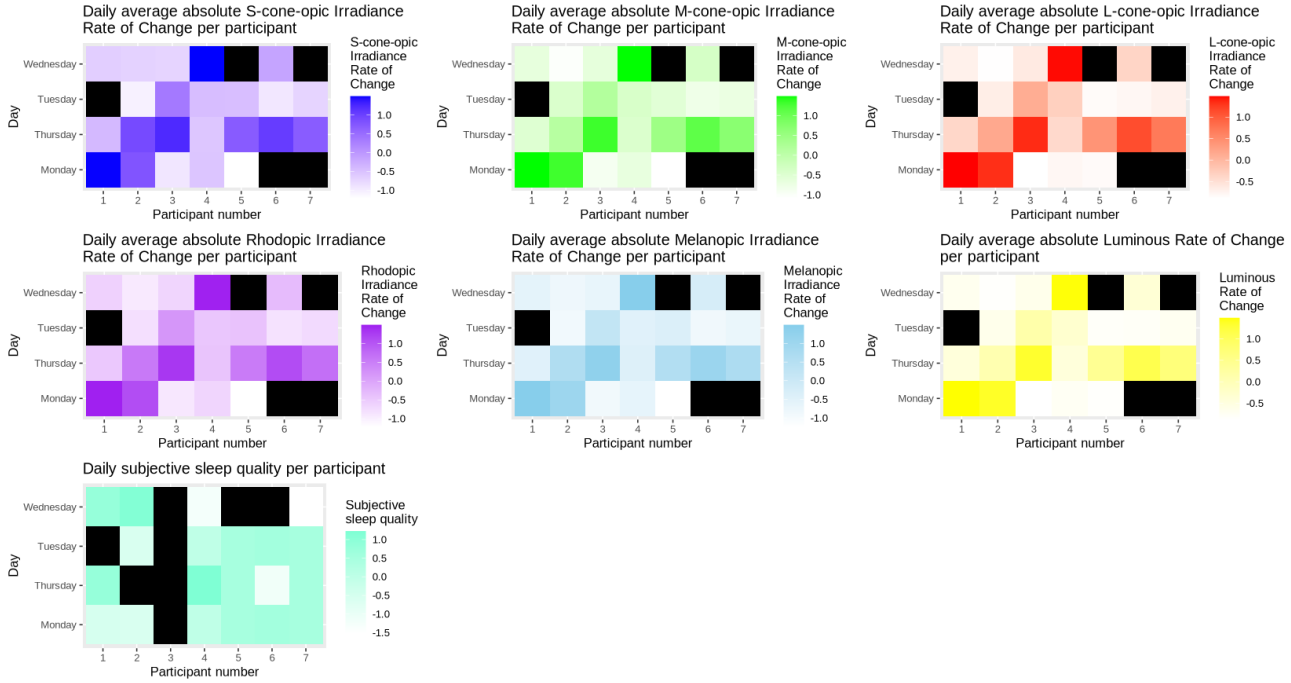


Table 8: Shapiro-Wilk and Levene's tests, ICC's, AIC's, and adjusted R^2's for the photoreceptor and illuminance models without outliers after cluster-based standardisation.

Model	$F_{Levene's}$	$p_{Levene's}$	W	$p_{Shapiro-Wilk}$	AIC	Adjusted R^2
S-cone	0.51	**0.762**	**0.96**	**0.557**	35.0	0.35
M-cone	0.38	**0.854**	**0.97**	**0.896**	30.7	0.50
L-cone	0.41	**0.832**	**0.97**	**0.891**	32.2	0.45
Rod	0.41	**0.834**	**0.98**	**0.905**	33.2	0.41
ipRGC	0.44	**0.812**	**0.97**	**0.865**	34.2	0.38
Illuminance	0.42	**0.823**	**0.97**	**0.897**	31.9	0.46

Note. $W \geq 0.95$ and $p \geq 0.05$ are marked in bold.

Figure 3: Heat maps of the variables in the photoreceptor and illuminance models without outliers after cluster-based standardisation. Black squares represent missing observations, and observations which were marked as outliers and removed.



The sample size was too small to allow for a hierarchical overall model to be constructed based on all light exposure based predictors. Therefore hierarchical modelling for the final model was conducted with the predictors from the separate models post hierarchical modelling. Combining these variables resulted in variance inflation. Therefore, before performing a hierarchical regression, the variable with the highest VIF score was removed in an iterative process until no variable in the regression had a VIF score higher than 5. This process can be seen in Table 9, in which each row represents a new VIF score calculation step with the previous highest VIF scoring predictor removed. The presence of variance inflation is no surprise given the high Pearson correlations between multiple variables, as can be seen in Table 10. These correlations were calculated without taking a multilevel structure into account, as the random intercepts were not statistically significant. The parameter estimates of the model after the first VIF based feature selection can be found below in Table 11. Neither of the two remaining predictors appears to significantly contribute to the prediction of subjective sleep quality when combined into one model.

Table 9: Variance inflation factor scores for the final model without outliers after cluster-based standardisation during the iterative removal of multicolinearity suspects based on their VIF score. [15]

Iteration	sRC	mRC	lRC	rodRC	melRC	illRC
1	**144.00**	**1940.80**	**5448.13**	**13959.71**	**8320.65**	**7220.85**
2	**139.25**	**150.16**	**1863.51**	**-**	**285.71**	**2150.77**
3	**139.24**	**127.01**	**59.35**	-	**284.67**	**-**
4	**15.56**	**55.99**	**52.64**	-	**-**	**-**
5	**14.03**	**-**	**14.03**	-	**-**	**-**

Note. VIF > 5 is marked in bold.

Table 10: Pearson's correlations overview of the variables potentially included in the final model without outliers after cluster-based standardisation. [15]

	sRC	mRC	lRC	rodRC	melRC
mRC	-0.01	-	-	-	-
lRC	-0.18	**0.82**	-	-	-
rodRC	0.18	**-0.96**	**-0.81**	-	-
melRC	-0.35	**0.91**	**0.80**	**-0.98**	-
illRC	0.15	**-0.86**	**-0.99**	**0.84**	**-0.82**

Note. R > 0.50 is marked in bold.

Table 11: Regression estimates for the final model before hierarchical modelling without outliers after cluster-based standardisation. [15]

Name	*Degrees of Freedom*	*Estimate*	*Standard Error*	*p-value*
Intercept	14	0.18	0.14	0.210
sRC		0.54	0.58	0.371
lRC		-1.09	0.58	0.080

Note. P < 0.05 is marked in bold. The VIF scores are too high to allow both predictors in one model. This model is therefore only displayed for demonstrative purposes and is not suitable to be interpreted. Random intercepts were not statistically significant.

The hierarchical multilevel regression modelling step removed one more predictor from the final model, and only the L-cone average absolute Rate of Change was found to be a statistically significant negative predictor of subjective sleep quality with a medium effect size. Hence the final model is the same as the L-cone-opic model. The parameter estimates of this final model can therefore be found in Table 7, and the scatter plots with the regression lines of this model can be found in Figure 2. As can be seen in Table 8, this model did not appear to suffer from heteroscedasticity, had no significant differences in intercept between participants as the automated feature selection rejected the multilevel structure, and had support for normally distributed residuals. Therefore, the regression assumptions for this model are not violated.

15 s: S-cone-opic, m: M-cone-opic, l: L-cone-opic, rod: Rhodopic, mel: Melanopic, ill: illuminance, Av: daily average irradiance or illuminance, CV: daily Coefficent of Variation, Disparity: daily consecutive Disparity index, LE: Luminous or Radiant Exposure, RC: daily average absolute Rate of Change, sleepq: subjective sleep quality.

Discussion

In the current study, a small literature research was conducted into the relations between light exposure and subjective vitality and subjective sleep quality, and which metrics were previously used to quantify these relations. Light sensors were employed which also provided insights in the spectral pattern of light exposure, and as such allowed for computation of α-opic irradiance based metrics. Combined with high resolution light monitoring and self-reported assessments of sleep quality and vitality during the wake episode, this allowed for the extraction of features related to light level, spectral pattern, and temporal pattern from the light exposure data. The aim of this research was to discover which light exposure aggregations would be best to predict subjective vitality throughout the day, and subjective sleep quality. A semi-longitudinal design was employed in a field setting with wearable pendant-worn spectroradiometers, an intake questionnaire, daily Consensus Sleep Diaries, and logbooks in order to answer this question for subjective sleep quality. Due to the small sample size attained in this research, the research question and methodology with regards to subjective vitality (for which an experience sampling questionnaire at random intervals was implemented), were removed and the focus shifted to proposing an analysis methodology suited to performing a feature selection in data with a multitude of light exposure variables. This analysis methodology proposal was combined with a demonstration in which light exposure data was analysed with the aim of predicting subjective sleep quality.

The proposed methodology differed from previous research in that it starts with a greater amount of measured variables; the five α-opic irradiances relating to the different photoreceptors and illuminance, rather than just illuminance or blue light exposure. All six measures were then used to calculate multiple different aggregation types, rather than just aggregating illuminance or blue light measurements. The innovative part of this analysis methodology, therefore, is working with a great number of predictors, 30 in the case of this research. In order to deal with such a large number of predictors, the predictors were first divided into six groups based on the measure used to derive them. These were then used to calculate six different models aimed at predicting subjective sleep quality, one for each photoreceptor and illuminance. After the removal of variance inflating predictors, an automated backwards feature selection was performed on each of the models in order to find the best models for each photoreceptor and illuminance in order to predict subjective sleep quality. These remaining predictors were then combined similarly as to what was done for the different photoreceptor and illuminance models in order to come to a final overall model; first by

removing variance inflating predictors, and and then by performing an automated backwards feature selection.

In spite of the small dataset the demonstrated analysis methodology appears to be a viable analysis method worth exploring further with larger datasets, as it successfully allowed for the study of a great number of variables and yielded results which were interesting for future research. Additionally, the aggregations explored in this analysis also show potential for further use and testing with larger datasets. The daily average absolute rates of change in particular appear to be useful in predicting subjective sleep quality, as all the separate photoreceptor focussed models, the illuminance model, and the final model incorporated this aggregate.

The statistically significant negative relations between subjective sleep quality and the daily average absolute rates of change imply that smaller or fewer changes in light level over 30 second intervals result in better subjective sleep quality. Because the daily average absolute rates of change appear to not have been included in other research studying subjective sleep quality, this result cannot yet be compared directly to other studies. However, the conclusion does appear to be in line with photoreceptor sensitivity increase and decrease effects found in prior research. Chang and colleagues (2011) found that when participants were exposed to low light levels of roughly 1 lux for three days instead of typical room light at 90 lux before receiving a higher light level of 150 lux, they showed stronger circadian effects. The study by Te Kulve et al. (2019) complements these results, as they found that exposure to high light levels at 1200 lux at 4000 K for 2.5 hours in the early evening as opposed to exposure to dim light levels at 5 lux at 4000 K resulted in a smaller magnitude of acute melatonin suppressing effects resulting from 750 lux at 4000 K light exposure in the later evening. Furthermore, Thomas and Lamb (1999) found that in human rods recovery from fully bright light adapted (i.e. fully bleached photoreceptors) took 30 minutes with an S shaped curve, but half of the sensitivity was recovered after 13 to 17 minutes. Govardovskii et al. (2000) modelled this photoreceptor sensitivity adaption process of bleaching and recovery in photoreceptors (as a function of the chemical processes in the photoreceptors and the light level of the preceding light pulse that caused the sensitivity reduction (bleaching)). Furthermore, Govardovskii and colleagues (2000) note that while a very high light level would be required to fully saturate (i.e. bleach) rods, cones virtually never fully saturate due to their adaption characteristics. Depending on the speed of the described sensitivity changes in photoreception, this would imply that exposures at a constant light level may be related to smaller magnitudes in neuro-behavioural effects such as melatonin suppression than exposure to more variable or dynamic light levels, and vice versa. Higher average absolute Rates of Change are representative of such dynamic

light levels, and would therefore likely be related to increase in neuro-behavioural effects such as melatonin suppression. Melatonin suppression due to light exposure in the evening was previously found to be related to a reduction in sleep quality (Blume et al., 2019; Cain et al., 2020). These relations potentially underlying the relation between the average absolute Rates of Change and subjective sleep quality described above are illustrated in Figure 4. Due to the small sample size of this study, these results ought to be interpreted with caution, and more research with larger sample sizes would be required to verify these relations between average absolute Rates of Change and photoreceptor sensitivity, and between Rates of Change and subjective sleep quality, however.

