Assessment protocol and effects of two dynamic light patterns on human well-being and performance in a simulated and operational office environment

Aries, M. B. C.; Beute, F.; Fischl, G.

Published in:
Journal of Environmental Psychology

DOI:
10.1016/j.jenvp.2020.101409

Journal of Environmental Psychology 69 (2020) 101409

Contents lists available at ScienceDirect

Journal of Environmental Psychology

journal homepage: www.elsevier.com/locate/jep

Assessment protocol and effects of two dynamic light patterns on human well-being and performance in a simulated and operational office environment

M.B.C. Aries[a,*], F. Beute[b,c], G. Fischl[a]

[a] Jönköping University, School of Engineering, Jönköping, Sweden
[b] LightGreen Health, Kolding, Denmark
[c] University of Groningen, Grongingen, the Netherlands

ARTICLE INFO

Handling Editor: L. McCunn

Keywords:
Human-centric lighting
Tuneable white light
Test protocols
Cognitive performance
Well-being

ABSTRACT

Sophisticated electric lighting solutions like tuneable white-light LED-systems, varying in light amount and/or colour temperature, can help to supplement or mimic daylight. Today's office environments are increasingly being equipped with dynamic lighting solutions even though it is yet unknown what a dynamic pattern looks like to optimally support human performance and well-being. In a pilot study, a dual-experimental methodology was employed to examine the effects of a dynamic lighting pattern. Two opposite dynamic electric light patterns were applied both in a controlled laboratory study as well as in a quasi-controlled field study. A momentary questionnaire concerning different aspects of well-being was repeated multiple times during the duration of the experiment, complemented by two performance tasks. The current results were inconclusive and inconsistent between the two study types, carefully pointing at the need to test dynamic light patterns in the field before implementing it in a real office environment.

1. Introduction

Humans have evolved to function in a cycle of day and night, responding to the orbit of the sun. Maybe not surprisingly, the strongest environmental cue or 'zeitgeber' for human behaviour and physiology is commonly daylight (e.g., Roenneberg, Kumar, & Merrow, 2007), with sunrise indicating the start of a new day for diurnal species like humans. Dynamic daylight, with variations ranging from milliseconds to months (Aries, Aarts, & Van Hoof, 2015), provides various stimulations throughout the day, and access to daylight can reduce stress and increase performance (Beute & De Kort, 2014). In an office environment, most of the employees spend 8 h or more indoors, and not all spaces in a building always have access to (sufficient) daylight. Sophisticated electric lighting solutions like tuneable white-light LED-systems, varying in light amount and/or colour temperature, can help to supplement daylight. Today's office environments are increasingly being equipped with dynamic lighting solutions aimed to combine the potential benefits of the lighting exposure by varying illuminance levels and colour temperature (or spectral power distribution) over time.

Light entering human eyes enables them to see and perceive the environment, but light affects more aspects of human physiology beyond vision (Boyce, 2014). Light in the eye, or more precisely retinal exposure to light, stimulates different types of photoreceptors: rods, cones, and light-sensitive retinal ganglion cells. Where visual effects of light like vision or perception are predominantly regulated by the rod and cone photoreceptors, effects 'beyond vision' are influenced largely by intrinsically photosensitive Retinal Ganglion Cells (ipRGCs) (Brainard et al., 2001; Thapan, Arendt, & Skene, 2001), potentially mediated by cones (e.g., Lucas et al., 2014). These ipRGC-influenced responses to light influence the human circadian rhythm and stimulate directly parts of the brain that influence, e.g., cognitive functions and operating capacity (e.g., Chellappa, Gordijn, & Cajochen, 2011; Hankins & Lucas, 2002; Lockley, 2009; Lucas, 2013; Vandewalle, Maquet, & Dijk, 2009). To date, six main parameters are known to influence the 'ipRGC-influenced responses to light': light directionality, spectral power distribution, light dose, exposure duration, timing of light exposure, and prior light exposure (e.g., Chellappa et al., 2011; Huiberts, 2018; Khademagha, Aries, Rosemann, & Loenen, 2016a; Rea, Figueiro, & Bullough, 2002).

Regarding light **amount**, exposure to high light levels, especially with content that is related to the 'blue' colours of the visible light spectrum (between 400 and 500 nm) can increase alertness and

* Corresponding author. School of Engineering, Jönköping, P.O. Box 1026, Jönköping, SE-551 11, Sweden.
E-mail address: myriam.aries@ju.se (M.B.C. Aries).

https://doi.org/10.1016/j.jenvp.2020.101409
Received 28 June 2019; Received in revised form 23 February 2020; Accepted 6 March 2020
Available online 10 March 2020

decrease sleepiness (e.g., Cajochen et al., 2019; Hanifin et al., 2019; Keis, Helbig, Streb, & Hille, 2014; Lockley et al., 2006; Vandewalle et al., 2009; Viola, James, Schlangen, & Dijk, 2008). Light levels at eye height over 1000 lux are often considered as 'high'. Multiple studies on the psychological effects of static lighting suggest that a high illuminance level (and high correlated colour temperature including a high short-wavelength content) can have positive effects on people's well-being, health and performance (e.g., Cajochen et al., 2019; Pachito et al., 2018). In search of light's effects on cognition, studies have shown that illumination level may have beneficial effects on human performance, measured as sustained attention performance (PHIPPS-Nelson, Redman, Dijk, & Rajaratnam, 2003; Smolders, De Kort, & Cluitmans, 2012, Smolders & De Kort, 2014), as response inhibition/vigilance (Correa, Barba, & Padilla, 2016) and as working memory (Huiberts et al., 2015, 2016). In contrast, other studies have been unsuccessful in detecting positive relations between high light exposure, well-being and performance (e.g., Mccoll & Veitch, 2001). Several studies found no statistically significant improvement between illuminance levels for sustained attention (Huiberts et al., 2016; Lok, Woelders, Gordijn, Hut, & Beersma, 2018; Rüger, Gordijn, Beersma, Vries, & Daan, 2006; Santhi et al., 2013; Smolders, Peeters, Vogels, & De Kort, 2018) or working memory (Park et al., 2013).

Concerning **duration**, a daily dose of bright light at eye level (vertical) for at least 1 h can improve well-being aspects, represented by vitality and alleviated distress among office employees (Partonen & Lonnqvist, 2000; Smolders, De Kort, & Van Den Berg, 2013). A light exposure comparison between 200 lux and 1000 lux showed that an even shorter light exposure (30 min) could improve subjective alertness and attention (Smolders & De Kort, 2014). Yang et al. (2019) showed that during a 3-h experiment, an intermittent bright light exposure of 1000 lux at eye level in gaze direction for 30 min with alternating dim light (5 lux) for another 30 min was as effective in increasing the level of alertness (even during the dim light periods) as was continuous bright light for 3 h. However, the enhancement effect of bright light on vitality only occurred when the participants were in a state of relative low vitality. Furthermore, the authors reported minimal effects on mood and emotion. The effects of 30 min natural bright light exposure (> 3000 lux) on individuals in the study by Kaida et al. (2006) suggested that it may prevent the decline of physiologic arousal that usually occurs in the mid-afternoon (14:00); therefore, people may benefit from higher illuminance levels during daytime and under normal working conditions. Vandewalle et al. (2007) showed that an exposure of only 18 min to 'blue' (470 nm) compared with 'green' (550 nm) monochromatic light modulated certain regional brain responses while performing an auditory working memory task, even though the authors could not confirm an effect of light condition nor session interaction.

Accurately **timed** light exposure, and not only duration, can promote circadian entrainment and desired acute effects, and subsequently influence health and performance. Lewy et al. (1998) exposed subjects to bright light either early in the morning or in the evening for two weeks to investigate the effect of timing of light on depression reduction (treatment of Seasonal Affective Disorder). The study clearly showed that morning light is at least twice as antidepressant as evening light. Wright Jr et al. (2006) tested cognitive and vigilance performance in a laboratory for over a month and found that cognitive performance improved in the group with a synchronized day/night rhythm, but it was significantly impaired in the non-synchronized group. Moreover, results from more recent studies (e.g., Choi, Shin, Kim, Chung, & Suk, 2019; Munch et al., 2016; Sithravel et al., 2018) have indicated that (bright blue-enriched) morning light stabilizes the circadian phase, decreases sleep hormone levels, improves subjective perception of alertness, mood, visual comfort, and cognitive and visual task performance, suggesting that a morning boost could be an effective counterstrategy for poor lighting during the day and lighting in the late evening.

Even though several studies have investigated the effects of (specific contents of) dynamic lighting, only a few examined (and clearly reported) an actual dynamic light pattern over one full day. In their bright-light laboratory, ISKRA-Golec and Smith (2008) investigated the effects of an intermittent bright light regime (6 times 15 min pulses at hourly intervals starting at 11:00 h of 4000 lux horizontal at eye height) on performance and mood. Each subject participated twice, with two weeks in-between sessions. Nevertheless, they found only 'near to' statistically significant effects of the light regime (ISKRA-Golec & Smith, 2008). In a follow-up study (ISKRA-Golec, Wazna, & Smith, 2012) where blue-enriched white light was included (500 lux horizontally at eye height, 17000 K), the researchers found effects of blue-enriched white light on mood (energetic arousal) in the morning and at midday, where at the begin and end of the day, the subjects seemed to be more sensitive to the brightness of the lighting. The study found an increasing trend in sleepiness over the day for the blue-enriched white light and a decreasing trend for the regular white lighting (500 lux, 4000 K). In their field study, De Kort and Smolders (2010) followed office employees for three winter months, exposing them to both static and dynamic electric light scenarios (500–700 lx, 3000–4000 K, with daylight access enabled). During the dynamic scenario, participants received a boost in the morning as well as in the early afternoon. Even though the employees were more satisfied with the dynamic lighting, the researchers could not find significant differences in need for recovery, vitality, alertness, headache and eyestrain, mental health, sleep quality, or subjective performance (De Kort & Smolders, 2010).

As demonstrated above, divergent lighting scenarios were tested in both the laboratory and in the field. Both a field study and a laboratory study have their advantages and disadvantages. While a laboratory study is nearly always controlled, a field study provides high ecological validity. The lion's share of studies investigating the effects of light on human functioning have analysed effects of electric light, especially the studies under laboratory conditions. In field studies, exposure to daylight, if only brief, besides the dynamic electric light exposure is inevitable.

As mentioned earlier, sophisticated electric lighting solutions like tuneable white-light LED-systems can help to supplement daylight. If the six main parameters known to impact the ipRGC-influenced responses to light (see i.e., Khademagha, Aries, Rosemann, & VAN Loenen, 2016b) are intentionally balanced in a lighting design, a true 'dynamic lighting scenario' can be created. Even though the technical opportunities for dynamic light patterns delivered by electric lighting are plentiful, little consensus has yet been reached concerning what dynamic lighting pattern is most beneficial (e.g., Van Den Beld, 2004; Van Bommel, 2006, De Kort & Smolders, 2010; Keis et al., 2014, Sithravel et al., 2018). The question is whether, especially in cases where daylight is accessible, the tuneable electric light system should supplement a daylight situation rather than imitate it. Moreover, it is still unclear whether the influence of dynamic lighting with tuneable-white LED-lighting is at all beneficial for both user performance and well-being. Furthermore, testing lighting patterns in a real-life situation has only been done sporadically.

To contribute to this complicated issue, the current study aims to investigate the effect of two opposite daily patterns of dynamic light exposure for maintaining or improving mood and objective performance. In two pilot studies with circa 20 participants each, triangulation using a dual-experimental methodology is employed to examine the effects of a dynamic lighting pattern. The two dynamic electric light patterns are applied in both a controlled laboratory study as well as in a quasi-controlled field study, and next to an increase of illuminance level in either the morning or the afternoon also a decrease is investigated. At the same time, practical issues regarding the applied assessment protocol are evaluated and discussed.

2. Materials and methods

2.1. Study design

This study was a within-subjects design with occupants in a simulated (laboratory) and a fully operational open plan office environment in Sweden (field). The study was conducted from January to March 2018. The duration of the laboratory study was two days (26 February and 5 March) with one week in between, and the field study lasted for six consecutive weeks (9 January – 13 February).

2.2. Participants

In a simulated laboratory office, 20 occupants (14 females, 6 males; age 24.6 ± 3.8 years old) participated; all were second-year BSc-students participating in a course. In the real office, 21 employees of one company participated (5 females, 16 males; age 40.4 ± 9.9 years old) with either a marketing or a development job function. In both studies, the sample size was mainly determined by pragmatic factors rather than an a-priori power analysis. Prior to the experiment, for both populations separately, the general setup and procedure of the experiment were explained. All employees of departments equipped with dynamic lighting were invited to an information lecture and signed up for participation afterwards. The participants were aware of partaking in an experiment related to lighting but unaware of the exact lighting scenarios and study purpose. All participants got a unique ID-code to ensure confidentiality of their identity and gave their written consent for participation and data collection.

2.3. Experimental spaces

In a laboratory space (50 m^2; white walls; dark floor) with two large windows (3.00 × 2.50 m, sill 0.70 m) in the South façade, an open plan office environment was created using light-colored office furniture (desks, chairs, bookcases) and decorations (plants, curtains), see Fig. 1a. An adjacent white building at 5 m distance strongly limited daylight from entering and provided a static, urban view. Since the study was performed in February and March, the daylight contribution was even more limited. The space was equipped with suspended direct/indirect luminaires (Fagerhult Notor 78; 50/50) above each desk (h = 2.20 m). There were five desk groups in the space which seated four students, each sharing one luminaire. The room's West wall had two luminous panels (Lumlyx Wall LED; 0.50 × 1.00 m) with a green nature image.

