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Contrasting dynamic light scenarios in an operational office: Effects on visual experience, alertness, cognitive performance, and sleep

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ABSTRACT

In this field study, we tested the effects of dynamic light scenarios and personal illuminance on visual experience, sleepiness, cognitive performance and sleep in an operational office. Two dynamic light scenarios, different in timing but with equal luminous exposure, were tested against a reference scenario in a counterbalanced crossover design. Frequent assessments of visual experience, alertness, performance and sleep showed that in both dynamic light scenarios visual comfort was slightly lower compared to the constant scenario. Additionally, sleepiness was lowest in the scenario with the brighter light timed around noon, whereas task performance and actual sleep were not significantly affected. The measured personal illuminance did not predict sleepiness and performance, yet variation and timing of these illuminances did positively relate to sleep onset and duration. When studying or implementing light scenarios aiming to deliver integrative lighting, the spatial and behavioral context should be considered as well.

1. Introduction

Environmental conditions in offices greatly influence people’s health, as many employees spend almost one third of their time in an office environment [1]. The light in the office, including both daylight and electric light, is one of the working conditions that affects office workers in various meaningful ways. The light must not disturb occupants, such that they feel visually satisfied and can focus on their work. In addition, light can support employees’ performance and alertness [2], but also indirectly promote alertness via improved sleep [3,4]. Whereas control over daylight is limited, electric light can be adjusted to achieve what is called ‘integrative lighting’. Integrative lighting refers to lighting that is designed to support human psychological and physiological functioning based on empirical evidence on the effects of light via both visual and non-visual pathways [5]. Although the exact timing, duration, intensity and spectral characteristics of the required light likely depend on the context, general guidelines for practical applications have been written recently (e.g., Refs. [6–8]).

The many different responses to light (i.e., visual, acute and circadian) have been studied extensively, but still numerous questions remain in every subdomain (for reviews see: e.g., Refs. [2,7,9–13]). While the neural processes underlying visual performance have been quite accurately determined [9], the experience of visual comfort is less well understood [14–18]. The effects of light beyond vision (circadian and acute effects) are suggested to highly depend on the activation of intrinsic photoreceptive retinal ganglion cells (ipRGC), which constitute a photoreceptor class different from classical rod and cone photoreceptors. It is quite well established that ipRGCs are of tremendous importance in light-induced resetting of the circadian clock and melatonin suppression [19], and thus affect sleep timing and quality. Additionally, ipRGC activation supposedly impinges transiently on alertness, mood, cognitive performance and a variety of physiological parameters [2,20], but the exact processes underlying these acute effects are less clear or even unknown [21–23]. Controlled laboratory studies investigating isolated visual, acute or circadian responses can provide valuable insights in understanding the relationship between light and neurobehavioral responses, yet simultaneously it is incredibly important to evaluate whether these effects also hold in real life, such as in an office environment, for which field studies are required. Furthermore, the visual, acute and circadian responses are effective simultaneously in real

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life [24], yet most studies on the effects of light in the field targeted only a selection of these responses. For instance, when studying acute or circadian effects of light in the field, often the visual experience is not evaluated at all (e.g., Refs. [25–27]). Other studies did test both acute responses and visual experiences, yet probed (a selection of) the responses at the end of the exposure period only (e.g., Ref. [28]). With repeated measurements of visual, acute, and circadian responses throughout the exposure period in an operational office environment, the relevance and robustness of these different types of effects can be identified more closely. The current study aims to investigate the effects of two different light scenarios on visual experience, alertness, cognitive performance, and sleep simultaneously — using repeated measurements during two weeks of exposure to each scenario — in an operational office environment.

Several field studies have investigated the relationship between the natural variation in luminous exposure and the experiences of individuals. Some studies reported that increased luminous exposure significantly relates to higher levels of vitality [25,29], better mood [30] and better sleep quality [25,31]. In contrast, others found no significant relation between luminous exposure and alertness [31,32], mood [29] or sleep [33]. Research has shown that increased melatonin stimulation induced via spectral changes (e.g., constant exposure to cool light of 17,000 K) can benefit building occupants’ alertness, arousal, concentration and mood compared to warm (2900 K) or neutral (4000 K) white light [34–36]. These findings denote that the effective luminous exposure is crucial in supporting daytime alertness and performance. Therefore, more light than currently recommended by the standards is potentially needed [26,37–39]. Additionally, others have shown, albeit in laboratory settings, that the timing of bright light is essential in generating the desired circadian [40,41] and acute effects [42–45].