The high variance inflation scores and correlation analyses showed that the different α-opic irradiance and illuminance daily average absolute Rates of Change were very strongly related to each other. This part of the analysis methodology then clearly fulfilled it's purpose; when used sequentially it allows for the study of which variables are strongly related to each other in terms of how much they overlap in the parts of the dependant variable variance they explain.

When this information is taken into account together with the small sample size, it is difficult to hold that any of the α-opic irradiance and illuminance daily average absolute Rates of Change would be a better predictor than the others, even though there appear to be differences between them in terms of how well they appear to predict subjective sleep quality in this small sample. Therefore, the most important conclusion from this finding is that it is very important to study the spectrum of light, rather than only illuminance in general. Further research is required to determine which of the alpha opic irradiances and illuminance are most strongly related to subjective sleep quality, and which aggregations are most suitable to perform in order to predict subjective sleep quality.

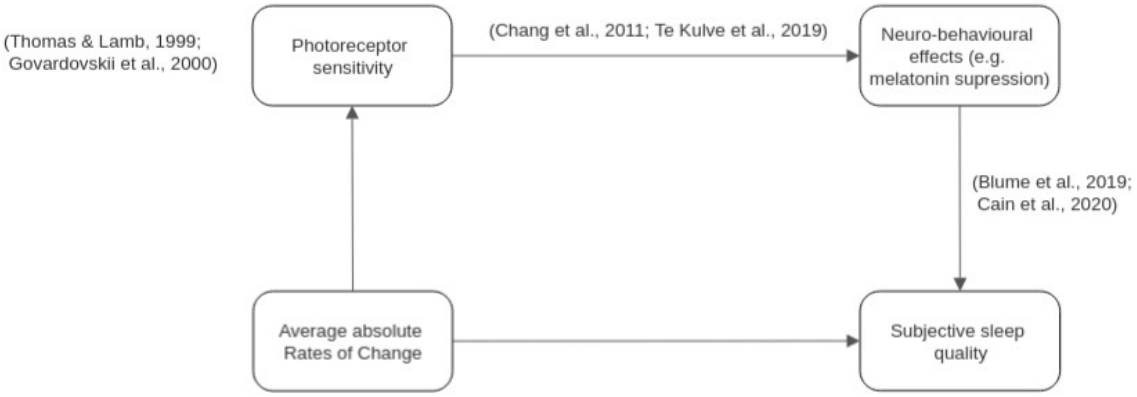


Figure 4: Hypothetical relations underlying the potential relation between subjective sleep quality and the average absolute Rates of Change.
Note. Due to the small samplesize, this as of yet unstudied hypothetical mediation process ought to be interpreted with caution.

4.1 Limitations

The first and foremost limitation of this research, is the small sample size. This study had only 7 eligible participants over only 4 days due to issues with compliance found in the student sample and multiple missing observations and outliers. This resulted in a sample size of 17 observations which had both light exposure and subjective sleep quality data, while the aim was to assess 30 different predictor variables. Because the multilevel structure was rejected for this dataset, a post-hoc sensitivity analysis for single-level data was performed using G*Power (Faul et al., 2007) to estimate the effect sizes that could reliably be detected. The sensitivity analysis showed that with an α of 0.05, a power of 0.90, and a sample size of 17, the smallest detectable effect size of regression parameter estimates that could be detected was 0.709. Because the effect sizes found for the significant predictors were smaller than the smallest effect size that could be found reliably, the found effects may be false positives, and hence should be interpreted with caution. Another limitation is the lack of variance in terms of the dependent variable sleep quality. All in all, this resulted in attempting to explain a small subjective sleep quality variance in a small sample, with many predictor variables. Feature selection strategies to prevent over-fitting the data were attempted, but false positive results cannot be fully ruled out due to the large amount of fitted models and the small sample size.

The second limitation is related to the small sample size; this research was conducted during the Covid-19 pandemic, just before the Christmas and new year's holiday period. It is therefore likely that people were still limiting interactions with strangers, and were busy with holiday preparations and as such less likely to participate in a semi-longitudinal research with daily diaries, logbooks and the originally planned randomly timed experience sampling questionnaires. The current pandemic has also been shown to affect people's sleep schedule and sleep quality, in part because people work more from home and hence sleep when preferred, thus reducing social jetlag and sleep restriction while increasing sleep duration (Blume et al., 2020). The pandemic has also been found to decrease sleep quality, however, which is likely due to increased self-perceived burden according to Blume et al. (2020). The research by Blume et al (2020) was conducted at the start of the pandemic, however. Since then, restrictions have eased up throughout the past two years while people were still advised to work from home at least half the time during the time this study was conducted. Therefore, the self-perceived burden of the restrictions potentially masking the effects of the improved sleep timing and duration on sleep quality may have been (partially) alleviated. This presumed reduction in self-perceived burden in combination with the improved sleep timing and duration could in part explain the small variance in sleep quality in the data, as

people were found to mostly report good sleep quality.

Another limitation is in terms of the nanoλ XL-500H BLE sensors and how they were to be used. This was the first larger scale longitudinal experiment with these sensors within the faculties of Human Technology and Built Environment, and they were chosen because they allowed for wearable ambulant measurement of the spectrum of light that participants were exposed to. However, because they have relatively little storage, participants had to download the data every morning and evening to prevent the data being overwritten. In addition, the devices had to be charged when necessary with the provided charger. This required additional conscientiousness on the part of the participants and therefore these devices caused an increase in participant burden.

As this research already took a great number of predictors into account some features of light exposure could not be studied due to time constraints and the small sample size. This includes light exposure history and timing, neither in terms of light exposure during prior days nor in terms of prior light exposure during the same day, as well as interaction effects between light exposure features. Furthermore, timing could also not be studied in terms of first or last exposure to a certain light level threshold, as previously researched by (Wams et al., 2017), in terms of exposures > 10 lux, as participants generally did not wear the measurement device for roughly the first and last hour of their day. This is a limiting factor, considering light history of up to three days prior can affect the effect light has on people (Khademagha et al., 2016). The timing of light has also been found to be relevant previously; Hubalek (2010) found a negative relation between subjective sleep quality and blue light level throughout the day, whereas Figueiro et al., (2017) found a positive relation between subjective sleep quality and sleep quality throughout the morning specifically. Hence studying the timing (of the blue light exposure in particular) is important, as results differ based on which part of the day was studied. They did use different scales to assess subjective sleep quality, however. Previous research demonstrated the importance of prior light exposures in terms of how previous exposure to a high light level was related to a dampening of melatonin supressing effects of subsequent brighter light exposures (Te Kulve et al., 2019), and previous exposure to a low light level before a high light level was found to be related to an increase in circadian effects (Chang et al., 2011). The research by Peeters et al., (2022) showed that interaction effects can be important in assessing the relations between light exposure and sleep. However, only main effects were assessed in the current research due to the small sample size. It is therefore unclear how the potential relationship between the daily average absolute Rates of Change and subjective sleep quality is influenced by timing and prior light exposure during the same day, and how the daily average absolute Rates of Change interact with other predictors.

Another limitation concerns the daily average absolute rates of change. This metric solves the issue of negative and positive changes (partially) cancelling each other out in the averaging process, thereby allowing for a good estimate of the actual average magnitude of change. It does not, however, allow for a distinction to be made between the effects of positive and negative changes in light level. This is important, because for example an increase in blue light in the evening has been shown to cause more melatonin suppression, whereas a decrease in blue light could allow melatonin production to increase again (Blume et al., 2019; Cain et al., 2020; Reiter, 1993) This illustrates the importance of timing for increases and decreases in light level.

A further limitation inherent to the described methodology is the lack of an automated forward feature selection function for multilevel data in R. Performing both a forward and backward analysis and comparing the results would offer more insights into the relations under scrutiny. The main advantages of a forward feature selection over a backward feature selection directly apply to the problem at hand; it is employed to model data with an abundance of predictors and a paucity of observations, as it starts with an empty model and enters predictors into the model one by one. Therefore such a procedure can be presented with all predictors at once, rather than having to perform several intermediate feature selection procedures as was the case in the backward feature selection method applied in this research. The downside to this forward methodology, however, is that a variance inflation analysis still needs to be performed after the forward feature selection procedure. Furthermore, a forward feature selection may not include any (further) predictors in case of strong multicollinearity, potentially resulting in a a less fine-grained model with fewer predictors. However, a backward feature selection might not remove any or very few predictors from the model (Mantel, 1970). It is therefore important to carefully choose the feature selection method, as they have different benefits and downsides and can lead to different outcomes.

While stepwise feature selection methodologies are easy to apply due to its automated nature and inclusion in statistical software packages and relatively easy to explain, they are also limited. They intentionally does not consider all potential predictor combinations, which can lead to different selections of predictors, i.e. instability in the selection of predictors, in small sample sizes. Moreover, they cannot consider causality, and they inflate regression coefficients, confidence intervals, p-values, and R^2 values as these are not adjusted for the multitude of tests (Kuhn & Johnson, 2019). In order to circumvent the biases introduced by the methodology, a sufficiently large dataset is required which can be split into two, in which one half serves as a training set, and the other half serves as a test set to verify the produced model, and to estimate more accurate metrics (Heinze et al., 2018). Performing both a forward and a backward feature selection would then yield two models that could be tested against a test data set, in order to compare models

created by both methodologies. The instability in predictor selection may be alleviated when the sample size is large enough to have more than 50 observations times the number of potential predictors (Steyerberg et al., 2001).

4.2 Implications for future research

This study has several implications for future work. To aid the search for the best options for different aspects of light exposure and constructs such as subjective sleep quality, multiple metrics, scales, and factors of light exposure should be compared within the same study. The analysis methodology presented in this research allows for this. The pattern of light exposure holds more information than can be expressed in just one aggregate variable. Studying multiple options will aid in standardisation and finding the best practices for tools and methodology, which is required in order to enhance comparability between studies and facilitate meta-analyses (Böhmer et al., 2020; Münch et al., 2020). With meta-analyses in mind, researchers are also encouraged to report power analyses, sample size justifications, or sensitivity analyses; only two researches did so from the articles included in the literature search (Itzhacki et al., 2019; Peeters et al., 2021).

The study of multiple predictors in one research also allows researchers to study which predictors hold similar information by studying the variance inflation factors in a sequential manner as was done in the above analysis. This information can then be used to inform further studies, as studies which require a more fine-grained model can then exclude metrics which overlap strongly in predictiveness with other predictors while including more predictors with a unique contribution to the explained variance in the outcome variable. Inversely, studies which would prefer a less fine-grained model could specifically opt for the predictors which do have a strong overlap with multiple other variables in order to cover as much information as possible with as few predictors as possible.

Future research is also encouraged to also study light history, timing, and interactions between light exposure features when the measurement period allows for this. While the temporal pattern of light exposure has been studied in this research in such a way that the small scale changes over time are preserved, rather than the large scale changes which have been studied previously (Espiritu et al., 1994; Grandner et al., 2006; Jean-Louis, Kripke, Cohen, et al., 2005; Jean-Louis, Kripke, Elliott, et al., 2005; Koller et al., 1993; Kripke et al., 2004; Van Der Maren et al., 2018), the timing of light exposure and its history have not been studied with particular aggregates in this study. Such an analysis could be performed with the currently proposed quantifications after dividing the data of a day up into timeslots, as was done in previous research, and by taking consecutive days into account in the analysis. An example of a research which split data up into

timeslots is the laboratory study by (te Kulve et al., 2019) who studied a combination timing and recent light history. They found that daytime or early evening high light level exposure of 1200 lux at 4000 K for two and a half hours can mitigate the melatonin and subjective sleepiness suppressing effects and skin temperature changing effects of exposure to light levels of 750 lux at 4000 K in the late evening. Moreover, future research may benefit from the inclusion of interactions, as highlighted by the research by Peeters et al. (2022) on the interaction between MLiT and TaT.