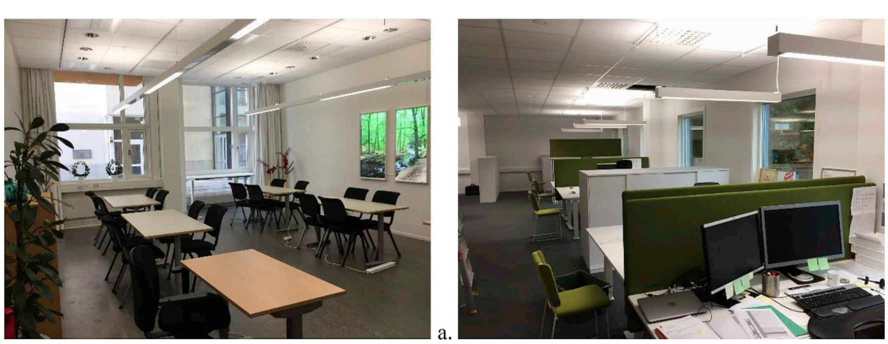
The field study in the real office was executed in two open-plan spaces (white walls; dark carpet; Group A: 165 m^2; 12 desks; Group B: 122 m^2; 13 desks) connected via a wide corridor. The first space had multiple East-oriented (1.20 × 1.50 m, sill 0.70 m; view on a parking lot/road) and West-oriented (1.20 × 1.50 m, sill 0.70 m; view on semi-flat roof and buildings) daylight openings. Daylight openings in the second space were on the West (limited in size: 1.20 × 0.50 m; high up: h = 2.00 m; limiting a view out) and North orientation (1.20 × 1.50 m, sill 0.70 m; view on (green) vegetation), see Fig. 1b. Large windows were equipped with white Venetian blinds, except on the North. Since the study was performed in January and February, the daylight contribution was limited. The room was equipped with suspended direct/indirect luminaires (Fagerhult Notor 78; 50/50, see Fig. 2a) above each desk that provided light on the desk of each employee as well as on the ceiling. In between two desks, there was a green divider and in the middle of both spaces, there was an area for breaks equipped with pendant, direct/indirect lighting (Fagerhult Scoot).

2.4. Lighting patterns

The output levels of both the direct and indirect component of the luminaires were manipulated. The correlated colour temperature (CCT) of the electric lighting was kept constant at 4000 K for the entire duration of the experiment (see Fig. 2 for the relative spectral intensity). Normally, the employees in the real office have personal control over the direct component, but this was disabled during the experiment. This also applied to the luminaire's presence and daylight detection. All luminaires were centrally controlled and followed, per space, a 'static', or one of the two 'dynamic' patterns. The settings were chosen based on illuminance measurements at one (reference) desk in the real office. Additionally, spectral power distribution (see Fig. 2b) and luminance measurements using High Dynamic Range (HDR) images were performed at multiple places in both spaces. The measurements were random control measurements, performed with electric lighting only (after 17:00) and are not further reported. As a first step regarding reporting of the stimulus conditions involving light as an intervention in environmental psychology experiments as suggested by Spitschan et al. (2019), for the extreme settings 'High' and 'Low', the five corresponding human retinal photoreceptor weighted "alpha-opic" irradiance values in mW/m^2 are given in Table 11 in Appendix A (Lucas et al., 2014; Commission Internationale de L'eclairage, 2018).

During both the field and the laboratory test, the horizontal illuminance levels, temperature and humidity were logged every 5 min using Grant Instrument YoYo data loggers (type 2 YL-M61/M62-4M Lux) at multiple places in the room. In the laboratory, one logger was placed on the windowsill to log the entering daylight amount, and two loggers were placed at the students' desks in the middle and back of the room (see Fig. 8 in Appendix B). In the field study, two loggers were placed in room A (East and West orientation) and two in room B (East and West orientation) to measure daylight and electric lighting combined (see Fig. 9 in Appendix B). Unfortunately, the logger on the West orientation in room B was malfunctioning. The influence by daylight in both studies was noticeable on some of the experimental days, especially during lunch time for the employees, but the actual contribution to the experimental light conditions was low (between 0 and 32% on average, see Fig. 10 in Appendix B).

Baseline (static): The static setting was chosen based on light levels that the employees experienced in the real office before the experiment



a. b.

Fig. 1. a) The simulated laboratory office, and b) One of the two open-plan spaces of the real office.

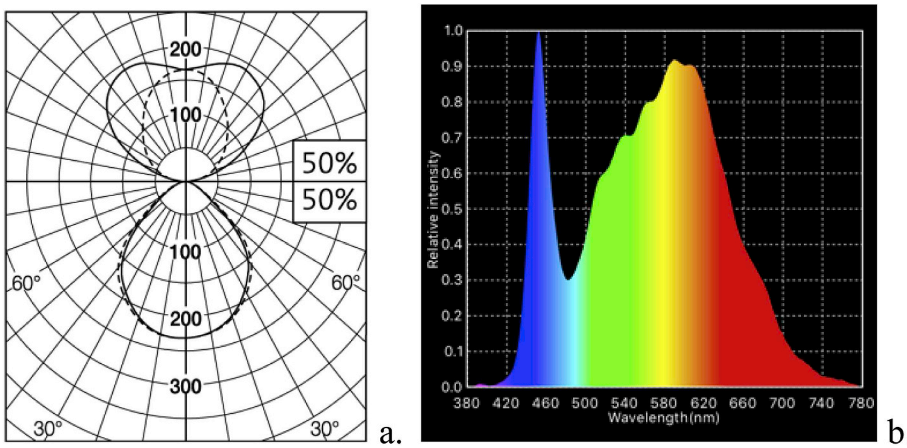


Fig. 2. The light distribution of the used luminaire (a); the relative spectral intensity of the light source at CCT = 4000 K (b).

(average horizontal illuminance $E_{hor\ desk\ avg}$ = 503 lx). The baseline setting at the reference desk (direct 70%, indirect 70%) resulted in $E_{hor\ desk}$ = 487 lx and a vertical illuminance at eye height (h = 1.30m) $E_{vert\ eye}$ = 384 lx.

HighLow (dynamic): The horizontal illuminance at the desk started at the static level (± 500 lx) and increased between 8:00 and 10:00 up to $E_{hor\ desk}$ = 870 lx and $E_{vert\ eye}$ = 690 lx (direct 100%; indirect 100%). After 11:30, the light decreased to the static level again and remained that level over lunchtime. A decrease started at 13:30 and dimmed the lighting to $E_{hor\ desk}$ = 238 lx and $E_{vert\ eye}$ = 185 lx (indirect 25%, direct 35%). After 15:30, the light increased to the static level again, see Fig. 3 – upper part.

LowHigh (dynamic): The horizontal illuminance at the desk started at the static level (± 500 lx) and decreased between 8:00 and 10:00 to $E_{hor\ desk}$ = 238 lx and $E_{vert\ eye}$ = 185 lx (indirect 25%, direct 35%). After 11:30, the light increased to the static level again and remained that level over lunchtime. An increase started at 13:30 and dimmed the lighting up to $E_{hor\ desk}$ = 870 lx and $E_{vert\ eye}$ = 690 lx (direct 100%; indirect 100%). After 15:30, the light increased to the static level again, see Fig. 3 - lower part.

2.5. Procedure

Before the start of the experiment, all participants filled out a general questionnaire containing questions regarding personal and job characteristics as well as a practice for the performance tasks included in the experiment. A questionnaire inquiring after different aspects of well-being was repeated multiple times during the duration of the experiment and ended with two performance tasks. At the end of the study, participants were asked to fill out a third questionnaire, meant for feedback and reflection. The questionnaires were online in English and created using the web-based 'PsyToolkit' (Stoet, 2010, 2017). During the study, questionnaire access was disabled for use on tablets and smartphones, as it had to be filled in behind the desk.

In the simulated office (laboratory study), participants (students; N = 20) attended two times a full day (8:00–16:30) on the Monday in two consecutive weeks and had five trials (Time 0 = 8:30, Time 1 = 10:15 ('morning'), Time 2 = 12:00 ('lunch'), 12:00, Time 3 = 14:30 ('afternoon'), and Time 4 = 16:00) interrupted by two short breaks and a long (lunch) break. On the first day, the lighting was controlled according to the 'HighLow' pattern; on day two participants experienced 'LowHigh' (see Fig. 4).

In the real office (field study), the participants were asked, by e-mail, to fill out the questionnaire three times per day (Time 1 = 10:00, Time 2 = 12:00, and Time 3 = 14:00) on three consecutive workdays (Tuesday to Thursday) in a period of six weeks; in the first and last week participants filled out the questionnaire only on one day. The people were asked to fill out the questionnaire within 1 h (after the reminder, i.e., between 10:00 and 11:00 for Time 2) as the employees had their normal work schedule and activities. In the first week, the light pattern was the same for both groups (Baseline) and Group A (N = 10) experienced the 'HighLow' pattern during week 2 and 3 and 'LowHigh' during week 4 and 5. Group B (N = 11) experienced the opposite. The last week was 'Baseline' (static) for both groups. See Fig. 4 for a

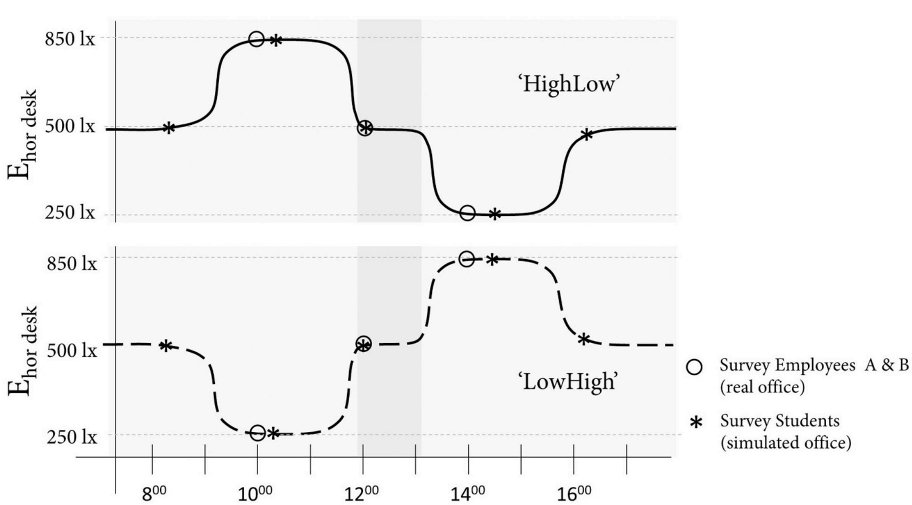


Fig. 3. Schematic representation of the dynamic light procedures including the survey moments for all groups.

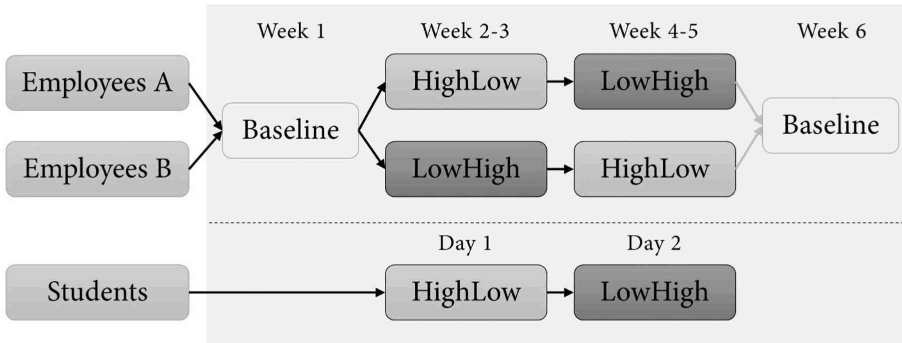


Fig. 4. Schematic representation of the research design and the light patterns for all three groups (Employees in the field study and Students in the laboratory study).

schematic overview of the procedure.

2.6. Measures

As said, questionnaire 1 and 2 collected data for the study's measures (covariates and momentary questions) where questionnaire 3 was meant for reflection and feedback. At the end of the test period, user feedback on the entire process was requested. Participants were asked to describe what happened according to them and gave feedback on practical issues regarding the applied protocol (i.e., frequency of assessment, duration of assessment). Even though a lot of information was collected, this paper will only report seven dependent variables; three to represent 'human well-being'; sleepiness, pleasantness, and satisfaction, and four to represent 'human performance'; performance score and reaction time for the Mental Rotation Task and the Mackworth Vigilance Task.

At multiple moments over the day, a question regarding 'sleepiness/alertness' was asked using the Karolinska Sleepiness Scale (KSS) by Åkerstedt and Gillberg (1990), where a higher score means more sleepy/less alert The Self-Assessment Manikin (SAM) by Lang (1980) and Bradley and Lang (1994) was used to rate three items of 'mood' (pleasantness, arousal, and dominance) on a 9-point rating scale and a higher score means more pleasant/aroused/controlling. To rate the comfort level and satisfaction with lighting, the Office Lighting Survey (OLS) by Eklund and Boyce (1996) was used. As scoring the sum of all eight items (1 reversed) was used with a higher score meaning a higher satisfaction with the lighting. At each momentary assessment, two performance tests were performed: a vigilance test and a mental rotation exercise (see Fig. 5). The stimulus size was fitted to the available size of computer screens (1280*960 pixels) and both tests were executed on full screen with a black background. **Vigilance** was measured via a 3-min visual Vigilance Task (VT) to indicate the level of sustained attention using a Mackworth Clock test (Mackworth, 1948). The standard 10-min VT was considered impractical, and Loh, Lamond, Dorrian, Roach, and Dawson (2004) demonstrated that VT performance during the first five and 2 min deteriorated in a similar manner compared to the whole 10-min task (using another type of vigilance task, the Psychomotor Vigilance Task). Basner, Mollicone, and Dinges (2011) concluded that a 22.7% average decline in the effect size of a 3-min PVT was an acceptable trade-off between duration and sensitivity. The subject had to press the keyboard's space bar as fast as possible in response to short signals at random intervals. For the Vigilance Task, the reaction times (RT), omissions, and false alarms (response without stimulus) were measured. The performance score was calculated as 100% minus number of lapses (errors of omission) relative to the number of valid stimuli. It ranged from 100% (optimal performance, no lapses) to 0% (worst possible performance, only lapses). The mean RT was calculated for the correct trials (i.e., with a response to an actual stimulus). A **three-dimensional Mental Rotation exercise** is a spatial task that requires abilities to mentally retain and rotate objects in space (Shepard & Metzler, 1988). The task involved an original and a target object (adapted from Ganis & Kievit, (2015)), and respondents were asked to indicate whether these two objects are identical or different (mirrored). The objects being viewed were a combination of interconnected blocks with increasing size and shape differed in several experiments. The respondents went through a set of randomized trials with a varying angle rotation. For the Mental Rotation Task, the reaction times (RT) and status (correct/incorrect response) were measured. The performance score was calculated as the number of correct trials (with a maximum score of 40). The mean RT was calculated for the correct trials. Rotation angle and complexity were recorded, but not included in the analysis.

2.7. Data analysis strategy

Due to the nested structure of the momentary assessment data, Hierarchical Linear Models (HLM) were employed to analyse the effect of lighting level as well as the timing of the light exposure on well-being. Analyses were performed in STATA 13.1. A series of models were run comparing effects on well-being and cognitive performance

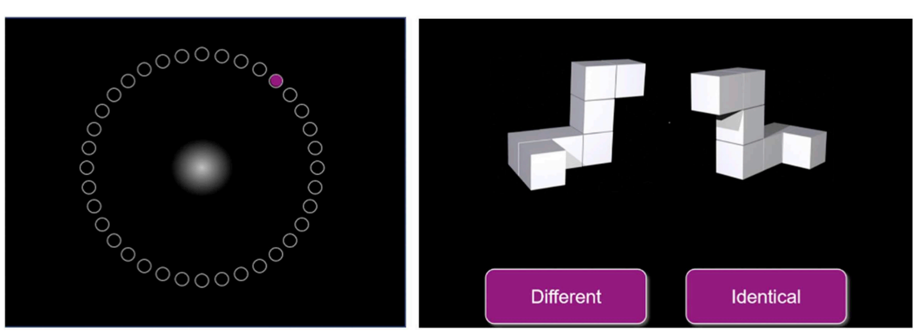


Fig. 5. The impression of the two performance tasks in the study: left the Vigilance Task (VT) using the Mackworth Clock test and right the three-dimensional Mental Rotation exercise.

between the different dynamic light patterns. The independent variables consisted of a (dynamic) light pattern (HighLow versus LowHigh) in the laboratory study and Baseline versus Highlow and LowHigh in the field study) and time (Time 1, 2, and 3), in a full-factorial model. Differences at the individual time points were assessed using post-estimation contrasts. Due to the large number of post-estimation analyses performed, a Bonferroni correction was applied and only results below $\alpha = 0.006$ were considered statistically significant after this correction. For the laboratory study, additional analyses were performed to investigate baseline differences (at Time = 0), and to see whether effects of the light manipulations lingered into the afternoon (at Time = 4). In case baseline differences occurred, scores were adjusted for baseline differences by subtracting the score at Time = 0 on respectively day one or day two from the other time points of that day. For the field study, additional analyses consisted of planned contrasts investigating the differences between the two experimental conditions. In the field study, there was one week Baseline at the beginning of the protocol, but it is not certain that all potential spill-over effects of the light exposure of the previous weeks were entirely washed out. There were too few responses in the second Baseline week (last week of the protocol) to investigate any aftereffects; hence data from the second baseline week were omitted from the analyses. Likelihood Ratio Tests (LRT) were performed to ascertain that the nested model had the best fit (normal regression versus a random intercept model).

3. Results

The results of both studies will be presented consecutively, starting with the Laboratory study: Simulated office. Each section will present the results for well-being indices (pleasantness, sleepiness, and satisfaction) and cognitive performance (reaction times and performance score) for both Mental Rotation and Vigilance tasks separately. As a second objective of the field study was to pilot how participants experienced the protocol in different settings, this will also be briefly reported. This reflection focusses on the response rate, the distribution of responses over time and per group as well as on the preferred questionnaire rate.

3.1. Laboratory study: simulated office

Before performing the main analyses, it was first investigated whether baseline differences occurred between the two days (at Time = 0). These analyses revealed significant baseline differences between the two light patterns for pleasantness (*b(SE)* = −1.60 (0.48), $p = 0.001$), the score on the Mental Rotation task (*b(SE)* = 5.25 (0.95), $p < 0.001$), and reaction time on the Mental Rotation task (*b (SE)* = −506.55 (109.94), $p < 0.001$). These three scores were therefore adjusted for baseline differences in subsequent analyses by subtracting the score at Time = 0 (for each day separately) from the other outcomes. Before starting the HighLow light pattern, pleasantness was higher (*EMM* = 6.0, *SE* = 0.39), the score on the Mental Rotation task was lower (*EMM* = 30.90, *SE* = 1.26), and reaction times on the Mental Rotation task were slower (*EMM* = 2611.75, *SE* = 104.51) than before starting the LowHigh pattern (pleasantness: *EMM* = 4.40, *SE* = 0.39; score: *EMM* = 36.15, *SE* = 1.26; reaction time: *EMM* = 2105.20, *SE* = 104.51).

Well-being - Table 1 shows the outcomes of the main model for all three investigated variables taken as representatives for 'human well-being' 'pleasantness', 'sleepiness', and 'satisfaction'. Fig. 6 displays the graphs for these three representatives for the laboratory and the field study. Post-estimation contrasts were conducted to further explore whether a) there were differences in scores at each time point between the two light patterns, and b) there were differences in scores between the time points within each of the light patterns, see Table 2 for these results for the laboratory study (simulated office).

Main analyses revealed no significant effects of LightPattern nor of the interaction of LightPattern * Time for pleasantness scores. The contrast analyses for pleasantness revealed no significant differences between the time points either, not within the same light pattern, and not between the two light patterns.

For sleepiness, no significant effects surfaced either. The planned contrasts yielded a significantly lower sleepiness score in the 'afternoon' (Time 3; *EMM* = 4.20, *SE* = 0.34) than during 'lunch' (Time 2; *EMM* = 5.00, *SE* = 0.34) during the HighLow light pattern. The sleepiness score in the afternoon of the HighLow light pattern was also lower (*EMM* = 4.20, *SE* = 0.34) than in the afternoon of the LowHigh light pattern *EMM* = 5.05, *SE* = 0.34). None of these effects remained after applying the Bonferroni correction.

For satisfaction, a significant decrease of satisfaction was found from time 1 to time 3., as well as a marginally significant interaction effect of LightPattern * Time for this timeframe, see Fig. 6. Contrast analysis revealed further differences. Satisfaction was significantly lower during the afternoon (*EMM* = 14.20, *SE* = 0.34) than during 'lunch' (*EMM* = 15.00, *SE* = 0.34) and the 'morning' (*EMM* = 15.25, *SE* = 0.34) in the HighLow pattern, see Table 2. Again, none of these effects remained after applying the Bonferroni correction.

A third model was run comparing scores in the afternoon (Time = 4). These analyses revealed no significant effects of LightPattern.

Cognitive performance - Table 3 displays the outcomes for the main analyses for all cognitive performance outcomes (reaction time and score), see also Fig. 7 for the graphs for cognitive performance for both the laboratory and field study.

For the Mental Rotation task, the main model revealed a main effect of LightPattern for the baseline-adjusted score. Post estimation contrast analyses (see Table 4) revealed that the baseline-adjusted score on the Mental Rotation task was higher during the HighLow light pattern at all three measurement times (morning: *EMM* = 1.75, *SE* = 0.71; lunch: *EMM* = 2.00, *SE* = 0.71; afternoon: *EMM* = 2.00, *SE* = 0.71) than during the LowHigh light pattern (morning: *EMM* = −0.30, *SE* = 0.71; lunch: *EMM* = −0.45, *SE* = 0.71; afternoon: *EMM* = −0.40, *SE* = 0.71). The differences between the 'lunch' and 'afternoon' measurements remained significant after the Bonferroni correction.

For the baseline-adjusted reaction times on the Mental Rotation task, the nested model was only marginally significantly better ($p = 0.054$) for the reaction times compared to a regular regression. In addition, the ICC was relatively low, and therefore the outcomes for this analysis should be dealt with caution. Results reported here were from the random effect model. This model revealed a main effect of Time ('afternoon' versus 'morning'). Contrasts revealed a significant difference between the 'morning' and 'afternoon' measurement during the HighLow light pattern, as well as a significant difference in the 'afternoon' measurements between the two light patterns. The baseline-adjusted reaction times were faster in the afternoon during the HighLow light pattern (*EMM* = −383.30, *SE* = 68.12) than during the 'morning' measurement (*EMM* = −141.40, *SE* = 68.12), and also faster compared to the 'afternoon' measurement during the LowHigh light pattern (*EMM* = −175.25, *SE* = 68.12). None of these effects remained, though, after applying the Bonferroni correction.

For the Vigilance Task, no significant effects surfaced for the score. The contrast analyses revealed no significant differences between time points and between days for the score on the Vigilance Task.

For the reaction times on the Vigilance Task, no main or interaction effects were found. Contrasts revealed one significant difference between the 'morning' and 'afternoon' reaction times on the Vigilance Task for the LowHigh light pattern, with faster reaction times in the 'morning' (*EMM* = 500.10, *SE* = 14.12) than in the 'afternoon' (*EMM* = 525.45, *SE* = 14.12).

When investigating potential differences in cognitive performance in the afternoon (Time = 4), one significant effect surfaced for the Mental Rotation task. The (baseline-adjusted) score was significantly higher (*b(SE)* = −2.85 (1.08), $p = 0.008$) during the HighLow light

Table 1
Outcomes of main HLM model for the simulated office for Well-being (with significant effects before Bonferroni correction in bold; significant effects after Bonferroni correction in bold and with grey background).

		Estimate (SE)	p	95% Confidence Interval	ICC ID	LRT χ (p)
Pleasantness[a]	LightPattern	−0.05 (0.61)	0.935	−1.25–1.15	0.14	4.39 (0.036)
	Time 2 vs 1	−0.80 (0.61)	0.192	−2.00–0.40		
	Time 3 vs 1	−0.40 (0.61)	0.514	−1.60–0.80		
	LightPattern [a] Time Time 2 vs 1	0.60 (0.87)	0.489	−1.10–2.30		
	LightPattern [a] Time Time 3 vs 1	0.30 (0.87)	0.729	−1.40–2.00		
Sleepiness	LightPattern	0.60 (0.36)	0.093	−0.10–1.30	0.44	35.21 (< 0.001)
	Time 2 vs 1	0.60 (0.36)	0.093	−0.10–1.30		
	Time 3 vs 1	−0.20 (0.36)	0.576	−0.90–0.50		
	LightPattern [a] Time Time 2 vs 1	−0.95 (0.51)	0.060	−1.94–0.04		
	LightPattern [a] Time Time 3 vs 1	0.25 (0.51)	0.621	−0.74–1.24		
Satisfaction	LightPattern	−0.60 (0.38)	0.112	−1.34–0.141	0.38	26.79 (< 0.001)
	Time 2 vs 1	−0.25 (0.38)	0.508	−0.99–0.49		
	Time 3 vs 1	**−1.05 (0.38)**	**0.005**	**−1.79–−0.31**		
	LightPattern [a] Time Time 2 vs 1	0.20 (0.53)	0.708	−0.85–1.25		
	LightPattern [a] Time Time 3 vs 1	0.90 (0.53)	0.092	−0.15–1.95		

[a] Adjusted for baseline differences.

pattern (*EMM* = 3.25, *SE* = 0.81) than during the LowHigh light pattern (*EMM* = 0.40, *SE* = 0.81). This difference did not remain after applying the Bonferroni correction.

3.2. Field study: real office

Two series of models were run. A first series investigated differences between the baseline week and the experimental weeks (HighLow versus LowHigh light pattern), and subsequent planned contrast analysis directly compared the two light patterns.

Well-being - Table 5 displays the outcomes for the main analyses for well-being, represented by the variables 'pleasantness', 'sleepiness' and 'satisfaction'. See Fig. 6 for the graphs for these three outcomes. Table 6 contains the outcomes for the planned contrasts, comparing the two light patterns.

For pleasantness, a significant effect of LightPattern was found for the LowHigh light pattern as compared with the baseline week, with overall higher scores during the baseline week than during the LowHigh light pattern. Planned contrasts revealed a significant difference in pleasantness scores between the HighLow and LowHigh light pattern, with higher pleasantness scores in the morning of the HighLow light pattern (*EMM* = 5.84, *SE* = 0.40) than in the morning of the LowHigh light pattern (*EMM* = 5.20, *SE* = 0.40); these effects did not hold after the Bonferroni correction.

For sleepiness, none of the models yielded any significant main or interaction effects.