The current research made an attempt at accounting for interpersonal differences as was advised by Münch et all (2020), in this case by attempting to model an intercept for each participant in order to take interpersonal differences in subjective sleep quality into account. Future research is, sample size permitting, advised to advance the participant focussed analysis approach even further by modelling a slope for each participant in addition to an intercept for each participant, thereby taking individual differences in how strongly light exposure affects subjective sleep quality into account. Furthermore, future research is also encouraged to take covariates into account such as chronotype as such factors may cause different individuals to respond differently to light exposure, as advised by Böhmer et al. (2020) and Münch et al. (2020). Age may not be relevant, however; after comparing studies with younger and older participants, Böhmer et al. (2021) found no indication for a contribution of age differences to the mixed results in the studies on the relation between light exposure and sleep and mental health. However, as the eye ages, the lens accumulates yellow pigment and therefore becomes less transmissible to blue light (Salvi et al., 2006). Furthermore, lab studies also show that the eye degenerates with age beyond the yellowing of the lens; it suffers from loss of contrast sensitivity and image quality, and increases in optical aberrations, forward scatter, and reaction times (Hennelly et al., 1998; Kline et al., 1983; McLellan et al., 2001). The influence of age on the neuro-behavioural effects of light has also been found more directly; sensitivity of cognitive brain activity such as those related to sleep-wake regulation and working memory to light exposure and blue light exposure specifically was found to decrease with age (Daneault et al., 2014; Daneault et al., 2016; Gaggioni et al., 2014). Therefore, it may still be useful to analyse the effects of age as it might influence the effects of light aggregations on subjective sleep quality that have not been tested often. The study of light aggregations based on α-opic irradiances may be especially useful, in order to study whether the effects of blue light exposure are moderated by age as a result of the yellowing of the lens, for example.

Moreover, future research is also advised to take the sensitivities to light level as related to time of day into account, for example with a set of scaling factors; these factors ranging from zero to one model the effectiveness of light exposure at influencing neuro-behavioural effects. A potential source to base a set of scaling factors on, which would take the moderating effects of

circadian rhythm and timing on sensitivity to light level into account, could be established circadian phase response curves to light with respect to the internal clock time. Lack & Bootzin, (2003) published a phase response curve graph for pulses of high light levels (>2000 lux), medium light levels (between 1200 lux and 2000 lux), and low light levels (between 100 lux and 1200 lux), and (Khalsa et al., 2003) published such a phase response curve for high light levels at roughly 10000 lux. However, they did not report whether this is horizontal or vertical illuminance, nor its spectrum as this was not yet common practice at the time. Ideally, such phase response curves would also be established for the different α-opic irradiances, in order to also take the spectrum of light exposure into account in the subsequently derived scaling factors.

This research has also given an indication as to what type of light exposure aggregations may be interesting for future research. Such a data driven approach is quite different from a theory driven approach, in which theories determine how data is analysed in order to find support (or lack thereof) for the theory in question. A data driven approach, however, may come to different models, and can therefore aid in the construction of new theories aimed at explaining demonstrated effects. This displays the importance of studying the spectrum of light exposure; doing so can lead to a better understanding of how the different photoreceptors and their interactions influence neurobehavioural effects. Therefore, future research ought to study the spectrum of light in relation to subjective sleep quality in more detail with a larger sample.

While the results suggest that the proposed light aggregations are indeed interesting for follow-up research, future research is advised to gather a larger sample. While the semi-longitudinal design is an asset to this research as it allowed for the analysis of multiple days and thus increased the statistical power and predictive strength of the explorative analysis, four measurements of sleep quality per participant is relatively little. Future research would benefit from a longer design, especially when attempting to reduce the impact of missing data.

Furthermore, it is advisable to employ a pendant-worn spectroradiometer (or worn in another location close to the eye, such as on glasses) as done in this research rather than the commonly employed wrist-worn devices, as the latter have a sizeable inaccuracy of up to 27% due to their reference position (Aarts et al., 2017). This device should have a storage and battery capacity large enough to allow researchers to download the data once after the measurement period has ended, in order to prevent loss of data and prevent increasing participant burden. The researchers are then advised to analyse α-opic irradiance based metrics as advised by the CIE, until the CIE endorses a better alternative.

Lastly, this research has implications for future research which is conducted specifically

with students. In this study, students showed greater issues with compliance and conscientiousness than did office workers. Future complex longitudinal research is encouraged to keep a close eye on the performance of participants throughout the duration of the study, and intervene or switch to a different sample population if required. In order for the researchers to be able to use the data from the wearable spectroradiometers, the participants needed to make note in the logbooks of when the sensors were and were not worn. The students in this sample frequently did not report such information and frequently missed diaries and questionnaires, as compared to the office workers in this sample. The information with regards to when these devices were worn was shown to be relevant in the logbooks of the office workers, who often reported that they started to wear the device up to one or two hours after waking up, and removed it up to one or two hours before going to sleep. This illustrates the importance of using a logbook in addition to a sleep diary quite well, and future research is encouraged to implement similar measures, such as a logbook or a combination of a temperature and a movement sensor, to track whether the measurement device was worn. Data from periods when participants did not wear the device are not based on a close approximation of the light participants received at eye level, and would therefore pollute the data and cloud the relations between the measures and derived aggregations and a dependant variable. Moreover, researchers should take care to use methodologies with as little participant burden as possible, and give participants materials which aid them in properly following the experiment protocol, without adding to the participant burden. For example, researchers should refrain from handing out materials which require participants to read large amounts of text. While participants were aided in terms of compliance in this research, future research is encouraged to add smartphone reminders to download data from wearable sensors when required in addition to the reminders to complete questionnaires. However, this is likely not a solution to the lack of conscientious reporting on when the device was and was not worn. Such compliance issues and the differences between students and other populations merit further research, as they may well impact the viability of research with similar requirements.

4.3 Conclusion

In conclusion, the original methodology had to be altered due to issues with participant recruitment. As a result of this, subjective vitality throughout the day could not be studied. As the sample-size remained low, results ought to be interpreted with caution and no definitive conclusion can be drawn with regards to the research question of this study; which light exposure aggregations would be best to predict subjective sleep quality. In spite of this, this study gave much information on the

possibilities with and the challenges related to monitoring, quantifying, and modelling continuous multilevel light data. Furthermore, this study has important implications for further studies on light exposure monitoring. Moreover, it was still possible to demonstrate the proposed analysis methodology which allows for the study of a multitude of predictors in multilevel data, and for the study of which predictors have much information on a dependant variable in common with other predictors. Lastly, while the sample size was too small for any definitive conclusions, the neuro-behavioural effects of the spectrum of light and the daily average absolute rates of change in particular appear to be worth studying further in studies with a larger sample size.

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Appendix 1 – Literature search

This section describes the methods of the literature search extension performed for this study. It started with the articles by Böhmer et al.(2021) in their literature review, and was extended with an additional literature search. This was done in order to include articles which had been published since the last search performed by Böhmer et al. (2020), as well as to find out whether research had already been conducted using α-opic irradiances or new light aggregations.

Böhmer and colleagues (2021) searched five data-bases in total: Embase, Medline, Psychinfo, Web of Science, and Google Scholar, on June 14th, 2019. Their search terms were not the same for each database, and were quite elaborate. They published a full overview of their search terms in Appendix A of their review. Their search yielded 8140 different articles. 25 of these were included in their analysis after exclusion, three of which were found through the reference lists of the other included articles. The included articles were assessed in terms of quality through the use of the NIH National Heart, Lung, and Blood Institute Study quality assessment tool. Out of the 14 points that could be awarded, articles scored between five and ten, encompassing a range of poor to good.

Studies including participants with irregular light exposure patterns as seen in, for example, shift work, jetlag, extreme chronotypes, participants with pre-existing mood or sleep disorders, or physical or mental conditions, were excluded. To be included, studies had to be conducted on participants who were at least 18 years old, light exposure had to be measured directly on the participant (presumably with a wearable device) for at least one day, had to be conducted in daily-life (not a laboratory), and the study had to assess the relationship between light exposure and sleep and/or mood.

Seventeen articles from the review by Böhmer et al. (2017) were excluded for this research for various reasons which made them unrepresentative of the general population studied in this research; some researches specifically studied older or elderly people (mean age upwards of 67 years old), night-shift workers, menopausal, post-menopausal, or post-partum women, specifically researched the results of undiagnosed eye health issues, studied a pre-industrialised society, had vastly different amounts of data for participants that were still averaged (e.g. some participants had one week's worth of data, others had up to a month's worth of data), did not analyse the relationship between light and sleep or light and mental state, or treated light exposure as an outcome measure.

As mentioned above, because Böhmer et al. conducted their search in mid 2019, a short search

extension was conducted. The last iteration of this search was conducted on the 29th of November 2021 in Web of Science, with the search terms: ("field study" AND (Vitality OR Mood OR Affect OR "Sleep quality") AND light*). These search terms were chosen because of the focus on sleep quality and vitality of this research. This search yielded 77 results, and a forward citation search for the articles by (Figueiro et al., 2019; Wams et al., 2017) yielded 79 results. These two articles were selected for a forward citation search as the former was the most recent study that found a relation between light and subjective vitality while studying (aspects of) the spectrum of light (using Circadian Stimulus) and the latter was considered by Böhmer et al. (2021) to be a good quality research on sleep, and would therefore be likely to be cited in further sleep research. From these articles, two were included for the research into the relations between light and sleep quality or vitality, and two more were included in the research into the light aggregations used in the literature. Articles were included if they reported on field studies which studied associations between light and vitality, mood, affect, or sleep quality in humans in a field study, and were published after the literature search by Böhmer et al. (2021) was conducted. Exclusion criteria were the same as those used to decide which articles from the list from Böhmer et al. (2019), as well as not objectively measuring light exposure. This search yielded two more eligible articles, which, contrary to most other studies in this research, used experimental manipulations in a field study (Figueiro et al., 2019; Peeters et al., 2021), as well as two articles which were ineligible for inclusion in the research into the relations, but were included for the research into the light aggregations used in the field. One due to its sample population (Sahin & Figueiro, 2021), and the other because it did not study sleep quality, but did study associated metrics often used in the calculation of sleep quality (Estevan et al., 2021). A flowchart about the article inclusions and exclusions can be found below in Figure 5. Details about all studies included in this research can be found in Table 12, and details about their results can be found in Tables 13 and 14 below. Result details were divided into two tables, so that mental health and sleep results could be presented separately. Formula’s for light aggregations can be found in Table 23 below.

Figure 5: Flowchart of article selection

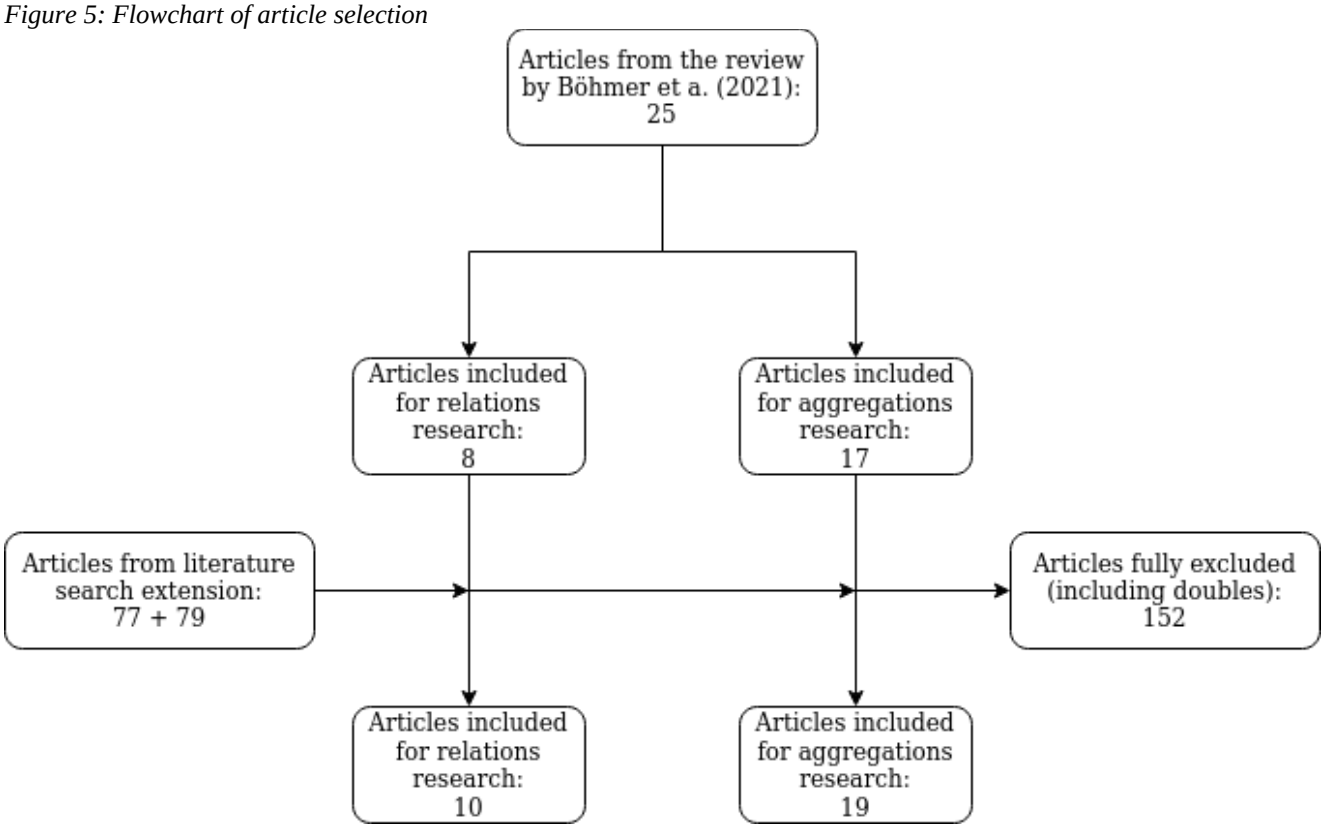


Table 12: Study specifics overview.

Study	Photometer	Photometer location	Sample	Duration	Light aggregations	Other Findings
Aan Het Rot et al. (2008)	Actiwatch-Light	Wrist	48 mildly seasonal participants (SPAQ) (35 in summer and winter, 13 in only one of the two)	20 days	Bright Light Exposure (TAT ≥1000 lux, no at 0 min, low at ≤ 19.6 min, high at > 19.6 min) for day, morning (wake to 11.59h), afternoon (12.00h to 16.59h), evening (16.59h to sleep or 23.59h).	BLE was higher in summer than in winter, during weekends rather than weekdays, in the afternoon (and lowest during the evening), and lower at home or work rather than recreation or anything else. Winter was associated with more submissive behaviour, lower levels of arousal, less negative affect.
Hubalek et al. (2010)	LuxBlick	Eye level	23 office workers	7 days	Measurements: white light illuminance, blue light level as weighted with c(λ) TAT, difference in log transformed blue and log transformed white light illuminance, luminous exposure, vis-nonvis, morning (10.00h to 11.00h), evening (21.00h to 22.00h) ratio Illuminance and morning/evening ratio appears to not be reported on	Total daily sky radiation energy density did not help predict mental state or sleep. Light exposure on office days was steady, but variable on free days. Light data was corrected for transmittance of glasses.
Martinez-Nicolas et al. (2011)	HOBO Pendant Temperature/ Light Data Logger UA-002-64	Chest height	88 students	7 days	First log transformed and averaged for each 10 minutes, illuminance ranges (very dim <10 lux, indoor dim 10-500 lux, indoor bright 500-1000 lux, outdoor bright >1000 lux), Light quality index (oscillates between +1 (only >500 lux light) and -1 (only <10 lux light)), rate of change of light exposure, mean light level, mean light level during the day, morning (08.00h to 15.50h), evening (16.00h to 13.50h), and night (00.00h to 7.50h). Device had a measurement range between 0 and 320,000 lux, lightspectrum wavelength recording capacity of 150 – 1200 nm.	Negative relation between rate of change in light exposure and rate of change in wrist temperature. Positive relation between light exposure interdaily stability and relative amplitude, and wrist temperature interdaily stability. Positive relation between morning light light level and wrist temperature phase advance.

Study	Photometer	Photometer location	Sample	Duration	Light quantifications	Other Findings
Smolders et al. (2013)	Daysimeter	Eye level	42 office workers and students	3 days	First log transformed. illuminance (photopic (V(λ)), circadian), TAT, timing of morning and evening was not reported.	More light is received during spring and summer vs winter and spring. Vitality was lower during autumn and winter, and in the morning. Amount of social interaction, physical activity, prior sleep duration, and chronic fatigue significantly predicted vitality
Figueiro et al. (2017)	Daysimeter	Chest height	109 office workers	7 days	Circadian stimulus, circadian entrainment amplitude and phase The R, G, B, and IR photo-elements have peak spectral responses at 615 nm, 530 nm, 460 nm, and 855 nm, respectively. Morning (8.00h to 12.00h)	Phasor angle was negatively associated with season in summer, but positively in winter. Sleep onset had a stronger significantly negative association with morning circadian stimulus in winter than in summer. Stress, depressive symptoms, and affect were lower in winter than in summer.
Wams et al. (2017)	MotionWatch 8	Unspecified. Wrist?	20 (light loging, actigraphy), 14 (polysomnography) undefined participants	6 days (light logging, actigraphy) + 2 nights (polysomnography)	First log transformed. Regression-predicted first and last >10 lux light exposures and maximum illuminance, raw log transformed average illuminance	

Study	Photometer	Photometer location	Sample	Duration	Light quantifications	Other Findings
Van Der Maren et al. (2018)	Acti-watch Spectrum	Shoulder height	28 (partly students, half delayed, half control)	7 days	First log transformed. Cosine regression predicted light-dark amplitude (from hourly average light level across all days), hourly percentages of daily mean illuminance respective of DLMO. white light and blue (400-500 nm), green (500-600 nm), and red (600-700 nm) light. Calibration curves were used for for white light, blue (480 nm), green (550 nm), and red (620 nm) light. Sensor data was linearly corrected after comparisons with a photometer (Lutron LX-1108) and radiometer (PM100D). Green and blue light were combined due to inaccuracies in the sensor.	Delayed group used light emitting devices (mostly computers) in the three hours before bedtime more than the control group. This was significantly positively correlated with the light exposure in the three hours before bedtime
* Figueiro et al. (2019)	Daysimeter	Chest	3 days (baseline on day 1, intervention on days 2 and 3)	94 office and embassy workers (26 participated in twice once in summer and once in autumn)	Illuminance, Circadian Light → Circadian stimulus Desk luminaires: cool-white (CCT = 6000 K) or blue (λ_{max} = 470 nm), overhead luminaires: 4000 K, 4500 K or 5000 K, each supplementing more than 0.3 CS at eye level	Desktop (cool white or blue) or overhead (4000K, 45000K, or 5000K) lamps were used to supplement light in order to achieve CS≥0.3. Vitality increased from arrival to noon, then decreased from 3pm to departure. Sleepiness decreased from arrival to noon, then increased from noon to departure. No differences were found for luminaire or location.
Itzhacki et al. (2019)	Dimesimeter (Daysimeter-D)	Chest	27 office workers	7 days	Circadian stimulus, subject-centred CS, subject average CS Sensor was optimised for blue light, assessed photopic illuminance and multi-band spectrum	Light exposure was significantly modulated by time of day. Wanting and liking were significantly modulated by time of day and positively related to within participant light CS. Average wanting and liking were not related to between participants CS differences. Most of the variance in liking and wanting was attributed to the between participants level. Positive mood was modulated by time of day, but negative was not. Positive and negative mood had a greater contribution of between rather than within subjects variance.

Study	Photometer	Photometer location	Sample	Duration	Light quantifications	Other Findings
* Estevan et al. (2021)	GENEactive Activinsight	Wrist	15 high-school students	23 days (11 holiday days, 12 school days)	Daily log illuminance average, and TaT at 500 lux	Sleep onset was 2 hours later on vacation days, sleep offset was 4 hours later on holiday days and one hour later on free days. Sleep duration was shorter on school days. Light level was twice as high during holiday days as compared to free and school days when adjusted for timing of sleep. Average daily log illuminance and TaT 500 lux were highly correlated ($r = 0.83$, $p < 0.001$)
* Peeters et al. (2021)	2 Eltek photometers, Specbos 1201 spectrometer, TAOS TCS34725	Photometers and spectrometer at desk level, ambulatory TAOS at chest height	20 office workers (10 in spring, 10 in winter, 8 participated in each season)	3 weeks	α-opic EDI's from spectrometer (for report, not analysis), log transformed illuminance Morning (08.30h to 12.30h), afternoon (12.30h to 17.00h) Low light: 125 lux supplemented horizontally on the desk (40 lux at eye level). High light: 900 lux supplemented horizontally on the desk (300 lux at eye level) Light measurement devices were calibrated with multiplication factors.	One week for HighLow, one for LowLow, and one for LowHigh supplementation of electric lighting (first part denoting morning, second to afternoon amount). In spring, brighter light was considered less pleasant than dim light, but this was not found for winter. Fatigue was moderated by time of day. Higher light levels were experienced as cooler than lower levels.
* Sahin & Figueiro (2021)	Daysimeter, LX-1108, Lutron, Taipei, Taiwan illuminance meter, MK350 N, UPRtek, Zhunan, Taiwan spectrometer	Chest	16 shift workers for baselines in Autumn of 2015, 10 followed up for intervention in Winter of 2019	Four discrete periods of three consecutive days, for the baseline and for the intervention	Photopic light, Circadian Light → Circadian Stimulus Windowless control room. Baseline: 3x8 grid of 4x4 luminaires with 3500K fluorescent lamps. Intervention: 6500 K or 4000 K tunable LED luminaires, with additional blue light in the morning (λ = 460nm; CS ≥0.3) and additional red light in the afternoon through night time (λ = 630nm; CS ≤ 0.1)	Intervention increased synchrony between day-shift participants light-dark and rest-activity cycles, without significant alteration to dim light melatonin onset. Subjective sleepiness was only reduced when participants were off-duty during the day.

Note. Studies from the search extension (which were not included by Böhmer et al. (2021)) are indicated with an "*" before the reference in the "Study" column.

Table 13: Results of research on effects of light exposure on sleep.

Variable	Marker	Study	Scale/measuring device	Results of light exposure
Sleep quality		Hubalek et al. (2010)	Two unstandardised items (Higher is better)	- Positive relation with longer exposure to >1000 lux and >2500 lux white light, - Positive relation with white light luminous exposure - Negative relation with luminous exposure to blue light.
		Figueiro et al. (2017)	PROMIS (lower is better)	Positive relation with circadian stimulus in the morning and during the whole workday
		Figueiro et al. (2017)	PSQI (lower is better)	Positive relation with circadian stimulus during the workday and during workday mornings (stronger in winter vs summer)
		* Peeters et al. (2021)	KSD	No effect.
Circadian alignment (Light-dark sleep-wake)	Phasor magnitude	Figueiro et al. (2017)		Positive relation with morning and workday circadian stimulus
Circadian phase	Sleep midpoint and pattern between days	Martinez-Nicolas et al. (2011)		- Positive relation with morning light illuminance - Positive relation with relative amplitude of illuminance - Positive relation with internal stability of illuminance across days. - Positive relation with light exposure quality (see table 1 of the appendix for an explanation of light exposure quality)
	Phasor angle	Figueiro et al. (2017)		No relation found
	DLMO	Wams et al. (2017)		Positive quadratic relation with later timed light exposure, which interacts negatively with light level (controlled for day length)
		Van Der Maren et al. (2017)	Delayed vs control participants	- Negative relation with blue and white light light-dark cycle amplitude - Positive relation with the timing of white light - Negative relation with averaged daily blue light - Positive relation with the timing of blue light - Positive relation with relative white light exposure two hours and five hours after DLMO and between seven and ten hours after DLMO - Negative relation with relative white light exposure between the first and seven hours after DLMO - Positive relation with relative blue light exposure two hours after DLMO and nine to ten hours after DLMO - Negative relation with relative blue light exposure two to five hours before DLMO