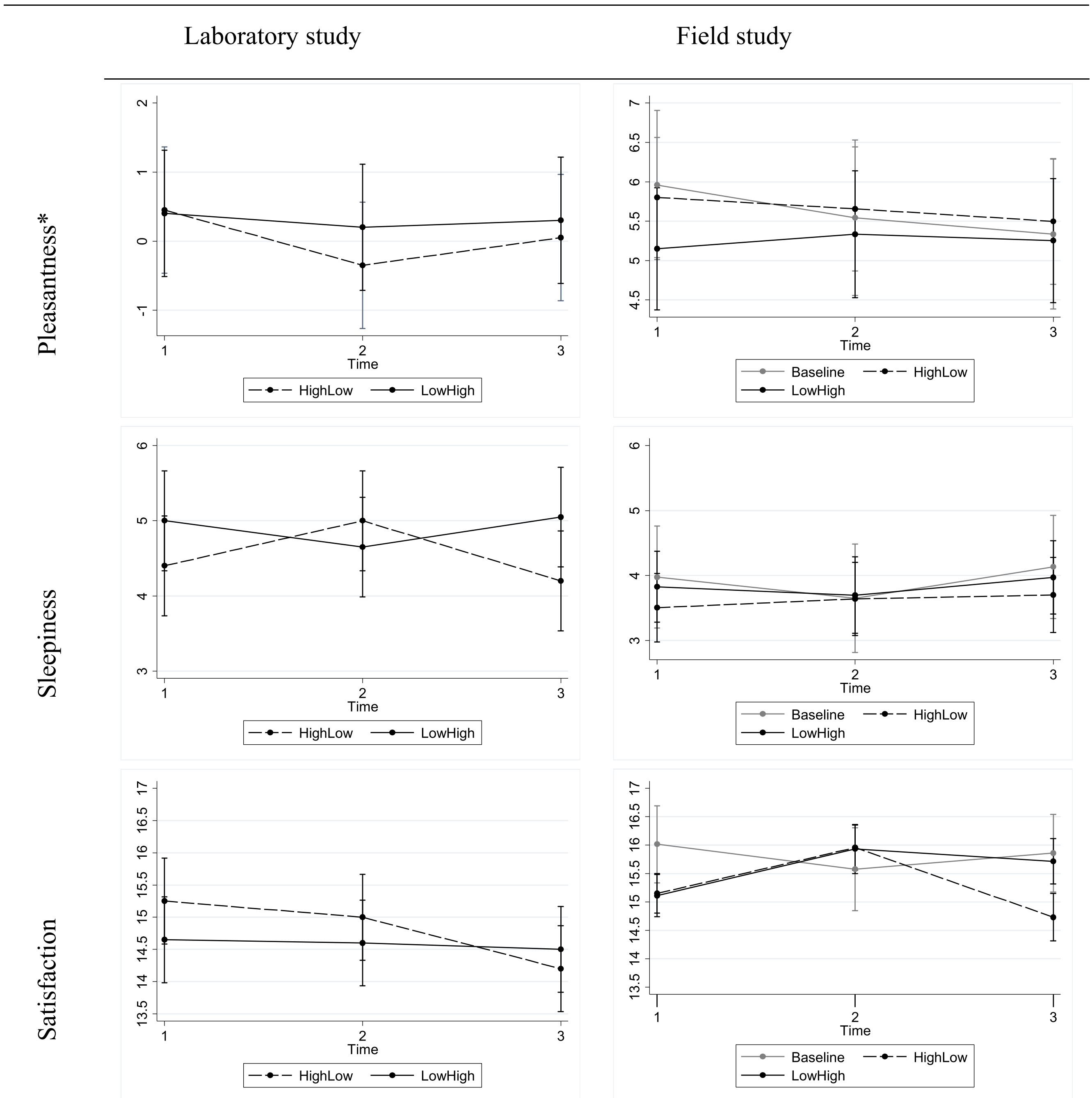
For satisfaction, the first model revealed several significant results. Satisfaction was higher during the baseline week (*EMM* = 15.84, *SE* = 0.22) than during the HighLow (*EMM* = 15.26, *SE* = 0.13) and LowHigh (*EMM* = 15.54, *SE* = 0.14) light patterns. Significant interaction effects were found between the 'baseline', 'morning' measurement, and the HighLow 'lunch' (Time 2) measurement and the between the 'baseline', 'morning' measurement, and the LowHigh 'lunch' (Time 2) measurement, see Fig. 6. Satisfaction increased from morning to lunch for the two experimental light patterns, whereas satisfaction decreased in the baseline from morning to lunch.

Planned contrast revealed several differences between the two light patterns as well. A significant increase in satisfaction was found in the HighLow light pattern from 'morning' (*EMM* = 15.14, *SE* = 0.18) to 'lunch' (*EMM* = 15.96, *SE* = 0.21), and a significant decrease from 'lunch' to 'afternoon' (*EMM* = 14.73, *SE* = 0.22). Likewise, satisfaction increased from 'morning' (*EMM* = 15.11, *SE* = 0.18) to 'lunch' (*EMM* = 15.93, *SE* = 0.23) in the LowHigh light pattern as well, and the 'afternoon' score for satisfaction (*EMM* = 15.71, *SE* = 0.21) was higher than the 'morning' satisfaction score. Satisfaction with the light in the afternoon was higher in the LowHigh light pattern than in the HighLow light pattern. Only the difference in satisfaction in the LowHigh light pattern, between 'morning' and 'afternoon' disappeared after applying the Bonferroni correction.

Cognitive performance - Table 7 displays the outcomes for the main analyses for all four cognitive performance outcomes. Table 8 displays the outcomes for the planned contrasts.

For the Mental Rotation task, the scores were significantly higher during the HighLow light pattern (*EMM* = 36.87, *SE* = 0.63) and the LowHigh light pattern (*EMM* = 38.39, *SE* = 0.64) than during Baseline (*EMM* = 34.02, *SE* = 0.73). No interactions of LightPattern * Time were found. Planned contrasts revealed a significantly higher score on the Mental Rotation task for the LowHigh light pattern than for the HighLow light pattern, on all three time points ('morning' HL: *EMM* = 36.72, *SE* = 0.60; LH: *EMM* = 38.14, *SE* = 0.62 | 'lunch' HL: *EMM* = 36.84, *SE* = 0.63; LH: *EMM* = 38.06, *SE* = 0.65 | 'afternoon' HL: *EMM* = 36.86, *SE* = 0.64; LH: *EMM* = 38.67, *SE* = 0.63). The effects for the 'morning' and 'afternoon' remained after applying the Bonferroni correction, but not the effects during 'lunch'.

The reaction times on the Mental Rotation task showed a similar pattern, with faster reaction times during the HighLow (*EMM* = 1945.15, *SE* = 108.50) and LowHigh (*EMM* = 1754.46, *SE* = 96.11) light patterns than during Baseline (*EMM* = 2562.15, *SE* = 108.50). There was also a main effect of Time, with reaction times getting faster as the day progressed. One significant interaction of Time * LightPattern (HighLow 'morning' with LowHigh 'afternoon') was also found. Planned contrasts further revealed a significant difference in reaction time for the HighLow light pattern, with slower reaction times in the morning (*EMM* = 2031.96, *SE* = 106.53) than in the afternoon (*EMM* = 1896.57, *SE* = 110.51). In addition, again, the LowHigh light pattern had significantly faster reaction times on all three timepoints



* Pleasantness scores for the students were adjusted for baseline differences

Fig. 6. Linear Prediction, Fixed Portion values for the three wellbeing representatives over time, with 95% confidence intervals. Note that the y-axis for Pleasantness (laboratory) is different due to baseline adjustments.

than during the HighLow light pattern (‘morning’ HL: *EMM* = 2031.96, *SE* = 106.53; LH: *EMM* = 1801.08, *SE* = 108.11 | ‘lunch’ HL: *EMM* = 1969.78, *SE* = 109.65; LH: *EMM* = 1801.06, *SE* = 111.51 | ‘afternoon’ HL: *EMM* = 1896.57, *SE* = 110.51; LH: *EMM* = 1769.24, *SE* = 109.65). Only the morning effect remained for the reaction times after the Bonferroni correction.

For the Vigilance Task, the score yielded an ICC below 0.1, rendering the reliability for assessing group-level means poor. For this reason, this outcome variable was excluded from further analyses.

Vigilance reaction times did yield an acceptable ICC. The main model revealed a significant effect of time, for the ‘afternoon’ in comparison to the ‘morning’. Reaction times were generally faster in the morning (EMM = 496.33, SE = 10.25) than in the afternoon (EMM = 504.90, SE = 10.50). The interaction of Time * LightPattern turned significant for this timeframe for the baseline versus the LowHigh light pattern. During baseline, the reaction times appeared to get slower throughout the day, whereas the opposite occurred during the LowHigh light pattern, see Fig. 7. Planned contrast revealed only one significant difference. For the HighLow light pattern, reaction times were significantly slower in the afternoon (*EMM* = 508.16, *SE* = 10.81) than in the morning (*EMM* = 492.29, *SE* = 10.05); this difference vanished after applying the Bonferroni correction.

Table 2
Outcomes of post estimation contrast analyses for the simulated office for Well-being (with significant effects before Bonferroni correction in bold; significant effects after Bonferroni correction in bold and with grey background).

	LightPattern	Time	χ^2	p
Pleasantness[a]	HL	1 vs 2	1.71	0.192
	HL	2 vs 3	0.37	0.504
	HL	1 vs 3	0.43	0.514
	LH	1 vs 2	0.11	0.744
	LH	2 vs 3	0.04	0.860
	LH	1 vs 3	0.03	0.870
	HL vs LH	1	0.01	0.935
	HL vs LH	2	0.81	0.369
	HL vs LH	3	0.17	0.683
Sleepiness	HL	1 vs 2	2.82	0.093
	HL	**2 vs 3**	**5.01**	**0.025**
	HL	1 vs 3	0.31	0.576
	LH	1 vs 2	0.96	0.328
	LH	2 vs 3	1.25	0.263
	LH	1 vs 3	0.02	0.889
	HL vs LH	1	2.82	0.093
	HL vs LH	2	0.96	0.328
	HL vs LH	**3**	**5.65**	**0.017**
Satisfaction	HL	1 vs 2	0.44	0.508
	HL	**2 vs 3**	**4.48**	**0.034**
	HL	**1 vs 3**	**7.72**	**0.006**
	LH	1 vs 2	0.02	0.895
	LH	2 vs 3	0.07	0.791
	LH	1 vs 3	0.16	0.691
	HL vs LH	1	2.52	0.112
	HL vs LH	2	1.12	0.290
	HL vs LH	3	0.63	0.472

[a] Adjusted for baseline differences.

3.3. Protocol

In the laboratory study, all participants responded at all assessment moments (100 out of 100 moments; 100%, leading to a very high response rate, which can be expected in a controlled study.

In the field study, a total of 342 responses were collected (out of a possible 882; 42.5%). As the two groups of participants had different job descriptions, at first, it was tested whether response rates differed between the two groups. Table 9 presents an overview of the response rates per group and per week. A significant difference was found in response rates between the two groups ($t(5) = 5.25$, $p = 0.003$). Participants of group B filled in significantly fewer questionnaires compared to their colleagues in group A. This difference may be explained by the differences in work tasks, as one of the groups had appointments outside the company more frequently. Modelling in the two groups was applied, but these models generally did not improve model fit; hence, analyses were continued with a combined group.

Table 10 shows the distribution of responses over the three measurement times. The highest response rates were found during the morning and lowest response rates during lunchtime, probably as the 12:00 h reminder coincided directly with lunch.

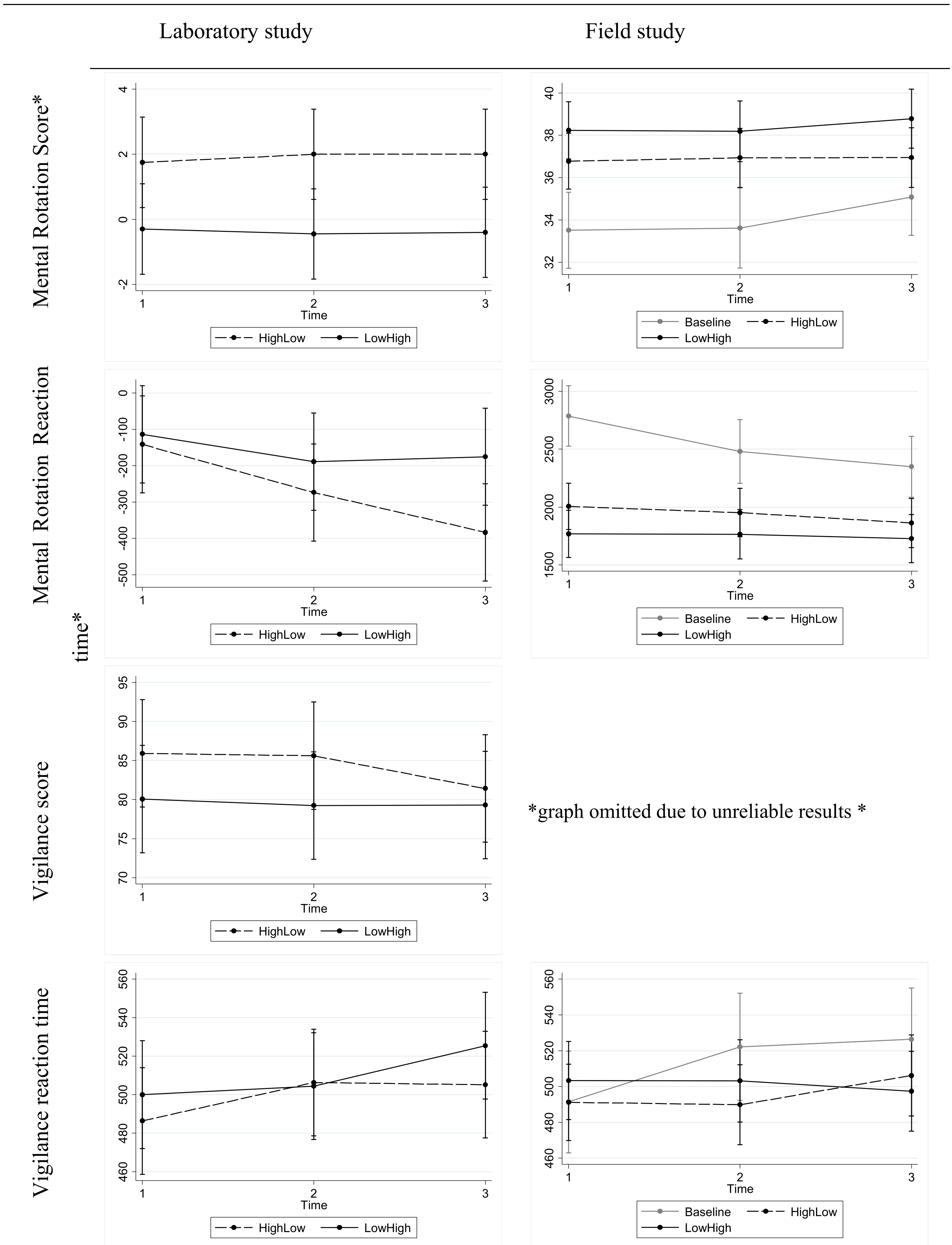
The employees received a reminder 15 min before the planned questionnaire moment. Of the 342 responses, a total of 207 responses were given within 1 h after the reminder (60.5%). The last column in Table 10 shows the number of responses over the day that were not given within a 75-min period after the reminder (15 min +1 h). As can be seen, compliance was lowest again during lunchtime.