Variable	Marker	Study	Scale/measuring device	Results of light exposure
	DLMO	Van Der Maren et al. (2017)		- Negative relation with blue and white light light-dark cycle amplitude - No relation with averaged daily white light exposure - Negatively related with average daily blue light exposure
Sleep disturbance		Figueiro et al. (2017)	PROMIS	Negative relation with morning and workday circadian stimulus
		Wams et al. (2017)	Actigraphy	Positive relation with later timed >10 lux light exposure
Sleep onset latency		Figueiro et al. (2017)	Actigraphy	Negative relation with morning circadian stimulus (stronger in winter vs summer)
		*Estevan et al. (2021)	Actigraphy	Negative relation with average log illuminance (10x higher resulted in 32 minute earlier sleep). Similar for TaT 500 lux
		* Peeters et al. (2021)	KSD, actigraphy	When assessed with KSD; positivefrom the search extension (which were not included by Böhmer et al. (2021)) relation with morning light light level, negative with afternoon light light level in winter, no effect in spring. No relation when assessed with actigraphy.
Sleep offset latency		*Estevan et al. (2021)	Actigraphy	Negative relation with light level (22.7% lower light level, 18 mins less TaT 500 lux, and a 20 minutes delay in first TaT 500 lux were associated with a delay of an hour
REM onset latency		Wams et al. (2017)	Polysomnography	Negative relation with later >10 lux light exposure
REM duration		Wams et al. (2017)	Polysomnography	Clock phase modulated negative relationship with light exposure
Sleep duration		Wams et al. (2017)	Polysomnography	Clock phase modulated negative relationship with light exposure
		*Estevan et al. (2021)	Actigraphy	Positive relation with average log illuminance (10x higher resulted in 18 minutes longer sleep). Similar for TaT 500 lux
		* Peeters et al. (2021)	KSD, actigraphy	When assessed with KSD; negative relation with morning light level in winter, no effect in spring. No relation when assessed with actigraphy.
Slow wave sleep duration		Wams et al. (2017)	Polysomnography	Positive relation ship with with maximum light level, positive relation with earlier >10 lux light exposure
Sleep midpoint		* Peeters et al. (2021)	KSD, actigraphy	No relation found

Note. PROMIS: Patient-Reported Outcomes Measurent Information System; PSQI: Pittsburg Sleep Quality Index; KSD: Karolinska Sleep Diary; DLMO: Daylight Melatonin Onset. Studies from the search extension (which were not included by Böhmer et al. (2021)) are indicated with an "*" before the reference in the "Study" column. The "-" sign is used in the "Results of light exposure" column to differentiate between results when a study reported more than one result.

Table 14: Results of research on effects of light exposure on mental state.

Variable	Subvariable	Study	Scale	Results of light exposure
Affect	Positive affect	Aan Het Rot (2008)	Affect adjectives score	Positive relation with >1000 lux light exposure
	Pleasure	Hubalek et al. (2010)	PAD	No relation found
	Positive affect (happy)	Smolders et al. (2013)	Single unstandardised item	No relation found
	Positive affect	Figueiro et al. (2017)	PANAS	No relation found
	Positive affect	Itzhacki et al. (2019)	VAS	No relation found
	Negative affect	Aan Het Rot (2008)	Affect adjectives score	No relation found
	SAD	Hubalek et al. (2010)	SPAQ	No relation found
	Negative affect (sad)	Smolders et al. (2013)	Single unstandardised item	No relation found
	Negative affect	Figueiro et al. (2017)	PANAS	No relation found
	Depressive symptoms	Figueiro et al. (2017)	CES-D (lower is better)	Negative relation with morning and workday circadian stimulus
	Negative affect	Itzhacki et al. (2019)	VAS	No relation found
	Valence	Aan Het Rot (2008)	Russel's 1980 Affect grid	Higher for high amount of >1000 lux exposure (but no difference between low and no exposure)
		* Peeters et al. (2021)	Singular unstandardised item	No relation found
	Arousal	Aan Het Rot (2008)	Russel's 1980 Affect grid	Higher for high amount of >1000 lux exposure than no exposure
	Arousal	Hubalek et al. (2010)	PAD	No relation found
Quarrelsome behaviour		Aan Het Rot (2008)	Social behaviour dimensions	Lower for high amount of >1000 lux exposure (but no difference between high and no exposure)
Agreeable behaviour		Aan Het Rot (2008)	Social behaviour dimensions	Positive relation with amount of >1000 lux exposure (but no difference between high and no exposure)
Dominant behaviour		Aan Het Rot (2008)	Social behaviour dimensions	No relation found
Submissive behaviour		Aan Het Rot (2008)	Social behaviour dimensions	No relation found
Vitality		Smolders et al. (2013)	AD-ACL	Positive relation with light exposure during 5 minutes to an hour before vitality measurement, even after controlling for time of day, personal characteristics, activity, prior sleep duration. Lower during autumn, winter, and morning
		* Figueiro et al. (2019)	SVS	Significant increase after exposure to CS ≥ 0.3 after two days.
		* Peeters et al. (2021)	Singular unstandardised item	Negative relation to higher morning illuminance in spring,no effect in winter
Sleepiness		* Figueiro et al. (2019)	KSS	Significant decrease after exposure to CS ≥ 0.3 after two days.
		* Peeters et al. (2021)	KSS	Positive relation with morning light level in spring, no effect in winter
Tension		Smolders et al. (2013)	AD-ACL	No relation found
		* Peeters et al. (2021)	Singular unstandardised	No relation found(low variance)

Variable	Subvariable	Study	Scale	Results of light exposure
			item	
Stress		Figueiro et al. (2017)	PSS-10	Negative relation with morning circadian stimulus and workday morning circadian stimulus (both stronger in winter vs summer)
Fatigue		* Peeters et al. (2021)	Three unstandardised items	No relation found

Note. PAD: Pleasure Arousal Dominance; PANAS: Positive And Negative Affect Schedule; SPAQ: Seasonal Pattern Assessment Questionnaire; VAS: Visual Analogue Scale; CES-D: Center for Epidemiologic Studies-Depression; AD-ACL:Activation-Deactivation Adjective Checklist; SVS: Subjective Vitality Scale; KSS: Karolinska Sleepiness Scale PSS: Perceived Stress Scale. Studies from the search extension (which were not included by Böhmer et al. (2021)) are indicated with an "*" before the reference in the "Study" column.

Table 15: Light aggregations and their formula's

Name	Formula
Time above Threshold (TAT) (Aan Het Rot, 2008)	$TAT_E = \Delta t_{E_\lambda}$
Percentual Time above Threshold (%TAT) (Espiritu et al., 1994)	$\%TAT_E = TAT_E / \Delta t_{measurement\ period}$
Mean Light Timing above threshold (MLiT) (Reid et al., 2014) (Espiritu et al., 1994)	$MLiT^C = \frac{\sum_{j=1}^{720}\sum_{k=1}^{7} I_{jk}^C * Y_j}{\sum_{j=1}^{720}\sum_{k=1}^{7} I_{jk}^C}$
Circadian Light (CL) for $\int P_\lambda S_\lambda d\lambda - 0.31\int P_\lambda V_{10\lambda} d\lambda \geq 0$ (Rea et al., 2010)	$CL = [(0.285\int P_\lambda M_\lambda d\lambda - 0.01) + 0.2(\int P_\lambda S_\lambda d\lambda - \int P_\lambda V_{10\lambda} d\lambda) - 0.001] - 0.72(1 - e^{\frac{\int P_\lambda V'_\lambda d\lambda}{6.5}})$
Circadian Light (CL) for $\int P_\lambda S_\lambda d\lambda - 0.31\int P_\lambda V_{10\lambda} d\lambda \leq 0$ (Rea et al., 2010)	$CL = 0.285\int P_\lambda M_\lambda d\lambda - 0.01$
Circadian Stimulus (CS) (Rea et al.,2010)	$CS = 0.75 - \frac{0.75}{1 + (\frac{5831\,CL}{215.75})^{0.864}}$
α-opic irradiance (W/m²*sr) (CIE, 2018) (CIE, 20118)	$E_\alpha = \int E_{e,\lambda}(\lambda) S_\alpha(\lambda) d\lambda$ (with $S_\alpha(\lambda)$ as the spectral sensitivity curve of photoreceptor α)
α-opic efficacy of luminous radiation (W/lm) (CIE, 2018)	$K_{V,\alpha} = \frac{\Phi_\alpha}{\Phi_V}$
α-opic Equivalent Daylight Illuminance (α-opic EDI; lx) (CIE, 2018)	$E_{V,\alpha}^{D65} = \frac{E_\alpha}{K_{V,\alpha}^{D65}}$
visual Relative Spectral Effectiveness (RSE v, α) (Ámundadóttir, 2016)	$RSE_{v,\alpha} = \frac{\int_{\lambda_1}^{\lambda_2} E_{e,\lambda} S_\alpha(\lambda) d\lambda}{\int_{\lambda_1}^{\lambda_2} E_{e,\lambda} V_{10}(\lambda) d\lambda} * \int_{\lambda_1}^{\lambda_2} V_{10}(\lambda) d\lambda$

Name	Formula
Spectrally-weighted effective illuminance (lx(effective)) (Ámundadóttir, 2016)	$E_{v,\alpha}^{eff} = E_{v,\lambda_2-\lambda_1} * RSE_{v,\alpha}$
energy Relative Spectral Effectiveness (RSE e, α) (Ámundadóttir, 2016)	$RSE_{e,\alpha} = \frac{\int_{\lambda_1}^{\lambda_2} E_{e,\lambda} S_\alpha(\lambda)\, d\lambda}{\int_{\lambda_1}^{\lambda_2} E_{e,\lambda}\, d\lambda} * (\lambda_2 - \lambda_1)$
Spectrally-weighted effective irradiance (W/m^2 (effective)) (Ámundadóttir, 2016)	$E_{e,\alpha}^{eff} = E_{e,\lambda_2-\lambda_1} * RSE_{e,\alpha}$
Weighted Illumination (WI) (Espiritu et al., 1994)	$WI = \frac{TAT(\lambda)}{\log(E)}$
Vis - nonvis (Hubalek et al., 2010)	$Vis - nonvis = \log(median(E)) - \log(median(E_{blue\ component}))$
Light Quality Index (LQI) (Martinez-Nicolas et al., 2011)	$LQI = \frac{TAT_{E>500\,lux} - TAT_{E<10\,lux}}{TAT_{E>500\,lux} + TAT_{E<10\,lux}}$
Coefficient of Variation (Relative Standard Deviation; CV) (Brown, 1998)	$CV = \frac{\sqrt{\sum_{i=1}^{n} (x_i - \mu)^2}}{\mu}$
Rate of Change (RC) (Adams & Essex, 2018b)	$\frac{\Delta E}{\Delta t} = \frac{E_2 - E_1}{t_2 - t_1}$
Consecutive Disparity Index (D) (Férnandez-Martínez et al., 2018)	$D = \frac{\sum_{i=1}^{n-1} \left\lvert \ln \frac{E_{i+1} + 0.01\mu}{E_i + 0.01\mu} \right\rvert}{n-1}$
Luminous Exposure (LE) (area under the illuminance/irradiance curve)	$Luminous\ Exposure = \int_{\lambda_1}^{\lambda_2} E(\lambda)\, dt$ ($AC = \sum_{\lambda_1}^{\lambda_2} E(\lambda) \Delta t_{E\lambda}$)

Appendix 2 – Workplace characteristics questionnaire

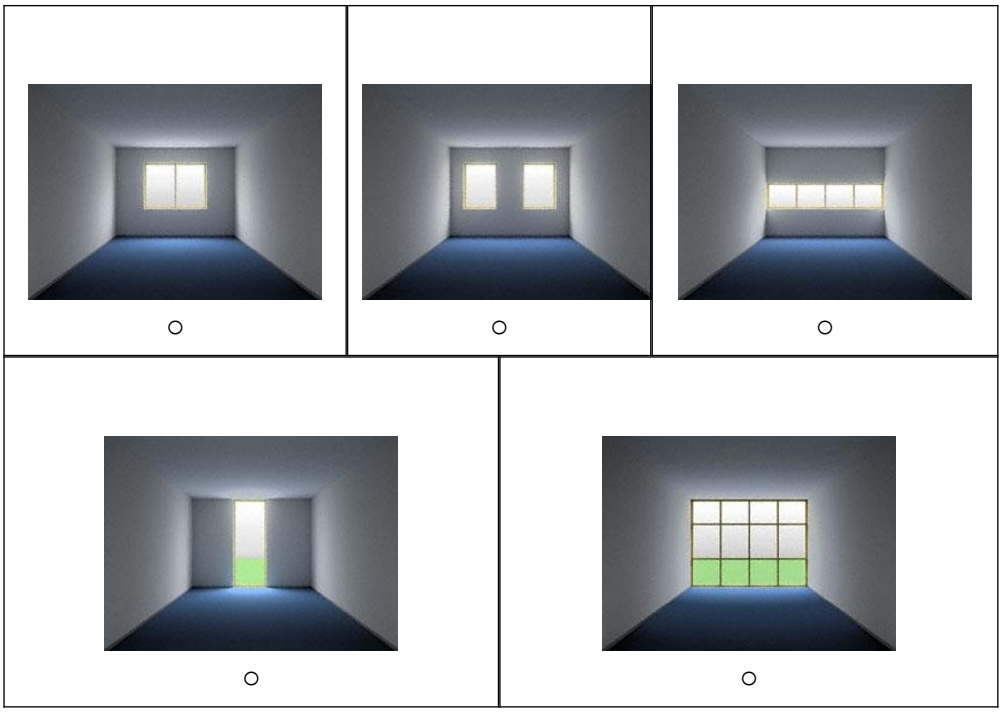
Workplace characteristics

Workplace characteristics at home

- Where do you mostly work/study when you work/study from home?
  During the measurement period, please use chosen location as much as possible when working at home.
  - Home, separate work-/study room
  - Home, kitchen (table)
  - Home, bedroom
  - Other, _____

- What was the distance from you seating/working position at your desk to the closest window?
  - < 1m
  - 1 – 4m
  - > 4m

- What figure represents best the type of window(s) that are closest to you seating/working position at home? (figures from http://www.jandiepens.nl/varbook/overzicht_plaats.html)



- What is the window orientation of the window closest to you seating/working position?
    - North
    - North-East
    - East
    - South-East
    - South
    - South-West
    - West
    - North-West

- What is your view from the window closest to your seating/working position at home?

  For example are there trees in front of your window, or other buildings.

  It is also possible to take a picture with the provided phone. If you use your own phone, please send the picture to [removed] and specify which picture is from which location.

  _____

  _____

- Are there any obstructions like curtains in front of the window closest to you seating/working position at home?

  _____

  _____

- What is the window orientation relative to your seating/working position in the room?

  - Front
  - Behind
  - Left
  - Right

- Do you have an extra desk lamp besides the main lighting installation available at your work/study place at home?
  - Yes
  - No

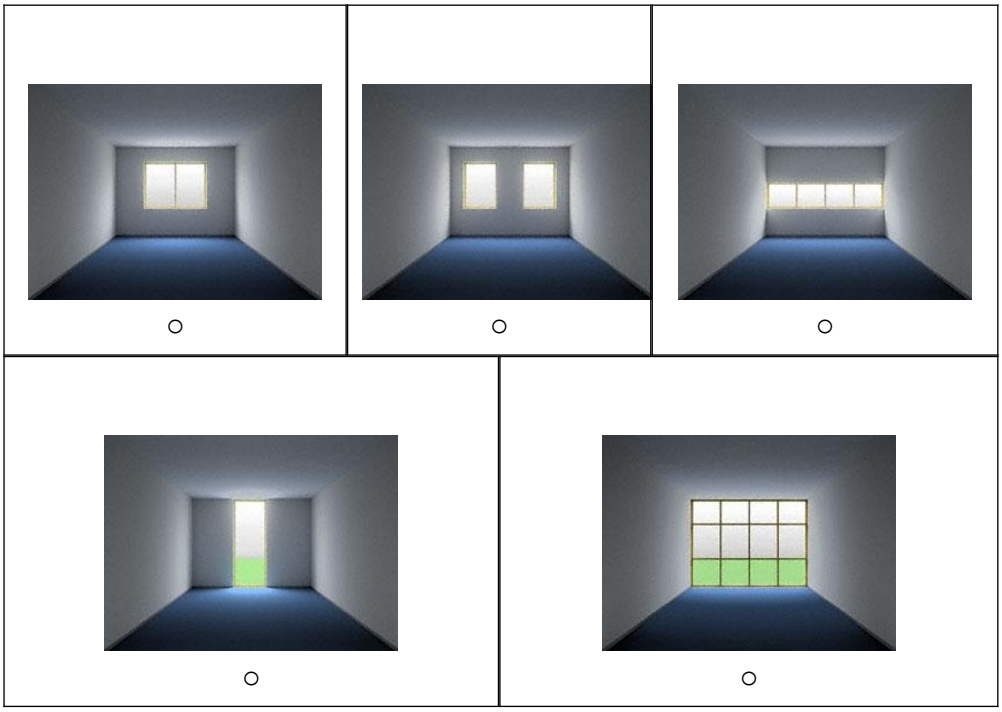
- If you do have an extra lamp available, between what times do you use it regularly?
  - Yes, between 08.00AM and 10.00AM
  - Yes, between 10.00AM and 12.00AM
  - Yes, between 12.00AM and 02.00PM
  - Yes, between 02.00PM and 04.00PM
  - Yes, between 04.00PM and 06.00PM
  - No
  - Other, _____

Workplace characteristics at the office or university

- Where do you mostly work/study when you work/study the office or university? During the measurement period, please use chosen location as much as possible when working at the office or university.
    - Office, 1 person
    - Office, 2 persons
    - Office, 3 – 4 persons
    - Office, open office
    - University, open space
    - University, meeting room
    - University, class room
    - Other, _____

- What was the distance from you seating/working position at your desk to the closest window?
    - < 1m
    - 1 – 4m
    - > 4m

- What figure represents best the type of window that was closest to you seating/working position at home? (figures from http://www.jandiepens.nl/varbook/overzicht_plaats.html)



- What is the window orientation of the window closest to you seating/working position?
    - North
    - North-East
    - East
    - South-East
    - South
    - South-West
    - West
    - North-West
- What is your view from the window closest to your seating/working position at home?

  For example are there trees in front of your window, or other buildings.

  It is also possible to take a picture with the provided phone. If you use your own phone, please send the picture to [removed] and specify which picture is from which location.

  _____

  _____

- Are there any obstructions like curtains in front of the window closest to you seating/working position at home?

  _____

  _____

- What is the window orientation relative to your seating/working position in the room?

  - Front
  - Behind
  - Left
  - Right

- Do you have an extra desk lamp besides the main lighting installation available at your work/study place at home?
  - Yes
  - No

- If you do have an extra lamp available, between what times do you use it regularly?
  - Yes, between 08.00AM and 10.00AM
  - Yes, between 10.00AM and 12.00AM
  - Yes, between 12.00AM and 02.00PM
  - Yes, between 02.00PM and 04.00PM
  - Yes, between 04.00PM and 06.00PM
  - No
  - Other, _____

Appendix 3 – Spectroradiometer calibration

The wearable spectroradiometers were calibrated by comparing them to a Konica Minolta CL-500A (Konica Minolta Inc, 2011) which served as a ground truth. In terms of the linearity index, measurements were performed vertically at a constant angle of 90° in two different setups. The first setup was an Ulbricht sphere; a hollow sphere with a diffuse white reflective coating on the interior which can emit roughly 10 lux to 100 lux at 5V or 100 to 1000 lux at 8V by varying the number of active light bulbs from one to six. The second setup was a 4.5 m by 4.5 m daylight room which simulates a fully overcast sky. This room was equipped with black curtains on the walls from the floor up to the measurement surface, and mirrors on the walls from the reference surface up to the ceiling, 135 58W dimmable illuminance fluorescent tubes and a translucent diffusing sheet. The voltage powering the lamps was increased by 1 Volt each minute, from 1 Volt to 10 Volt, resulting in a variable vertical illuminance from roughly 1000 lux to 10000 lux. Results of this can be seen in Tables 16, 17, 18, 19, 20, and 21, specified for each photoreceptor and illuminance. The derived multiplication factors to calibrate the data with can be found below in Table 22. Calculations for the linearity indices were only reported for the devices used by office workers, as only their data was used and had to be calibrated.

In terms of Directionality, only 4 wearable spectroradiometers and the Konica device were tested with regards to illuminance, as the devices could not be calibrated in terms of directionality, and these tests were very time and labour intensive. These tests were performed under a sun simulator emitting a parallel beam of light with a Philips type 6958 EVC/FGX M33 24V 250W light source and a large Fresnel lens at a constant light level by varying the angle of light incidence between 0° and 90° in steps of 10°, in the four cardinal directions. These results can be seen below in Table 23.

Table 16: S-cone-opic linearity test results

Device ID	*F3-index*$_{10\text{-}100\ lux}$ *(%)*	Class$_{10\text{-}100lux}$	*F3-index*$_{100\text{-}1000\ lux}$ *(%)*	Class$_{100\text{-}1000\ lux}$	*F-3 index*$_{1000\text{-}10000\ lux}$ *(%)*	Class$_{1000\text{-}10000\ lux}$
NanoLambda 3839	2.74	C	4.15	C	5.36	Insufficient
NanoLambda 3895	4.70	C	1.65	B	13.61	Insufficient
NanoLambda 3913	10.88	Insufficient	0.84	A	13.66	Insufficient
NanoLambda 3915	1.60	B	3.02	C	12.26	Insufficient
NanoLambda 3916	6.45	Insufficient	1.64	B	12.42	Insufficient
NanoLambda 3917	11.91	Insufficient	3.54	C	12.88	Insufficient

Table 17: M-cone-opic linearity test results

Device ID	*F3-index$_{10\text{-}100\ lux}$ (%)*	Class$_{10\text{-}100lux}$	*F3-index$_{100\text{-}1000\ lux}$ (%)*	Class$_{100\text{-}1000\ lux}$	*F-3 index$_{1000\text{-}10000\ lux}$ (%)*	Class$_{1000\text{-}10000\ lux}$
NanoLambda 3839	1.89	B	0.83	A	7.23	Insufficient
NanoLambda 3895	1.49	B	0.39	A	10.88	Insufficient
NanoLambda 3913	1.30	B	0.62	A	10.79	Insufficient
NanoLambda 3915	1.16	B	0.45	A	9.81	Insufficient
NanoLambda 3916	1.70	B	1.08	A	9.78	Insufficient
NanoLambda 3917	1.69	B	0.62	A	99.10	Insufficient

Table 18: L-cone-opic linearity test results

Device ID	*F3-index$_{10\text{-}100\ lux}$ (%)*	Class$_{10\text{-}100lux}$	*F3-index$_{100\text{-}1000\ lux}$ (%)*	Class$_{100\text{-}1000\ lux}$	*F-3 index$_{1000\text{-}10000\ lux}$ (%)*	Class$_{1000\text{-}10000\ lux}$
NanoLambda 3839	1.53	B	0.99	A	7.64	Insufficient
NanoLambda 3895	1.25	B	0.40	A	10.94	Insufficient
NanoLambda 3913	1.04	B	0.61	A	10.80	Insufficient
NanoLambda 3915	1.01	B	0.36	A	9.92	Insufficient
NanoLambda 3916	1.33	B	1.10	B	9.85	Insufficient
NanoLambda 3917	1.43	B	0.62	A	99.30	Insufficient

Table 19: Rhodopic linearity test results

Device ID	*F3-index$_{10\text{-}100\ lux}$ (%)*	Class$_{10\text{-}100lux}$	*F3-index$_{100\text{-}1000\ lux}$ (%)*	Class$_{100\text{-}1000\ lux}$	*F-3 index$_{1000\text{-}10000\ lux}$ (%)*	Class$_{1000\text{-}10000\ lux}$
NanoLambda 3839	1.97	B	0.80	A	5.99	Insufficient
NanoLambda 3895	2.43	C	0.65	A	11.20	Insufficient
NanoLambda 3913	1.54	B	0.79	A	11.03	Insufficient
NanoLambda 3915	1.40	B	0.64	A	9.87	Insufficient
NanoLambda 3916	2.56	C	0.89	A	10.00	Insufficient
NanoLambda 3917	2.04	C	1.03	B	10.18	Insufficient