At the end of the study, both the students and the employees were given the opportunity to reflect on the applied test protocol. In the laboratory study, 11 students (55%) indicated that they had experienced changes in the light. To the question about what kind of changes were experienced, eight students wrote that the illuminance level

Table 3
Outcomes of the main HLM model for the simulated office for Cognitive performance (with significant effects before Bonferroni correction in bold; significant effects after Bonferroni correction in bold and with grey background).

		Estimate (SE)	p	95% Confidence Interval	ICC ID	LRT χ (p)
MR_Score[a]	**LightPattern**	**−2.05 (0.86)**	**0.017**	**−3.74–−0.36**	0.26	13.65 (< 0.001)
	Time 2 vs 1	0.25 (0.86)	0.772	−1.44–1.94		
	Time 3 vs 1	0.25 (0.86)	0.772	−1.44–1.94		
	LightPattern [a] Time Time 2 vs 1	−0.40 (1.22)	0.743	−2.79–1.99		
	LightPattern [a] Time Time 3 vs 1	−0.35 (1.22)	0.774	−2.74–2.04		
MR_RT[a]	LightPattern	27.4 (90.04)	0.761	−149.07–203.87	0.13	3.72 (0.054)
	Time 2 vs 1	−132.25 (90.04)	0.142	−308.72–44.22		
	Time 3 vs 1	**−421.90 (90.04)**	**0.007**	**−418.37–−65.43**		
	LightPattern [a] Time Time 2 vs 1	57.45 (127.33)	0.652	−192.11–307.01		
	LightPattern [a] Time Time 3 vs 1	180.65 (127.33)	0.156	−68.91–430.21		
VIG_Score	LightPattern	5.85 (3.53)	0.098	−12.76–1.07	0.50	43.41 (< 0.001)
	Time 2 vs 1	0.31 (3.53)	0.931	−7.22–6.61		
	Time 3 vs 1	4.51 (3.53)	0.202	−11.42–2.41		
	LightPattern [a] Time Time 2 vs 1	.53 (4.99)	0.916	−10.30–13.50		
	LightPattern [a] Time Time 3 vs 1	−3.72 (4.99)	0.456	6.06–13.50		
VIG_RT	LightPattern	13.70 (12.45)	0.271	−10.71–38.11	0.62	66.84 (< 0.001)
	Time 2 vs 1	19.95 (12.45)	0.104	−4.09–43.99		
	Time 3 vs 1	18.80 (12.45)	0.125	−5.24–42.84		
	LightPattern [a] Time Time 2 vs 1	−15.60 (17.48)	0.372	−49.86–40.81		
	LightPattern [a] Time Time 3 vs 1	6.55 (17.48)	0.708	−27.71–40.81		

[a] Adjusted for baseline differences.



* Scores for the students were adjusted for baseline differences

Fig. 7. Adjusted Predicted values for cognitive performance over time, with 95% confidence intervals. Note that the analysis for the employees on the score on the Vigilance Task was excluded due to low reliability and the y-axis are alerted when there were baseline adjustments.

Table 4
Outcomes of planned contrasts for the simulated office for Cognitive performance (with significant effects before Bonferroni correction in bold; significant effects after Bonferroni correction in bold and with grey background).

	LightPattern	Time	χ^2	p
Mental Rotation score*	HL	1 vs 2	0.08	0.772
	HL	2 vs 3	<.001	1.00
	HL	1 vs 3	<0.01	1.00
	LH	1 vs 2	0.03	0.862
	LH	2 vs 3	<.001	0.954
	LH	1 vs 3	<0.01	0.984
	HL vs LH	**1**	**5.66**	**0.017**
	HL vs LH	**2**	**8.08**	**0.005**
	HL vs LH	**3**	**7.76**	**0.005**
Mental Rotation RT*	HL	1 vs 2	2.16	0.142
	HL	2 vs 3	1.48	0.223
	HL	**1 vs 3**	**7.22**	**0.007**
	LH	1 vs 2	0.69	0.406
	LH	2 vs 3	0.02	0.880
	LH	1 vs 3	0.46	0.496
	HL vs LH	1	0.09	0.761
	HL vs LH	2	0.89	0.346
	HL vs LH	**3**	**5.34**	**0.021**
Vigilance score	HL	1 vs 2	0.01	0.930
	HL	2 vs 3	1.42	0.233
	HL	1 vs 3	1.63	0.200
	LH	1 vs 2	0.06	0.813
	LH	2 vs 3	<0.01	0.988
	LH	1 vs 3	0.05	0.825
	HL vs LH	1	2.75	0.097
	HL vs LH	2	3.26	0.071
	HL vs LH	3	0.36	0.549
Vigilance RT	HL	1 vs 2	2.65	0.104
	HL	2 vs 3	0.01	0.925
	HL	1 vs 3	2.35	0.125
	LH	1 vs 2	0.12	0.727
	LH	2 vs 3	2.93	0.087
	LH	**1 vs 3**	**4.14**	**0.042**
	HL vs LH	1	1.21	0.271
	HL vs LH	2	0.02	0.877
	HL vs LH	3	2.73	0.099

** adjusted for baseline differences*

changed, even though three of them thought that the colour temperature had varied as well. One student noticed *"increased glare in the keyboard"*, one student noticed *"light changes during the questionnaire moments",* and one student did not answer the question. Two (10%) participants thought it would have been better if both test moments were within the same week and the majority (11 students, 55%) thought two days in two different weeks was good, even though one of them stated that "*it depends on how many scenarios there are, and we do not know that. I would have preferred as many times as there are scenarios"*. 7 people (35%) had no opinion/comment. When asking how many times per day should have been asked to fill out the questionnaire, 2 students (10%) answered 3 times, 3 students (15%) 4 times, 6 students (30%) 5 times, 2 students (10%) 6 times and 7 students (35%) had no opinion/comment. One student mentioned that there were "*too many questions"*.

In the field study, out of the 20 participants that filled in the final questionnaire, 17 (85%) indicated that they had experienced changes in the light. Some participants commented that the workload was too high, but most participants still indicated that they would prefer to have received two (30%) to three (30%) questionnaires per day, even though some also indicated to prefer 6 questionnaires per day (30%). One participant (5%) preferred only one questionnaire per day and another participant (5%) preferred five questionnaires per day.

4. Discussion

Two studies were conducted to investigate the effect of two opposite daily patterns of dynamic light exposure for maintaining or improving well-being and objective performance. Triangulation using a dual-experimental methodology was employed to examine the effects of a dynamic lighting pattern. The two dynamic electric light patterns were applied in both a controlled laboratory study as well as in a quasi-controlled field study, and next to an increase of illuminance level in either the morning or the afternoon also a decrease was investigated. A deliberate choice was made to implement illuminance levels in line with future practical applications in office environments, resulting in moderate changes in illuminance levels rather than using more extreme differences between the high and low illuminance levels as often implemented in laboratory studies into the effects of bright light exposure on human cognition and behaviour. At the same time, practical issues regarding the applied assessment protocol were evaluated and discussed. The outcomes showed mixed results of the light pattern.

4.1. Effect of dynamic light patterns on well-being

In the laboratory study, there was a baseline difference in **pleasantness** scores. After controlling for this baseline difference, no effects of the light patterns were found on pleasantness scores. In the field study, however, some evidence for effects of the light pattern on the pleasantness score was found, and in the expected direction. Reported pleasantness was higher in the morning during the HighLow light pattern - when participants were receiving the high illuminance levels - than in the LowHigh light pattern – when participants were receiving low light levels. However, no significant difference in pleasantness score was found in the afternoon, when the light exposure was reversed. No difference was found between the HighLow light pattern and

Table 5
Outcomes of the main HLM model for the field study for well-being (with significant effects before Bonferroni correction in bold; significant effects after Bonferroni correction in bold and with grey background).

		Estimate (SE)	p	95% Confidence Interval	ICC ID	LRT χ (p)
Pleasantness	LightPattern HL vs Base	−0.16 (0.36)	0.661	−0.86–0.55	0.61	175.79 (< .0001)
	LightPattern LH vs Base	**−0.81 (0.37)**	**0.028**	**−1.53–−0.88**		
	Time 2 vs 1	−0.42 (0.48)	0.384	−1.36–0.52		
	Time 3 vs 1	−0.62 (0.46)	0.175	−1.53–0.28		
	LightPattern * Time Base T1 vs					
	HL T2	0.27 (0.53)	0.606	−0.76–1.31		
	HL T3	0.32 (0.52)	0.538	−0.70–1.34		
	LH T2	0.60 (0.54)	0.267	−0.46–1.66		
	LH T3	0.73 (0.52)	0.161	−0.29–1.74		
Sleepiness	LightPattern HL vs Base	−0.47 (0.37)	0.207	−1.21–0.26	0.34	65.92 (< 0.001)
	LightPattern LH vs Base	−0.15 (0.38)	0.696	−0.90–0.60		
	Time 2 vs 1	−0.33 (0.50)	0.512	−1.30–0.65		
	Time 3 vs 1	0.15 (0.48)	0.747	−0.78–1.09		
	LightPattern * Time Base T1 vs					
	HL T2	0.46 (0.55)	0.400	−0.61–1.54		
	HL T3	0.04 (0.54)	0.939	−1.02–1.10		
	LH T2	0.20 (0.56)	0.726	−0.91–1.30		
	LH T3	−0.01 (0.54)	0.985	−1.07–1.05		
Satisfaction	**LightPattern HL vs Base**	**−0.87 (0.37)**	**0.020**	**−1.60–−0.14**	0.07	5.84 (0.016)
	LightPattern LH vs Base	**−0.90 (0.38)**	**0.017**	**−1.65–−0.16**		
	Time 2 vs 1	−0.44 (0.49)	0.375	−1.41–0.53		
	Time 3 vs 1	−0.16 (0.48)	0.742	−1.09–0.78		
	LightPattern * Time Base T1 vs					
	HL T2	**1.25 (0.55)**	**0.023**	**0.17–2.32**		
	HL T3	−0.26 (0.54)	0.626	−1.32–0.79		
	LH T2	**1.26 (0.56)**	**0.024**	**0.16–2.36**		
	LH T3	0.76 (0.54)	0.158	−0.29–1.81		

Table 6
Outcomes of planned contrasts for the field study for Cognitive performance (with significant effects before Bonferroni correction in bold; significant effects after Bonferroni correction in bold and with grey background).

	LightPattern	Time	χ^2	p
Pleasantness	HL	1 vs 2	0.68	0.408
	HL	2 vs 3	0.11	0.737
	HL	1 vs 3	0.50	0.480
	LH	1 vs 2	1.39	0.238
	LH	2 vs 3	0.09	0.766
	LH	1 vs 3	0.18	0.671
	HL vs LH	**1**	**7.58**	**0.006**
	HL vs LH	2	0.83	0.363
	HL vs LH	3	0.82	0.365
Sleepiness	HL	1 vs 2	0.25	0.614
	HL	2 vs 3	0.12	0.729
	HL	1 vs 3	0.76	0.383
	LH	1 vs 2	0.29	0.589
	LH	2 vs 3	1.18	0.277
	LH	1 vs 3	0.39	0.535
	HL vs LH	1	2.47	0.116
	HL vs LH	2	0.13	0.718
	HL vs LH	3	1.28	0.259
Satisfaction	**HL**	**1 vs 2**	**10.24**	**0.001**
	HL	**2 vs 3**	**19.01**	**<0.001**
	HL	1 vs 3	2.53	0.112
	LH	**1 vs 2**	**8.78**	**0.003**
	LH	2 vs 3	0.60	0.440
	LH	**1 vs 3**	**5.28**	**0.022**
	HL vs LH	1	0.02	0.886
	HL vs LH	2	0.01	0.922
	HL vs LH	**3**	**12.24**	**<0.001**

Table 7
Outcomes of the main HLM model for the field study for cognitive performance (with significant effects before Bonferroni correction in bold; significant effects after Bonferroni correction in bold and with grey background).

		Estimate (SE)	p	95% Confidence Interval	ICC ID	LRT χ (p)
Mental rotation score	**LightPattern HL vs Base**	**3.26 (0.78)**	**< 0.001**	**1.72–4.80**	0.46	92.82 (< 0.001)
	LightPattern LH vs Base	**4.72 (0.80)**	**< 0.001**	**3.15–6.29**		
	Time 2 vs 1	0.11 (1.04)	0.919	−1.94–2.15		
	Time 3 vs 1.	1.57 (1.00)	0.117	−0.39–3.53		
	LightPattern * Time Base T1 vs					
	HL T2	0.05 (1.15)	0.962	−2.20–2.31		
	HL T3	−1.40 (1.13)	0.216	−3.61–0.82		
	LH T2	−0.15 (1.18)	0.900	−2.46–2.16		
	LH T3	−1.01 (1.13)	0.369	−3.23–1.20		
Mental rotation reaction time	**LightPattern HL vs Base**	**−780.81 (108.09)**	**< 0.001**	**−992.67–-568.95**	0.52	88.32 (< 0.001)
	LightPattern LH vs Base	**−1017.09 (110.48)**	**< 0.001**	**−1233.63–-800.56**		
	Time 2 vs 1	**−305.95 (143.54)**	**0.033**	**−587.28–-24.61**		
	Time 3 vs 1	**−437.94 (138.05)**	**0.002**	**−708.51–-167.37**		
	LightPattern * Time Base T1 vs					
	HL T2	252.78 (158.38)	0.110	−57.64–563.20		
	HL T3	295.19 (155.57)	0.058	−9.72–600.10		
	LH T2	302.61 (155.63)	0.062	−15.40–620.64		
	LH T3	**395.82 (155.63)**	**0.011**	**90.80–700.85**		
Vigilance reaction time	LightPattern HL vs Base	−0.23 (12.07)	0.985	−23.88–23.41	0.50	107.16 (< 0.001)
	LightPattern LH vs Base	11.92 (12.33)	0.333	−12.24–36.09		
	Time 2 vs 1	30.76 (15.41)	0.055	−0.64–62.17		
	Time 3 vs 1	**35.02 (15.41)**	**0.023**	**4.81–65.22**		
	LightPattern * Time Base T1 vs					
	HL T2	−32.07 (17.65)	0.069	−66.66–2.52		
	HL T3	−20.00 (17.37)	0.249	−54.04–14.03		
	LH T2	−30.94 (18.11)	0.088	−66.44–4.56		
	LH T3	**−40.95 (17.37)**	**0.018**	**−75.00–-6.90**		

Table 8
Outcomes of planned contrasts for the field study for Cognitive performance (with significant effects before Bonferroni correction in bold; significant effects after Bonferroni correction in bold and with grey background).

	LightPattern	Time	χ^2	P
Mental Rotation score	HL	1 vs 2	0.07	0.794
	HL	2 vs 3		
	HL	1 vs 3	0.09	0.764
	LH	1 vs 2	0.03	0.870
	LH	2 vs 3		
	LH	1 vs 3	1.33	0.248
	HL vs LH	**1**	**10.95**	**<0.001**
	HL vs LH	**2**	**5.62**	**0.018**
	HL vs LH	**3**	**13.55**	**<0.001**
Mental Rotation RT	HL	1 vs 2	1.12	0.291
	HL	2 vs 3	1.27	0.259
	HL	**1 vs 3**	**5.26**	**0.022**
	LH	1 vs 2	<0.01	1.000
	LH	2 vs 3	0.25	0.619
	LH	1 vs 3	0.30	0.585
	HL vs LH	**1**	**17.59**	**<0.001**
	HL vs LH	**2**	**6.51**	**0.010**
	HL vs LH	**3**	**4.10**	**0.043**
Vigilance RT	HL	1 vs 2	<0.01	0.956
	HL	2 vs 3	3.45	0.063
	HL	**1 vs 3**	**3.86**	**0.049**
	LH	1 vs 2	<0.01	0.964
	LH	2 vs 3	0.39	0.533
	LH	1 vs 3	0.54	0.464
	HL vs LH	1	2.93	0.087
	HL vs LH	2	2.08	0.149
	HL vs LH	3	1.06	0.303

Table 9
Response rates per week and per sample group.

week	Group A n = 10 (%)	Group B n = 11 (%)
1	24 (80.0)	18 (54.5)
2	51 (56.7)	33 (33.3)
3	40 (44.4)	32 (32.3)
4	47 (52.2)	34 (34.3)
5	35 (38.9)	19 (19.2)
6	8 (26.7)	1 (.03)

Table 10
Distribution of responses over the two groups throughout the day and responses that were late.

Time of day	Group A n = 10 (%)	Group B n = 11 (%)	'Late' responses
Morning (Time 1)	81 (42.6)	54 (25.8)	5 (19.2%)
Lunch (Time 2)	59 (31.1)	44 (21.1)	15 (57.7%)
Afternoon (Time 3)	65 (34.2)	39 (18.7)	6 (23.1%)

baseline, implying that the baseline condition may have already been sufficient to improve affect. None of these effects remained after statistically controlling for the fact that multiple comparisons were made and therefore, they should be treated with caution.

A second important factor for well-being is **satisfaction** with the lighting. In the laboratory study, satisfaction scores followed expectations in the HighLow light pattern, with high satisfaction reported in the morning when a high light level was administered, and a low satisfaction score in the afternoon, when a low light level was administered. However, no differences in satisfaction were found when participants were exposed to the LowHigh light pattern. Importantly, these differences were no longer significant after applying the Bonferroni correction. The satisfaction results in the field study were very different from the results in the laboratory study, whereas all-but-one effect (the difference between morning and afternoon for the LowHigh light pattern) remained significant after controlling for the amount of comparisons. First, overall satisfaction scores were lower during the two light patterns than during the baseline week. The expected high satisfaction score during the High light condition was only observed for the LowHigh condition but not for the HighLow condition. However, this was also the only outcome that was no longer significant after applying the Bonferroni correction. Even though participants reported feeling more pleasantness in the morning when the light levels were high as compared to the low light levels, they reported lower satisfaction score under the high light levels than during the 'neutral' light settings during lunchtime as well. Potentially, the higher light levels were visually appreciated less but did have an acute effect on mood. Another explanation could be that, as the study was conducted during the winter, these outcomes may have been affected by the daylight contribution (Day, Theodorson, & Van Den Wymelenberg, 2012). Daylight levels were highest during lunchtime, see also Appendix B. In the laboratory study, the daylight contribution was more limited due to an adjacent building, and in that study, results for the HighLow light pattern were in line with expectations.

Subjective sleepiness appeared affected by the light pattern only in the laboratory study. The differences found, were, however, different from expectations. Sleepiness was lower in the 'afternoon' of the HighLow light pattern than during the 'lunch' measurement – under 'neutral' light exposure. Potentially, this may be lagged effects of the morning light exposure, but the present research cannot tell whether this was the case. Again, these results did not hold after applying a Bonferroni correction. Previous (laboratory) studies (e.g., Partonen & Lonnqvist, 2000; Smolders & De Kort, 2014; Yang et al., 2019) did show alerting effects of bright light exposure. However, it is important to realize that these studies usually use more extreme variations in lighting levels (i.e., lower light levels in the Low lighting condition and higher light levels in the High light level) than in the present study. Research field studies with comparable conditions (200–700 lx and daylight access enabled) did not find significant differences in alertness (De Kort & Smolders, 2010; Aarts, Aries, Straathof, & Hoof, 2014). The field study of Rautkylä, Puolakka, Tetri, and Halonen (2010) did not report a change in subjective alertness in the spring but found a significant decrease in alertness in the autumn, indicating a potential seasonal effect. Potentially, alertness in an office environment also fluctuates due to other factors than lighting, e.g., just having had a coffee break or the type of tasks performed throughout the day. These effects may be stronger than the variations in lighting employed in the present study. Conversely, alerting effects in a laboratory setting may differ from those in real life, as increased alertness in an office also may increase attention to distractors (e.g., colleagues chatting, someone walking past in the hallway).

Overall, for none of the well-being measures, strong evidence surfaced. Furthermore, the results were never consistent between the laboratory and the field study.

4.2. Effect of dynamic light patterns on performance

More objective measures of alertness, the outcomes on the **Vigilance** task, rendered mixed, but inconclusive results. In the laboratory study, no effect was found of the light pattern on the score. In the field study, the score on the Vigilance task had to be discarded altogether due to low reliability. Results on reaction times showed opposite effects between studies. In the laboratory, during the LowHigh light pattern, reaction times were faster in the morning than in the afternoon which is counter to expectations whereas in the field study reaction times were faster in the morning than in the afternoon for the HighLow light pattern. Thus, in the laboratory study, the response times were faster under low light exposure, whereas in the field study, response times were faster in the high light conditions. In both instances, faster response times were found in the morning. Importantly, the effects all disappeared after controlling for the number of analyses. Previous research has found a beneficial effect of high light exposure and pointed at more pronounced benefits of exposure to bright light in the morning (e.g., Figueiro & Rea, 2012; Sithravel et al., 2018; Tanaka et al., 2011). The present research showed faster response times in the morning but cannot relate this to a specific lighting condition.

In addition to the VigilanceTask, a higher-order executive functioning task, the **Mental Rotation** task, was added to investigate the effects of the light pattern on more deliberate cognitive performance. Again, the outcomes on the task rendered contrasting effects in both studies. In the laboratory study, there were baseline differences, potentially pointing at learning effects. In this study, the scores had to be adjusted for baseline differences and results indicated that the adjusted score was higher in the HighLow condition than in the LowHigh condition, throughout the day (at lunchtime and in the afternoon after the Bonferroni correction). Due to a relatively low ICC, the outcomes on the reaction times for the laboratory must be interpreted with caution. An almost exact opposite effect occurred for the field study, where scores and reaction times were overall better during the HighLow light pattern than during the LowHigh light pattern (in the morning and afternoon after the Bonferroni correction). Here, scores for HighLow and LowHigh pattern were better than during baseline, again suggesting that effects may be due to learning effects. During the HighLow light pattern, the reaction times were faster in the afternoon than in the morning, an outcome that was found for the laboratory study as well. These differences in results may, as with the Vigilance Task, further point to potential learning effects. Besides, several studies reported that men perform better than women in a Mental Rotation task using different strategies (e.g., Butler et al., 2006, Heil & JANSEN-Osmann, 2008). The gender distribution in the field and laboratory experiment were unequal and opposite with more female (N = 14) than male participants in the laboratory study. Debarnot, Piolino, Baron, and Guillot (2013) found that after training, women tended to enhance performance substantially, but the gender difference remained significant. In the field study, with the conditions counterbalanced over a much more extended study period and more male than female participants, results showed a very similar pattern with faster responses on correct trials - and better scores - during the LowHigh light pattern than during the HighLow light pattern. Only one finding was consistent over both studies: in the HighLow light pattern response times were slower in the morning - when exposed to high light levels - than in the afternoon – when exposed to low light levels. These outcomes may appear counterintuitive at first, but are actually in line with previous research (Huiberts et al., 2015), indicating that performance on higher-order cognitive tasks not always benefit from bright light exposure. However, more research is necessary to corroborate this finding.

4.3. Field studies versus laboratory studies

Many (laboratory) studies are performed under extreme conditions, testing with very high or extremely low light levels, standardizing work tasks and executing the test in an environment free from distractions. One may question what this means for translating and verifying outcomes of lighting research into practical implementations as research in real-time, fully operational environments is limited. Moreover, work executed in real life is much more dynamic than in laboratory settings; the environment is much more distracting, and the light levels will vary more frequently. Office employees are more mobile than participants in a laboratory by alternating (light) environments more frequently (i.e., home, outdoors, meeting rooms). Prior light history can sensitize the human biological clock and can impact a subsequent light exposure. A first study exploring prior light exposure by Smith, Schoen, and Czeisler (2004) demonstrated that prior light history over three days (200 lux vs 0.5 lux) changed the extent of melatonin suppression at the moment of a subsequent light stimulus. The follow-up study showed that a very dim light level (1 lux), compared to the typical room light level (90 lux), prior to the light exposure at night caused a much larger phase shift and acute melatonin suppression (Chang, Scheer, & Czeisler, 2011). One of the laboratory studies by Huiberts (2018) showed that acute alerting effects preceded by 1-h bright light (1700 lux) exposure only persisted for maximally half an hour after the exposure and dissipated afterwards. Huiberts (2018) concluded that a relatively short bright compared to regular light exposure may elicit positive acute ipRGC-influenced light effects, but that potential delayed effects after the light offset should be further investigated.Where field studies may have a much higher ecological validity, good data collection is much more complicated. The results in the field study were restricted by less-than-optimal response rates of 42.5%. Low response rates or missing information on the participation rates present a challenge in longitudinal field studies. ISKRA-Golec et al. (2012) investigated office employees in Poland three times per day and two times per week for nine weeks but did not report how participants experienced this. Neither is it reported how much data were missing. Smolders et al. (2012) investigated employees in the Netherlands for three months and reported a response rate of 35.5% for the first month of the field study which reduced to 23.2% in the second month. In the end, 84 of the in total 414 office employees completed the third period (response rate 20.3%). Laboratory studies are often only a short commitment; a longitudinal field study asks to participate over a long period. In the field study, on average, two-third of the participants (80% in group A and 55% in group B) filled out the questionnaires on the first day(s) of the experiment; after that the response rate dropped to approximately one-third of the people with a slight increase in the week that the light scenario changed (week 4) before dropping to one-third or less in the last weeks. At the same time, 16 (76%) of the 21 employees participated 10 times or more, roughly translating to two times per week on average.

4.4. Study limitations

The first limitation for the present study was that conditions in the laboratory study were not counterbalanced and did not contain a control/baseline measurement. The first test moment of each day was used as 'baseline' and differences did occur between the two experimental days. In addition, the baseline measurement in the field study was one week with only one day (3 assessment moments) compared to two weeks of the experimental conditions (9 assessment moments per week), which sometimes caused larger differences in standard deviations.

A second limitation is that the sample size was determined pragmatically rather than based on a-priori power analyses. Therefore, the results of both studies need to be considered as pilot outcomes. In addition, many of the results reported in this study disappeared after statistically controlling for making multiple comparisons. It is yet unclear whether a larger sample size would have yielded more robust effects.

A third limitation was (the difference in) study duration of the two studies. A six-week field study with circa nine assessment moments per week was a heavy burden in addition to the regular work. The response rate in the planned second baseline week at the end of the study was too low for inclusion in the analysis. A two-day laboratory experiment was too short for a full-fledged data set. With only one or two assessments per week, the anticipation of absence due to work tasks can be better facilitated. As the highest response rates were found during the morning and lowest response rates during lunchtime, an assessment moment in the morning, around 10:00, may be the most convenient for office employees, followed by a moment in the afternoon. In a laboratory study, a more prolonged study duration with multiple days per intervention is required to allow counterbalancing the conditions. On the other hand, the number of trials on an experimental day may have been too few. The effects of light exposure may be limited during the workday, but potentially the effect of the high light exposure in the afternoon comes later in the evening when people are already at home. Future research should include a longer effect period.

A fourth limitation relates to the selected performance tasks. Even though the Mackworth Vigilance Task (VT) and a higher-order executive functioning task like the Mental Rotation exercise are used frequently in experimental studies, the suitability related to the group of participants needs to be more critically studied. This applies specifically to tests that permit the use of different (neural) strategies and/or may be affected by prior experience (i.e., task training, difference in sleep/wake pattern which can also be affected by the light exposure during the day).