Table 20: Melanopic linearity test results

Device ID	*F3-index$_{10\text{-}100\ lux}$ (%)*	Class$_{10\text{-}100lux}$	*F3-index$_{100\text{-}1000\ lux}$ (%)*	Class$_{100\text{-}1000\ lux}$	*F-3 index$_{1000\text{-}10000\ lux}$ (%)*	Class$_{1000\text{-}10000\ lux}$
NanoLambda 3839	1.83	B	0.82	A	5.55	Insufficient
NanoLambda 3895	3.80	C	0.85	A	11.60	Insufficient
NanoLambda 3913	1.59	B	0.97	A	11.35	Insufficient
NanoLambda 3915	1.56	B	0.89	A	10.03	Insufficient
NanoLambda 3916	3.00	C	0.74	A	10.30	Insufficient
NanoLambda 3917	2.34	C	1.35	B	10.56	Insufficient

Table 21: Illuminance linearity test results

Device ID	*F3-index$_{10\text{-}100\ lux}$ (%)*	Class$_{10\text{-}100lux}$	*F3-index$_{100\text{-}1000\ lux}$ (%)*	Class$_{100\text{-}1000\ lux}$	*F-3 index$_{1000\text{-}10000\ lux}$ (%)*	Class$_{1000\text{-}10000\ lux}$
NanoLambda 3839	1.61	B	0.95	A	7.70	Insufficient
NanoLambda 3895	1.26	B	0.38	A	10.87	Insufficient
NanoLambda 3913	1.11	B	0.59	A	10.76	Insufficient
NanoLambda 3915	1.04	B	0.37	A	9.88	Insufficient
NanoLambda 3916	1.37	B	1.13	B	9.79	Insufficient
NanoLambda 3917	1.48	B	0.59	A	9.88	Insufficient

Table 22: A-opic and illuminance linearity calibration factors

Device	*Calibration factor$_{S\text{-}cone}$*	*Calibration factor$_{M\text{-}cone}$*	*Calibration factor$_{L\text{-}cone}$*	*Calibration factor$_{Rod}$*	*Clibration factor$_{ipRGC}$*	*Calibration factor$_{Illuminance}$*
NanoLambda 3839	1.29506477807832	1.21535841370312	1.22026848930963	1.20737258312154	1.20277713598857	1.22038866788976
NanoLambda 3895	1.34441412657955	1.27380683518409	1.29201510823026	1.26307744404 32	1.25843923460135	1.28848309631269
NanoLambda 3913	1.13683364764213	1.25992885699756	1.28824668019224	1.21764006365982	1.19221603968615	1.28488488658888
NanoLambda 3915	1.03583802758338	1.18876337658 24	1.21731314996366	1.14334859273588	1.11513127499176	1.21387689389613
NanoLambda 3916	1.00789515828758	1.15823016587215	1.19144957881 16	1.10985255853582	1.08424500281742	1.18643286176529
NanoLambda 3917	1.01963992111704	1.19351345255556	1.22137626799411	1.14760234665358	1.12119329787 78	1.21793111851732

Table 23: Directionality test results

Device ID	*F2-index (%)*	F2 class
NanoLambda 3855	3.31	C
NanoLambda 3856	1.71	B
NanoLambda 3914	1.65	B
NanoLambda 3916	1.48	B
Konica Minolta CL-500A	0.25	A

Appendix 4 – Invitation letter

Dear participant,

You may have received an invitation for this research before, but due to a small participant count we have reduced participant burden as this was found to be too great. We need more participants, so we hope you will reconsider participating now that participant burden has been reduced.

Due to the COVID-19 virus, a large part of the population works/studies from home. While some may have a fully furnished office at their home, others do not. This raises questions about ergonomics and well-being. Lighting conditions and light exposure are often disregarded in this context.

The current researches
This study combines the research of two master's theses and a research project at the Eindhoven University of Technology, in the departments of Human Technology Interaction and the Built Environment. Part of this research will be aimed at gathering data about the lighting conditions participants are exposed to whilst working from home, and comparing these with results obtained in offices during regular circumstances. The other parts of this research focus on analysing the relations between light exposure in such settings and sleep.

What does the research consist of?
The research concerns an intake questionnaire (5-10 minutes), daily morning diaries (2-3 minutes each), logbooks (5 minutes each) and light spectrum measurements using a wearable light sensor (worn as a pendant around the neck at chest height during the day, and on a bedside table during theDegrees of Freedom
17
night). Pictures of the light sensor can be found below in Figure 1. The intake questionnaire will have questions pertaining to your sleep, habitual light exposure, and general health in the past month and your work places. The morning diary contains questions on your sleep of the past night, and the logbook will reflect on how much time during the day was spent outdoors, and what light sources you were exposed to throughout the day. This logbook can be accessed throughout the day, and you will receive a reminder in the evening to copy any notes you may have made throughout the day into a digital logbook.
You will be wearing the sensor from the moment you wake up to the moment you go to bed, but will remove it when it could get wet (e.g. during showers) or during intensive sports with risk of damaging the device.

Figure 1. NanoLambda XL-500 BLE Spectroradiometer

Inclusion criteria
- No diagnosis of chronic sleep problems (diagnosed or self-reported)
- No use of (prescription) drugs or sleep medication
- Work or study at least four days a week for six hours each day
- Work roughly half of the time from home during the measurement period

Procedure after enrolment for the study
You will be invited to pick up the light sensor and a smartphone at the Eindhoven University of Technology, during which you will also be given extra instructions on paper regarding the use of the light sensor, the smartphone you will receive to store the light sensor data, and on the online platform to fill in the questionnaires. During any and all meetings, the RIVM and University guidelines with regards to COVID-19 will be followed strictly. The briefing will take place on Friday, 17th of December, at 17.45 in Atlas 8.324. The experiment will run from Sunday evening, 19th of December, to Friday morning, 24th of December. The debriefing will take place in the early or late afternoon of Friday the 24th. If you are not available the 24th we will schedule a debriefing with you another time after your Christmas break. If you are not able to be present for the briefing on the 17th but you would like to participate, we could schedule a briefing session in the week of the 20th and you start the measurement period on the 2nd of January. This is of course only possible if you will be working that week. For your participation, you will be compensated based on your response rate with up to €25.00 when answering all questionnaires. Participants from outside the TU/e will be compensated with €2.00 extra.

To enroll please fill in the registration table using the following below. Afterwards, please send an email with your chosen participation number to the email address listed below.

Link: [removed]

If you have any questions, please send an email to the email address listed below.

Kind regards,

Victor van de Gevel	(Human Technology Interaction master student)
Wenger Pwa	(Human Technology Interaction master student)
Clara Strathmann	(Human Technology Interaction master student)
B'Elanna Vugts	(Built Environment master student)
Rose Weterings	(Human Technology Interaction master student)

E-mail: [removed]
Phone/Whatsapp: [removed]

This study is supervised by dr. ir. Karin Smolders (k.smolders@tue.nl), dr. ir. Juliëtte van Duijnhoven (j.v.duijnhoven1@tue.nl), and dr. ir. Mariëlle Aarts [removed] from the Eindhoven University of Technology.

Appendix 5 – Statistical analysis with outliers

This section contains the statistical analysis which includes the outliers. When performing the six multilevel regressions focussed on the separate photoreceptors and illuminance based aggregations, there was evidence of multicolinearity in the M-cone and L-cone based models as some of the VIF scores in these models were larger than five (see Table 24). This variance inflation was reflected in the Pearson correlation between the M-cone-opic daily Average Irradiance and the daily Radiant Exposure (r = -0.80), and between the L-cone-opic daily Average Irradiance and the daily Radiant Exposure (r = -0.80). These correlations were calculated without taking a multilevel structure into account, as the random intercepts were not statistically significant. The aggregates representing the Average Irradiances had the highest VIF scores, therefore these were removed in the L-cone and M-cone based models. This resulted in VIF scores below five for all included predictors, as can be seen in Table 25. Regression parameter estimates of the six models for the five different photoreceptors and illuminance can be found in Table 26. As can be seen in Table 26, only the daily average absolute Rates of Change appear to be significant predictors of subjective sleep quality.

Table 24: Variance inflation factor scores for the separate models with outliers after cluster-based standardisation. [16]

Prefix	Av	CV	Disparity	LE	RC
s	3.57	1.22	1.25	2.69	1.52
m	**5.20**	1.81	1.46	3.32	1.70
l	**6.33**	2.22	1.64	3.79	1.78
rod	4.69	1.48	1.33	3.16	1.75
mel	4.42	1.38	1.32	3.09	1.74
ill	2.39	1.71	1.54	1.87	1.90

Note. VIF > 5 is marked in bold.

Table 25: Variance inflation factor scores for the separate models with outliers after cluster-based standardisation and after removing variance inflating aggregates. [16]

Prefix	Av	CV	Disparity	LE	RC
s	3.57	1.22	1.25	2.69	1.52
m	-	1.08	1.20	1.18	1.10
l	-	1.23	1.45	1.39	1.30
rod	4.69	1.48	1.33	3.16	1.75
mel	4.42	1.38	1.32	3.09	1.74
ill	2.39	1.71	1.54	1.87	1.90

16 s: S-cone-opic, m: M-cone-opic, l: L-cone-opic, rod: Rhodopic, mel: Melanopic, ill: illuminance, Av: daily average irradiance or illuminance, CV: daily Coefficent of Variation, Disparity: daily consecutive Disparity index, LE: Luminous or Radiant Exposure, RC: daily average absolute Rate of Change, sleepq: subjective sleep quality.

Table 26: Regression estimates for the separate models with outliers after cluster-based standardisation. [17]

Model	*Degrees of Freedom*	Predictor	*Estimate*	*Standard Error*	*p-value*
S-cone	13	Intercept	0.02	0.18	0.910
		sAv	-0.21	0.40	0.609
		sCV	0.15	0.24	0.530
		sDisparity	0.05	0.23	0.834
		sLE	0.39	0.35	0.286
		sRC	-0.62	0.25	**0.029**
M-cone	14	Intercept	0.02	0.16	0.900
		mCV	0.14	0.20	0.499
		mDisparity	0.00	0.22	0.999
		mLE	0.06	0.21	0.767
		mRC	-0.63	0.19	**0.005**
L-cone	14	Intercept	0.02	0.17	0.910
		lCV	0.13	0.22	0.556
		lDisparity	-0.10	0.24	0.678
		lLE	-0.03	0.24	0.902
		lRC	-0.66	0.22	**0.008**
Rod	13	Intercept	0.02	0.18	0.910
		rodAv	-0.13	0.46	0.787
		rodCV	0.13	0.25	0.619
		rodDisparity	0.09	0.24	0.728
		rodLE	0.26	0.37	0.490
		rodRC	-0.62	0.26	**0.035**
ipRGC	13	Intercept	0.02	0.18	0.910
		melAv	-0.11	0.45	0.807
		melCV	0.15	0.25	0.544
		melDisparity	0.10	0.24	0.680
		melLE	0.29	0.37	0.452
		melRC	-0.59	0.27	**0.044**
Illuminance	13	Intercept	0.06	0.17	0.710
		illAv	0.00	0.30	0.987
		illCV	-0.01	0.26	0.959
		illDisparity	-0.02	0.24	0.949
		illLE	-0.31	0.27	0.270
		illRC	-0.72	0.25	**0.013**

Note. P > 0.05 is marked in bold. Random intercepts were not statistically significant.

17 s: S-cone-opic, m: M-cone-opic, l: L-cone-opic, rod: Rhodopic, mel: Melanopic, ill: illuminance, Av: daily average irradiance or illuminance, CV: daily Coefficent of Variation, Disparity: daily consecutive Disparity index, LE: Luminous or Radiant Exposure, RC: daily average absolute Rate of Change, sleepq: subjective sleep quality.

Subsequently, stepwise feature selection, or hierarchical modelling, was performed for each of the separate models based on the different photoreceptors and illuminance. The regression estimates of this step can be found in Table 27. These models showed no significant differences in intercept between participants, as the automated feature selection rejected the multilevel structures. All different daily absolute Rates of Change were significant predictors of subjective sleep quality with small negative effect sizes. Figure 6 shows scatter plots with the regression lines of this model, and due to their great visual similarity high multicollinearity would be expected if they were to be combined into one model. Figure 7 shows heat maps of the variables in these models. The heat map for subjective sleep quality shows that there was little variance in this variable. As can be seen in Table 28, all models have support for normally distributed residuals as seen in the Shapiro-Wilk test results, and none of the models have heteroscedasticity issues as can be seen from the Levene's test results. Therefore, the regression assumptions held for all models. All the daily average absolute Rates of Change were found to be significant negative predictors in their respective models.