Finally, although hard to control in a field study, is the contribution and the potentially confounding impact of daylight. The applied light pattern in the laboratory study was able to replicate the intended pattern very well, and the influence of daylight on the light exposure of the participants is significantly lower compared with the field study. The fact that laboratory studies find, for example, effects on subjective sleepiness (alertness) and field studies do not, may be related to the significantly higher rate of variations in the lighting as a result of the allowed daylight. In the current study, the light levels were measured as a sum of daylight and electric lighting, and in follow-up studies, the influence of either of the two sources need to be studied separately.

5. Conclusions and practical implications

The choice of lighting levels was driven by practical implications (including needs for energy conservation and comfort and system possibilities); therefore, lighting levels were less extreme. The aim of this study was to test whether these relatively small variations in light level (compared to the often more extreme variations implemented in lighting research) over the day may affect human well-being and performance. The same light pattern was tested in a controlled laboratory experiment, as well as in a real-life field application in an office. Overall, the study yielded inconclusive differences between the different light patterns. Some counterintuitive results were found during the field study for satisfaction scores, pointing at higher satisfaction with constant light levels than with the two dynamic light patterns. Most of the effects vanished after controlling for the number of comparisons made, but before correction, the outcomes were often inconsistent between the laboratory and field study. Whether this inconsistency is due to the low sample size or the difference in test environment certainly deserves further research. A real office environment typically does not provide a quiet, controlled, and distraction-reduced environment, whereas a laboratory situation often does. Results of this pilot study may suggest that a direct translation or implementation of outcomes from (controlled) laboratory office experiments into a real office environment cannot be made directly. Field studies may prove essential before implementing laboratory findings in the real world.

Funding

This work was supported by the Bertil & Britt Svenssons Stiftelse för Belysningsteknik [2017-11-09] and the Jönköping University-School of Engineering - Internal Strategic Funds [2018-01-30].

CRediT authorship contribution statement

M.B.C. Aries: Conceptualization, Methodology, Software, Validation, Investigation, Resources, Data curation, Writing - original draft, Writing - review & editing, Visualization, Supervision, Project administration, Funding acquisition. **F. Beute:** Methodology, Formal analysis, Data curation, Writing - original draft, Writing - review & editing, Visualization. **G. Fischl:** Conceptualization, Methodology, Investigation, Resources, Writing - original draft, Funding acquisition.

Declaration of competing interest

The authors declare no conflict of interest.

Acknowledgements

The authors would like to thank the participants in both studies, the board and employees of Fagerhult Belysning AB, Sweden as well as the staff and students of Jönköping University, Lighting Design for their input, feedback and efforts for facilitating this project. Also, we would like to acknowledge the valuable comments by the reviewers of the journal and Professor Christine Räisänen for proofreading large parts of the manuscript.

Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.jenvp.2020.101409.

Appendices

Light exposure 'High' and 'Low' at eye level per photoreceptor type

For the settings 'High' and 'Low', the five corresponding human retinal photoreceptor weighted "alpha-opic" irradiance values in mW/m^2 are given in Table 11 (Lucas et al., 2014; Commission Internationale de L'eclairage, 2018).

Table 11
The α-opic irradiance [mW.m-2] values for the High and Low conditions

Setting	Direct – Indirect [%]	E_{hor} [lux]	E_{vert} [lux]	S-cone-opic irradiance [mW/m^2]	M-cone-opic irradiance [mW/m^2]	L-cone-opic irradiance [mW/m^2]	Rhodopic irradiance [mW/m^2]	Melanopic irradiance [mW/m^2]
High	100–100	870	690	379.25	963.81	1217.90	779.17	662.03
Low	35–25	238	185	106.12	272.03	342.40	222.43	190.08

Continuous illuminance measurements

Light (level) patterns in the laboratory study - During the two days of the laboratory test, the horizontal illuminance levels were logged at three places in the room. Fig. 8 shows the logged horizontal illuminance levels at the windowsill as well as on the desks in the middle and back of the room for the two light patterns/study days. The daylight levels near the window ranged between 200 and 1600 lux. The desk levels clearly show the applied light pattern with maximum levels around 850 lux and a minimum of around 250 lux. The baseline level was between 500 and 550 lux. A rough estimation of the average daylight contribution in Fig. 10 (left) shows that the daylight contribution to the overall horizontal illuminance levels was between 0 and 14%.

Light (level) patterns in the field study - During the entire duration of the field test, the horizontal illuminance levels were logged at three places in both office rooms. Fig. 9 shows the logged horizontal illuminance levels for the two intervention periods (week 2–3 and week 4–5), including two weekends. The desk levels show the applied light patterns with maximum levels around 700 lux and minimum around 250 lux. The baseline level was approximately 500 lux. The light patterns at the desk show that the daylight contribution was noticeable, especially during lunchtime but often not extreme (between 0 and 32% on average, see Fig. 10).

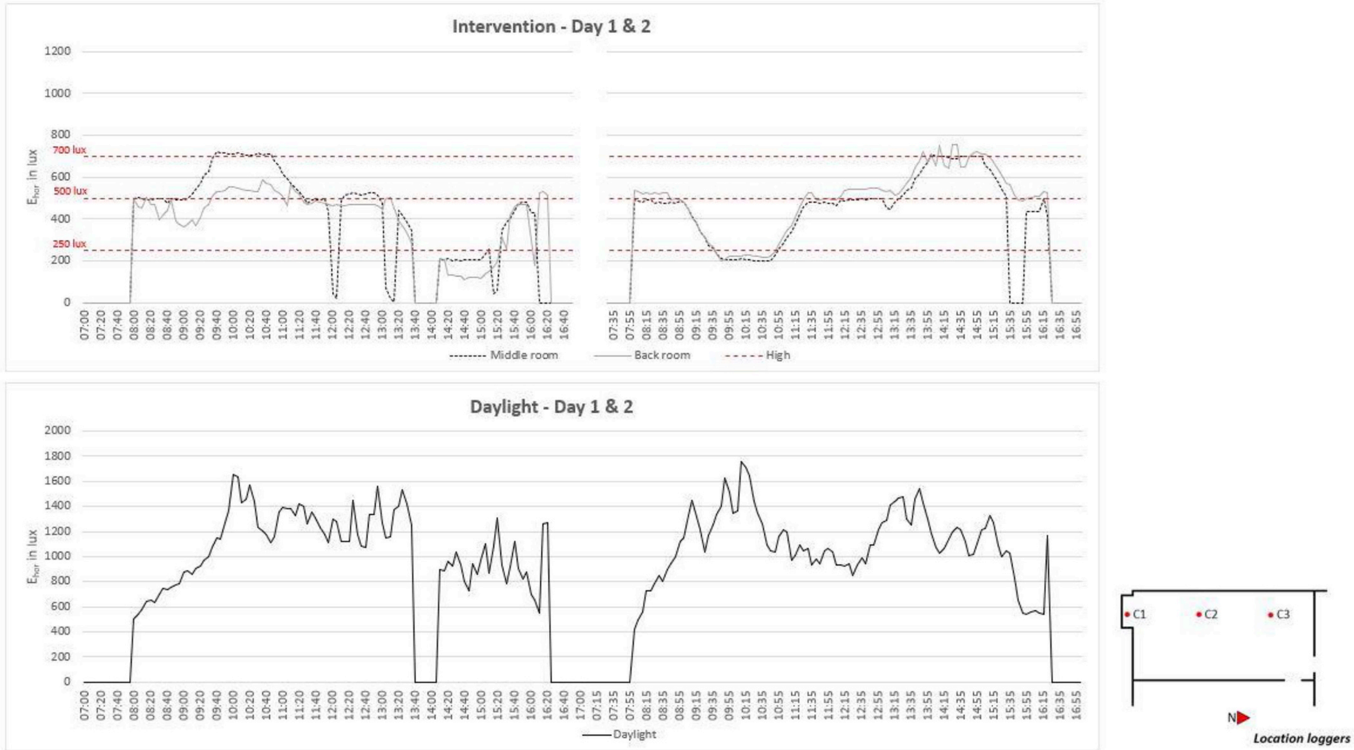


Fig. 8. The logged horizontal illuminance levels for three loggers (daylight, middle, and back of the room) for the two intervention days in the laboratory study. The red dotted lines indicate High, Low and baseline levels.

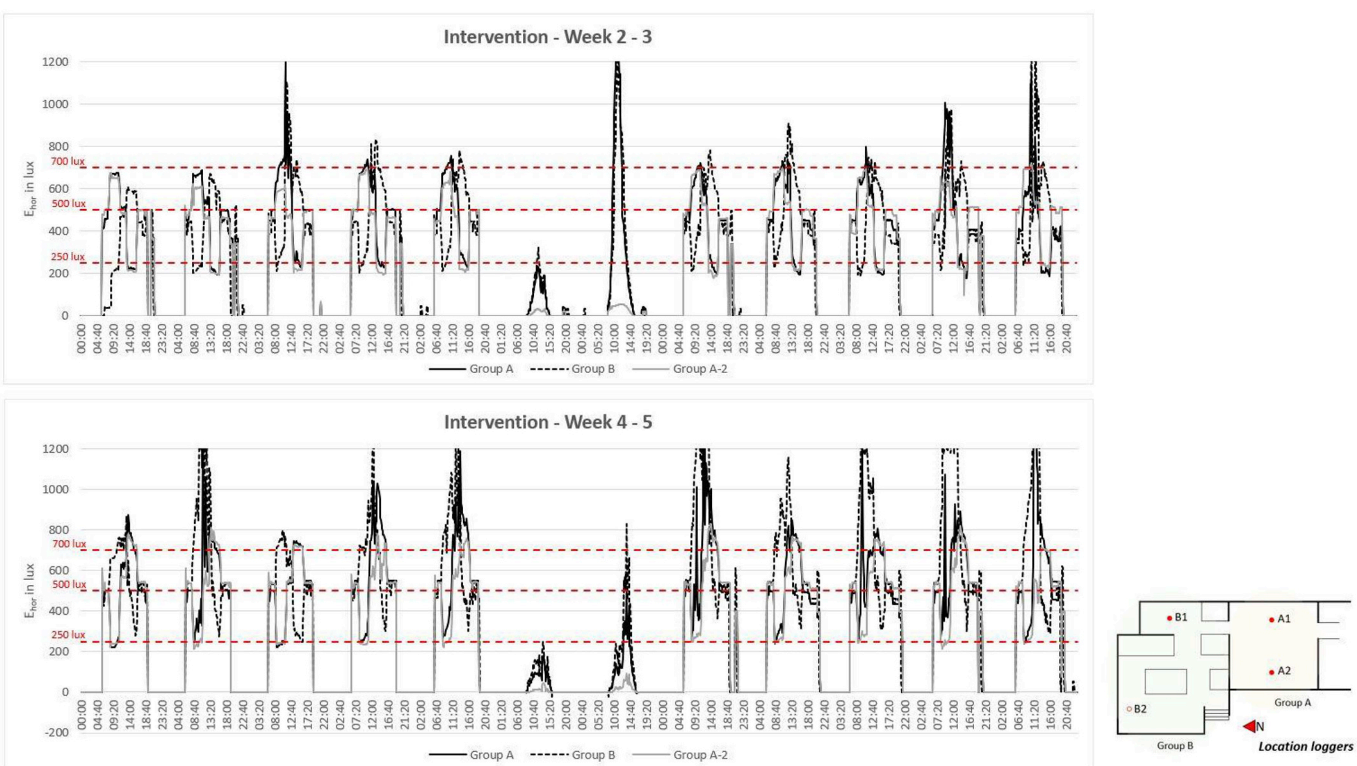


Fig. 9. The logged horizontal illuminance levels on the desk for three loggers (East and West orientation) for the four intervention weeks and two weekends in the field study. The red dotted lines indicate High, Low and baseline levels.

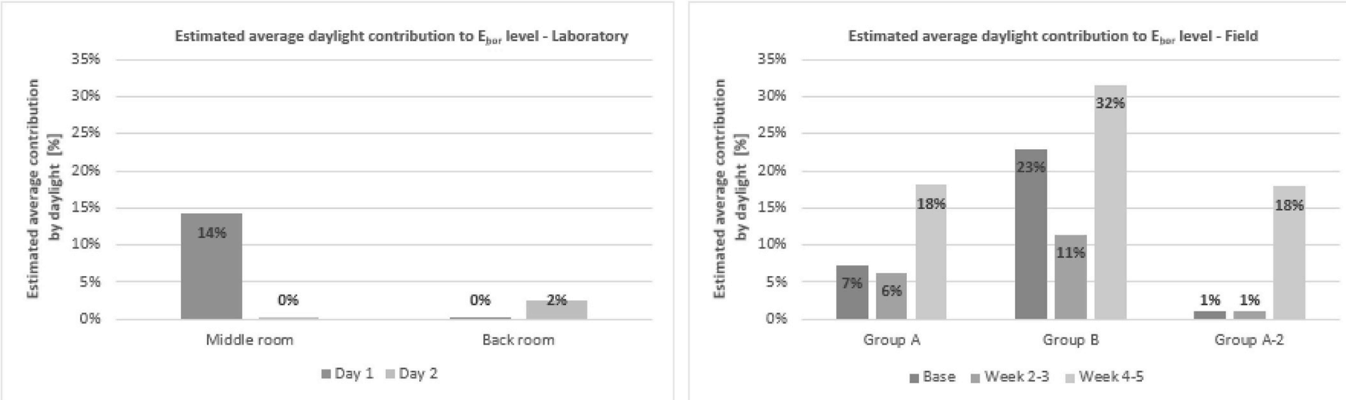


Fig. 10. The rough estimation of the average daylight contribution to the overall horizontal illuminance levels during the laboratory (left) and field study (right).

References

Aarts, M. P. J., Aries, M. B. C., Straathof, J., & Hoof, J. V. (2014). Dynamic lighting systems in psychogeriatric care facilities in The Netherlands: A quantitative and qualitative analysis of stakeholders responses' and applied technology. *Indoor and Built Environment,* 1–15 0.

Åkerstedt, T., & Gillberg, M. (1990). Subjective and objective sleepiness in the active individual. *International Journal of Neuroscience, 52*, 29–37.

Aries, M. B. C., Aarts, M. P. J., & Van Hoof, J. (2015). Daylight and health: A review of the evidence and consequences for the built environment. *Lighting Research and Technology, 47*, 6–27.