Table 27: Regression parameter estimates for the separate models with outliers after cluster-based standardisation after hierarchical modelling. [18]

Model	*Degrees of Freedom*	Name	*Estimate*	*Standard Error*	*p-value*
S-cone	17	Intercept	< 0.01	0.17	1.000
		sRC	-0.55	0.19	**0.010**
M-cone	17	Intercept	0.03	0.15	0.850
		mRC	-0.63	0.17	**0.002**
L-cone	17	Intercept	0.03	0.15	0.860
		lRC	-0.61	0.17	**0.003**
Rod	17	Intercept	0.01	0.16	0.930
		rodRC	-0.59	0.18	**0.005**
ipRGC	17	Intercept	0.01	0.16	0.950
		melRC	-0.57	0.19	**0.007**
Illuminance	17	Intercept	0.03	0.15	0.840
		illRC	-0.62	0.17	**0.002**

Note. P < 0.05 is marked in bold.

18 s: S-cone-opic, m: M-cone-opic, l: L-cone-opic, rod: Rhodopic, mel: Melanopic, ill: illuminance, Av: daily average irradiance or illuminance, CV: daily Coefficent of Variation, Disparity: daily consecutive Disparity index, LE: Luminous or Radiant Exposure, RC: daily average absolute Rate of Change, sleepq: subjective sleep quality.

Figure 6: Scatter plots and regression lines of the variables in their respective photoreceptor or illuminance specific models with outliers after cluster-based standardisation.

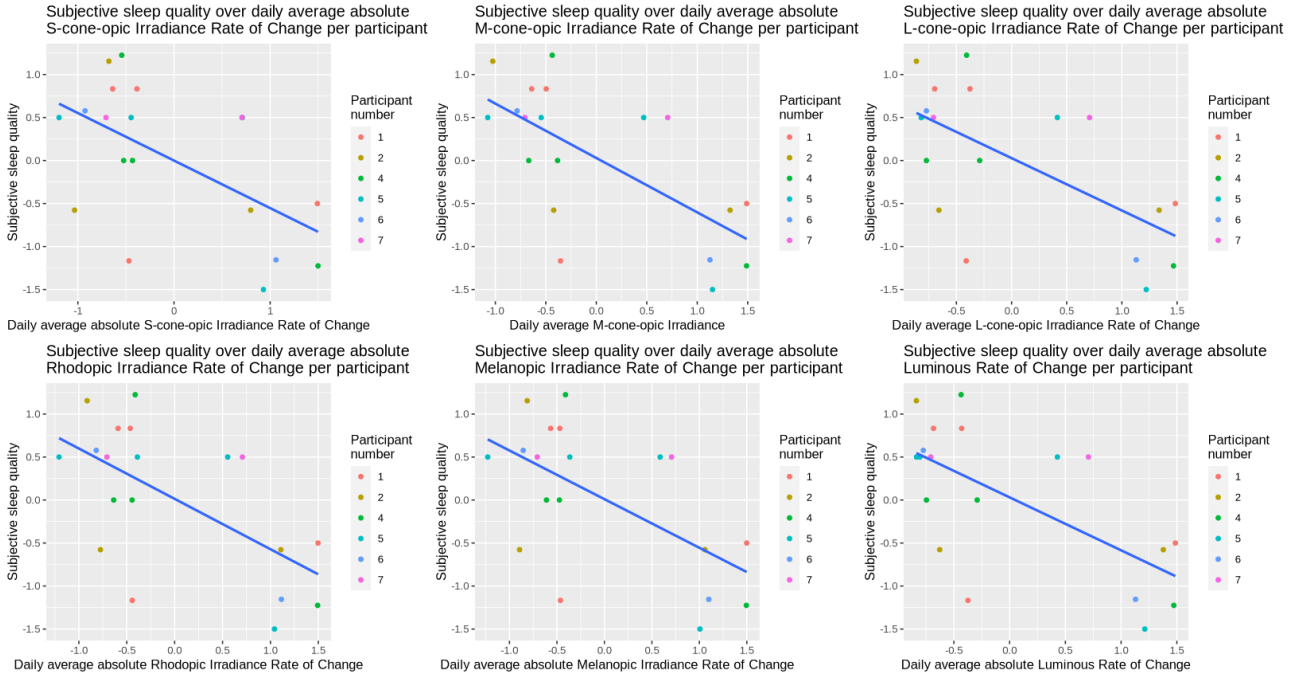


Figure 7: Heat maps of the variables in the photoreceptor and illuminance models with outliers after cluster-based standardisation. Black squares represent missing observations.

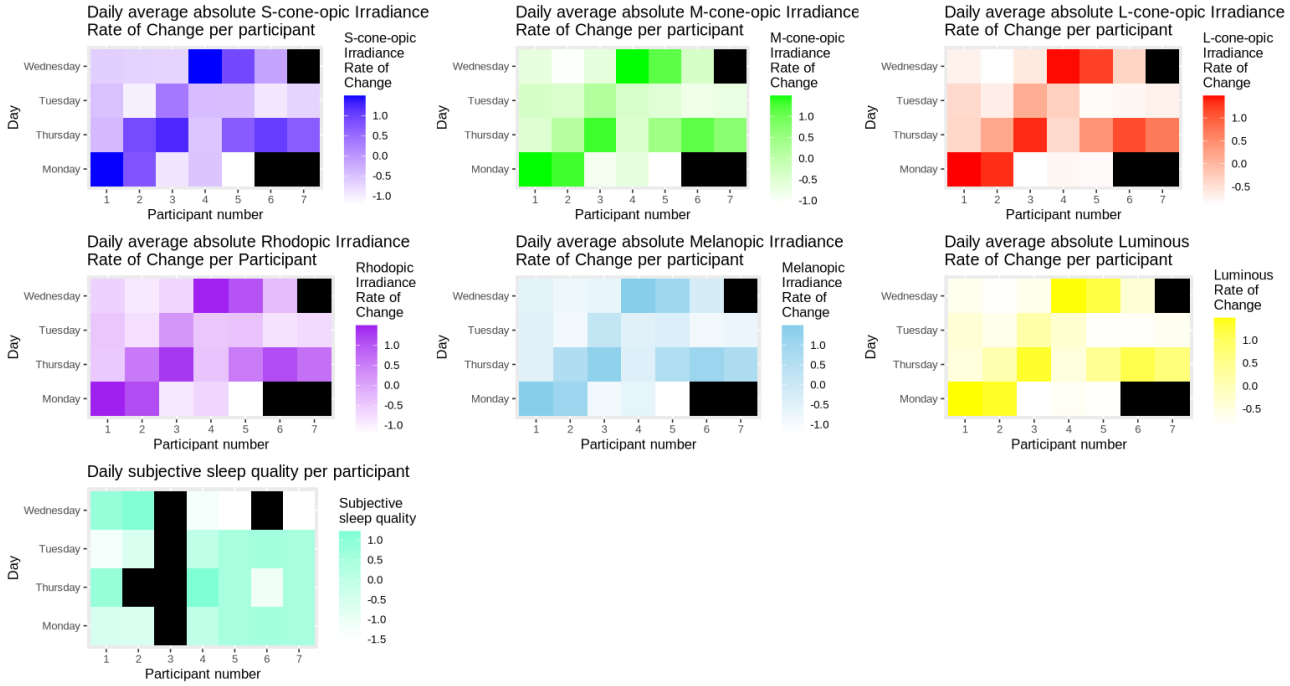


Table 28: Shapiro-Wilk and Levene's tests, ICC's, AIC's, and adjusted R^2's for the photoreceptor and illuminance models with outliers after cluster-based standardisation.

Model	$F_{Levene's}$	$p_{Levene's}$	W	$p_{Shapiro-Wilk}$	AIC	Adjusted R^2
S-cone	0.17	**0.970**	**0.95**	**0.385**	45.4	0.29
M-cone	0.06	**0.997**	**0.97**	**0.716**	41.5	0.42
L-cone	0.06	**0.997**	**0.97**	**0.741**	42.6	0.38
Rod	0.10	**0.991**	**0.96**	**0.659**	43.9	0.34
ipRGC	0.12	**0.986**	**0.96**	**0.623**	44.7	0.31
Illuminance	0.06	**0.997**	**0.97**	**0.725**	42.3	0.39
Final	0.06	**0.997**	**0.97**	**0.741**	42.6	0.38

Note. $W \geq 0.95$ and $p \geq 0.05$ are marked in bold.

Due to the small sample size the final hierarchical modelling step was based on the combination of the variables in the separate models attained through the previous hierarchical modelling step. Combining these variables resulted in variance inflation again. Therefore, before performing a hierarchical multilevel regression, the variable with the highest VIF score was removed in an iterative process until no variable in the regression had a VIF score higher than 5. This process can be seen in Table 29, in which each row represents a new calculation step of VIF scores with the previous highest VIF scoring variable removed. The presence of variance inflation is no surprise given the high Pearson correlation coefficients seen in Table 30. These correlations were calculated without taking a multilevel structure into account, as the random intercepts were not statistically significant. The last two predictors had equal VIF scores which were both higher than five, and VIF scores could not be used further for feature selection. The parameter estimates of this model are presented in Table 31. Neither of the two remaining predictors appears to significantly contribute to the prediction of subjective sleep quality when combined into one model.

Table 29: Variance inflation factor scores for the final model with outliers after cluster-based standardisation during the iterative removal of multicolinearity suspects based on their VIF score.[19]

Iteration	sRC	mRC	lRC	rodRC	melRC	illRC
1	**151.00**	**1991.64**	**4888.83**	**13976.69**	**8189.18**	**6603.47**
2	**148.33**	**165.97**	**1805.84**	-	**305.47**	**2127.15**
3	**147.70**	**134.14**	**63.12**	-	**301.30**	-
4	**16.44**	**60.96**	**56.50**	-	-	-
5	**14.71**	-	**14.71**	-	-	-

Note. VIF > 5 is marked in bold.

19 s: S-cone-opic, m: M-cone-opic, l: L-cone-opic, rod: Rhodopic, mel: Melanopic, ill: illuminance, Av: daily average irradiance or illuminance, CV: daily Coefficent of Variation, Disparity: daily consecutive Disparity index, LE: Luminous or Radiant Exposure, RC: daily average absolute Rate of Change, sleepq: subjective sleep quality.

Table 30: Pearson's correlations overview of the variables potentially included in the final model with outliers after cluster-based standardisation. [20]

	sRC	mRC	lRC	rodRC	melRC
mRC	0.04	-	-	-	-
lRC	-0.11	**0.81**	-	-	-
rodRC	0.13	**-0.96**	**-0.79**	-	-
melRC	-0.31	**0.90**	**0.77**	**-0.98**	-
illRC	0.07	**-0.86**	**-0.99**	**0.82**	**-0.80**

Note. R > 0.50 is marked in bold.

Table 31: Regression estimates for the final model with outliers before hierarchical modelling after cluster-based standardisation. [20]

Name	*Degrees of Freedom*	*Estimate*	*Standard Error*	*p-value*
Intercept	16	0.06	0.16	0.690
sRC		0.74	0.68	0.294
lRC		-1.31	0.66	0.067

Note. P < 0.05 is marked in bold. This model is therefore only displayed for demonstrative purposes and is not suitable to be interpreted. Random intercepts were not statistically significant.

The hierarchical multilevel regression modelling step removed one more predictor from the final model, and only the L-cone average absolute Rate of Change was found to be a statistically significant negative predictor of subjective sleep quality with a medium effect size. Hence the final model is the same as the L-cone-opic model. The parameter estimates of this final model can therefore be found in Table 27, and the scatter plots with the regression lines of this model can be found in Figure 6. As can be seen in Table 28, this model did not appear to suffer from heteroscedasticity, had no significant differences in intercept between participants as the automated feature selection rejected the multilevel structure, and had support for normally distributed residuals. Therefore, the regression assumptions for this model are not violated.

20 s: S-cone-opic, m: M-cone-opic, l: L-cone-opic, rod: Rhodopic, mel: Melanopic, ill: illuminance, Av: daily average irradiance or illuminance, CV: daily Coefficent of Variation, Disparity: daily consecutive Disparity index, LE: Luminous or Radiant Exposure, RC: daily average absolute Rate of Change, sleepq: subjective sleep quality.