Basner, M., Mollicone, D., & Dinges, D. F. (2011). Validity and sensitivity of a brief psychomotor vigilance test (PVT-B) to total and partial sleep deprivation. *Acta Astronautica, 69*, 949–959.

Beute, F., & de Kort, Y. A. W. (2014). Salutogenic effects of the environment: Review of health protective effects of nature and daylight. *Applied Psychology: Health and Well-Being, 6*, 67–95.

Boyce, P. R. (2014). *Human factors in lighting.* Taylor & Francis.

Bradley, M. M., & Lang, P. J. (1994). Measuring emotion: The self-assessment Manikin and the semantic differential. *Journal of Behavior Therapy and Experimental Psychiatry, 25*, 49–59.

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

Butler, T., Imperato-Mcginley, J., Pan, H., Voyer, D., Cordero, J., Zhu, Y. S., et al. (2006). Sex differences in mental rotation: Top-down versus bottom-up processing. *NeuroImage, 32*, 445–456.

Cajochen, C., Freyburger, M., Basishvili, T., Garbazza, C., Rudzik, F., Renz, C., et al. (2019). Effect of daylight LED on visual comfort, melatonin, mood, waking performance and sleep. *Lighting Research and Technology*.

Chang, A. M., Scheer, F. A. J. L., & Czeisler, C. A. (2011). The human circadian system adapts to prior photic history. *Journal of Physiology, 589*.

Chellappa, S. L., Gordijn, M. C. M., & Cajochen, C. (2011). Can light make us bright? Effects of light on cognition and sleep. In P. A. V. Hans (Vol. Ed.), *Progress in brain research, human sleep and cognition Part II - clinical and applied research: Vol. 190*Elsevier.

Choi, K., Shin, C., Kim, T., Chung, H. J., & Suk, H. J. (2019). Awakening effects of blue-enriched morning light exposure on university students' physiological and subjective responses. *Scientific Reports, 9*.

Commission Internationale de L'eclairage (2018). *CIE system for metrology of optical radiation for ipRGC-influenced responses to light.* Vienna, Austria: CIE Central Bureau.

Correa, Á., Barba, A., & Padilla, F. (2016). Light effects on behavioural performance depend on the individual state of vigilance. *PLoS One, 11*, e0164945.

Day, J., Theodorson, J., & Van Den Wymelenberg, K. (2012). Understanding controls, behaviors and satisfaction in the daylit perimeter office: A daylight design case study. *Journal of Interior Design, 37*, 17–34.

de Kort, Y. A. W., & Smolders, K. C. H. J. (2010). Effects of dynamic lighting on office workers: First results of a field study with monthly alternating settings. *Lighting Research and Technology, 42*, 345–360.

Debarnot, U., Piolino, P., Baron, J.-C., & Guillot, A. (2013). Mental rotation: Effects of gender, training and sleep consolidation. *PLoS One, 8* e60296-e60296.

Eklund, N. H., & Boyce, P. R. (1996). The development of a reliable, valid, and simple office lighting survey. *Journal of the Illuminating Engineering Society, 25*, 25–40.

Figueiro, M. G., & Rea, M. S. (2012). Short-wavelength light enhances cortisol awakening response in sleep-restricted adolescents. *The Internet Journal of Endocrinology,* 301935 2012.

Ganis, G., & Kievit, R. A. (2015). A New Set of Three-Dimensional Shapes for Investigating Mental Rotation Processes: Validation Data and Stimulus Set. *Journal of Open Psychology Data, 3*(1), P.e3. https://doi.org/10.5334/jopd.ai.

Hanifin, J. P., Lockley, S. W., Cecil, K., West, K., Jablonski, M., Warfield, B., et al. (2019). Randomized trial of polychromatic blue-enriched light for circadian phase shifting, melatonin suppression, and alerting responses. *Physiology & Behavior, 198*, 57–66.

Hankins, M. W., & Lucas, R. J. (2002). The primary visual pathway in humans is regulated according to long-term light exposure through the action of a nonclassical photopigment. *Current Biology, 12*, 191–198.

Heil, M., & Jansen-Osmann, P. (2008). Sex differences in mental rotation with polygons of different complexity: Do men utilize holistic processes whereas women prefer piecemeal ones? *Quarterly Journal of Experimental Psychology, 61*, 683–689.

Huiberts, L. M. (2018). Phd Thesis*Daytime light exposure: Optimizing effects on cognitive performance and subjective wellbeingVol. 1* (Research TU/e/Graduation TU/e), Technische Universiteit Eindhoven.

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

Huiberts, L. M., Smolders, K. C. H. J., & de Kort, Y. A. W. (2016). Non-image forming effects of illuminance level: Exploring parallel effects on physiological arousal and task performance. *Physiology & Behavior, 164*, 129–139.

Iskra-Golec, I. M., & Smith, L. (2008). Daytime intermittent bright light effects on processing of laterally exposed stimuli, mood, and light perception. *Chronobiology International, 25*, 471–479.

Iskra-Golec, I. M., Wazna, A., & Smith, L. (2012). Effects of blue-enriched light on the daily course of mood, sleepiness and light perception: A field experiment. *Lighting Research and Technology, 44*, 506–513.

Kaida, K., Takahashi, M., Haratani, T., Otsuka, Y., Fukasawa, K., & Nakata, A. (2006). Indoor exposure to natural bright light prevents afternoon sleepiness. *Sleep, 29*, 462–469.

Keis, O., Helbig, H., Streb, J., & Hille, K. (2014). Influence of blue-enriched classroom lighting on students' cognitive performance. *Trends in Neuroscience and Education, 3*, 86–92.

Khademagha, P., Aries, M. B. C., Rosemann, A. L. P., & Loenen, E. J. V. (2016a). Why directionality is an important light factor for human health to consider in lighting design? *International Journal of Sustainable Lighting, 18*, 3–8.

Khademagha, P., Aries, M. B. C., Rosemann, A. L. P., & Van Loenen, E. J. (2016b). Implementing non-image-forming effects of light in the built environment: A review on what we need. *Building and Environment, 108*, 263–272.

Lang, P. J. (1980). Behavioral treatment and bio-behavioral assessment: Computer applications. In J. B. Sidowski, J. H. Johnson, & T. A. Williams (Eds.). *Technology in mental health care delivery systems*. Norwood NJ: Ablex Publishing.

Lewy, A. J., Bauer, V. K., Cutler, N. L., Sack, R. L., Ahmed, S., Thomas, K. H., et al. (1998). Morning vs evening light treatment of patients with winter depression. *Archives of General Psychiatry, 55*, 890–896.

Lockley, S. W. (2009). Circadian rhythms: Influence of light in humans. In L. R. Squire (Ed.). *Encyclopedia of neuroscience*(5 ed.). Oxford, UK: Academic Press.

Lockley, S. W., Evans, E. E., Scheer, F. A., Brainard, G. C., Czeisler, C. A., & Aeschbach, D. (2006). Short-wavelength sensitivity for the direct effects of light on alertness, vigilance, and the waking electroencephalogram in humans. *Sleep, 29*, 161–168.

Loh, S., Lamond, N., Dorrian, J., Roach, G., & Dawson, D. (2004). The validity of psychomotor vigilance tasks of less than 10-minute duration. *Behavior Research Methods Instruments & Computers, 36*, 339–346.

Lok, R., Woelders, T., Gordijn, M. C. M., Hut, R. A., & Beersma, D. G. M. (2018). White light during daytime does not improve alertness in well-rested individuals. *Journal of Biological Rhythms, 33*, 637–648.

Lucas, R. J. (2013). Mammalian inner retinal photoreception. *Current Biology : CB, 23*, R125–R133.

Lucas, R. J., Peirson, S. N., Berson, D. M., Brown, T. M., Cooper, H. M., Czeisler, C. A., et al. (2014). Measuring and using light in the melanopsin age. *Trends in Neurosciences, 37*, 1–9.

Mackworth, N. H. (1948). The breakdown of vigilance during prolonged visual search. *Quarterly Journal of Experimental Psychology, 1*, 6–21.

Mccoll, S. L., & Veitch, J. A. (2001). Full-spectrum fluorescent lighting: A review of its effects on physiology and health. *Psychological Medicine, 31*, 949–964.

Munch, M., Nowozin, C., Regente, J., Bes, F., de Zeeuw, J., Hadel, S., et al. (2016). Blue-enriched morning light as a countermeasure to light at the wrong time: Effects on cognition, sleepiness, sleep, and circadian phase. *Neuropsychobiology, 74*, 207–218.

Pachito, D. V., Eckeli, A. L., Desouky, A. S., Corbett, M. A., Partonen, T., Rajaratnam, S. M. W., et al. (2018). Workplace lighting for improving alertness and mood in daytime workers. *Cochrane Database of Systematic Reviews*.

Park, J. Y., Min, B. K., Jung, Y. C., Pak, H., Jeong, Y. H., & Kim, E. (2013). Illumination influences working memory: An EEG study. *Neuroscience, 247*, 386–394.

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

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

Rautkylä, E., Puolakka, M., Tetri, E., & Halonen, L. (2010). Effects of correlated colour temperature and timing of light exposure on daytime alertness in lecture environments. *Journal of Light and Visual Environment, 34*, 59–68.

Rea, M. S., Figueiro, M. G., & Bullough, J. D. (2002). Circadian photobiology: An emerging framework for lighting practice and research. *Lighting Research and Technology, 34*, 177–187.

Roenneberg, T., Kumar, C. J., & Merrow, M. (2007). The human circadian clock entrains to sun time. *Current Biology, 17*, R44–R45.

Rüger, M., Gordijn, M. C., Beersma, D. G., Vries, B. D., & Daan, S. (2006). Time-of-day-dependent effects of bright light exposure on human psychophysiology: Comparison of daytime and nighttime exposure. *American Journal of Physiology - Regulatory, Integrative and Comparative Physiology, 290*, R1413–R1420.

Santhi, N., Groeger, J. A., Archer, S. N., Gimenez, M., Schlangen, L. J., & Dijk, D. J. (2013). Morning sleep inertia in alertness and performance: Effect of cognitive domain and white light conditions. *PLoS One, 8*, e79688.

Shepard, S., & Metzler, D. (1988). Mental rotation: Effects of dimensionality of objects and type of task. *Journal of Experimental Psychology: Human Perception and Performance, 14*, 3–11.

Sithravel, R., Ibrahim, R., Lye, M. S., Perimal, E. K., Ibrahim, N., & Dahlan, N. D. (2018). Morning boost on individuals' psychophysiological wellbeing indicators with supportive, dynamic lighting in windowless open-plan workplace in Malaysia. *PLoS One, 13*, e0207488.

Smith, K. A., Schoen, M. W., & Czeisler, C. A. (2004). Adaptation of human pineal melatonin suppression by recent photic history. *The Journal of Cinical Endocrinology and Metabolism, 89*, 3610–3614.

Smolders, K. C. H. J., & de Kort, Y. A. W. (2014). Bright light and mental fatigue: Effects on alertness, vitality, performance and physiological arousal. *Journal of Environmental Psychology, 39*, 77–91.

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

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

Smolders, K. C. H. J., Peeters, S. T., Vogels, I. M. I. C., & de Kort, Y. A. W. (2018). Investigation of dose-response relationships for effects of white light exposure on correlates of alertness and executive control during regular daytime working hours. *Journal of Biological Rhythms, 33*, 649–661.

Spitschan, M., Stefani, O., Blattner, P., Gronfier, C., Lockley, S. W., & Lucas, R. J. (2019). How to report light exposure in human chronobiology and sleep research experiments. *Clocks & Sleep, 1*, 280–289.

Stoet, G. (2010). PsyToolkit - A software package for programming psychological experiments using Linux. Behavior Research Methods. *Behavior Research Methods, 42*(4), 1096–1104.

Stoet, G. (2017). PsyToolkit: A novel web-based method for running online questionnaires and reaction-time experiments. *Teaching of Psychology, 44*, 24–31.

Tanaka, K., Takahashi, M., Tanaka, M., Takanao, T., Nishinoue, N., Kaku, A., et al. (2011). Brief morning exposure to bright light improves subjective symptoms and performance in nurses with rapidly rotating shifts. *Journal of Occupational Health, 53*, 258–266.

Thapan, K., Arendt, J., & Skene, D. J. (2001). An action spectrum for melatonin suppression: Evidence for a novel non-rod, non-cone photoreceptor system in humans. *Journal of Physiology, 535*.

Van Bommel, W. (2006). Dynamic lighting at work - both in level and colour. *2nd CIE expert symposium on 'lighting and health'. Ottawa, Canada*.

Van Den Beld, G. J. (2004). *Right light for productivity, health and well-being at the workplace.* Berlin: Licht und Gesundheit.

Vandewalle, G., Gais, S., Schabus, M., Balteau, E., Carrier, J., Darsaud, A., et al. (2007). Wavelength-dependent modulation of brain responses to a working memory task by daytime light exposure. *Cerebral Cortex, 17*, 2788–2795.

Vandewalle, G., Maquet, P., & Dijk, D. J. (2009). Light as a modulator of cognitive brain function. *Trends in Cognitive Sciences, 13*, 429–438.

Viola, A. U., James, L. M., Schlangen, L. J., & Dijk, D.-J. (2008). Blue-enriched white light in the workplace improves self-reported alertness, performance and sleep quality. *Scandinavian Journal of Work, Environment & Health,* 297–306.

Wright, K. P., Jr., Hull, J. T., Hughes, R. J., Ronda, J. M., & Czeisler, C. A. (2006). Sleep and wakefulness out of phase with internal biological time impairs learning in humans. *Journal of Cognitive Neuroscience, 18*, 508–521.

Yang, M. Q., Chen, Q. W., Zhu, Y. Y., Zhou, Q., Geng, Y. G., Lu, C. C., et al. (2019). The effects of intermittent light during the evening on sleepiness, sleep electroencephalographic spectral power and performance the next morning. *Lighting Research and Technology* 1477153519828414.