Embracing the importance of the timing of bright light to elicit these desired effects may result in dynamic light scenarios, which has been defined as electric lighting that is variable in its intensity and/or spectral power distribution over time [46]. Studies investigating such dynamic light scenarios showed that relatively brighter and bluer light in the morning compared to the evening can induce positive circadian effects [27,37,47]. Moreover, acute alerting effects of the employed dynamic light scenario may occur at specific times of day [38,48,49]. If and when the dynamic light scenario had circadian or acute alerting effects, these were generally positive, yet the visual experience was also sometimes compromised [37,50,48,51,52] (for a review see Ref. [46]). Most of these studies employed higher luminous exposure in the dynamic scenario compared to the control scenario. This prevents attributing effects uniquely to the luminous exposure or to the timing and dynamics of light during the day. Two recent field studies explicitly maintained the luminous exposure of the electric lighting, while varying its timing (i.e. brighter in the morning vs. afternoon: [51,53]). Both reported a mix of positive, null and negative effects, and emphasized the challenges related to conducting field studies due to the lack of experimental control. Among other things, office workers’ personal illuminance varies substantially throughout the day, even under constant electric light settings. These variations may be attributed to various factors such as façade design and daylight variations as a result of time of day, season and building location [54,55]. Additionally, considerable variance occurs between and within building occupants, for instance due to the exact location and orientation of their workstation and their spatial behavior inside and outside the building [56] (for simulation based analyses: [57,58]).

Although testing light scenarios in the field is indeed complicated, field studies allow for prolonged monitoring and have a high ecological validity which is essential for the validation of laboratory findings in operational office environments. The current longitudinal study contrasted two dynamic electric light scenarios similar in luminous exposure, but different in their timing of bright light. The dynamic scenarios were tested against each other and against a constant base level light condition with a lower luminous exposure. One dynamic scenario imitated the general temporal pattern of daylight, as daylight is often suggested to be beneficial for human functioning and well-being [59], although studies investigating such scenarios are actually quite scarce [60,61,62]. In this scenario, the light setting gradually increased just before noon to brighter light and after 3.5 hr of exposure the setting decreased to base level light. In the second scenario, the brighter light was instead timed at the beginning and end of the workday rather than around noon, resulting in the same luminous exposure. This scenario was inspired by the skeleton photoperiods used in chronobiological studies, in which short periods of light mark the beginning and end of the diurnal phase (e.g., Ref. [63]). Morning light exposure can induce phase advances [64], which may aid entrainment of the biological clock to the social clock [65] and reduce social jetlag. Additionally, to diminish unintended phase delays by evening light exposure [64], the sensitivity for evening light was reduced by providing brighter light at the end of the workday [66,67]. To maximize the effect from the lighting manipulation at the eye and in the visual field, the light scenarios were implemented using a combination of ceiling luminaires and customized desk luminaires that provided light from the front in the vertical plane. Furthermore, personal light sensors were used to measure the personal illuminance as prior research has shown that employed light scenarios are not always reflected in person-bound light measurements [56]. Additionally, highly frequent measurements of the participants’ experiences and behavior were taken to allow studying of the acute effects of the bright light periods and to be insensitive to any retrospective biases that post-hoc measurements might introduce [52,50].

The study investigated to what extent dynamic light scenarios and personal illuminance affect office workers’ visual experience, alertness, cognitive performance and sleep. It was hypothesized that in the weeks with a higher luminous exposure, participants would sleep better, and thus be more alert and perform better than in the static light condition. Furthermore, by comparing the dynamic scenarios we examined the extent to which the timing of exposure to brighter light moderates these light-induced responses. We expected that participants’ sleep, alertness and performance would be best in the weeks during which the bright light provided a skeleton around the diurnal phase (i.e., timed at the beginning and end of the workday). Additionally, we examined the relationship between measured personal illuminance and visual experience, alertness, performance and sleep. We hypothesized that participants would be feel more vital and less sleepy when exposed to a higher light levels during the prior 30 min.

2. Method

2.1. Design

Two experimental dynamic scenarios (Noon and Skeleton; Fig. 1) were tested against each other and against a static condition with base-level light among a group of office workers using a counterbalanced cross-over design. The control scenario had a lower luminous exposure compared to both dynamic scenarios, whereas the Noon and Skeleton...
scenarios had a similar average luminous exposure across the day, but differed in timing of the bright light exposure. The Noon scenario offered a brighter light setting around noon whereas the Skeleton scenario offered brighter light settings at the start and end of the workday. Participants repeatedly completed experience sampling questionnaires resulting in high frequency, in-the-moment measurements of subjective visual experience and sleepiness. Additionally, cognitive performance was targeted using a performance task that was administered twice a day, and sleep was assessed using actigraphy measurements. This field study consisted of six sampling weeks in total, in which each scenario lasted two weeks. The order of the scenarios was counterbalanced between three groups of participants. The study was preregistered at the Open Science Framework (osf.io/mvgf7) and approved by the Institutional Ethical Review Board.

The study was performed between the 27th of January and the 13th of March 2020. Due to technical failures, the data of the first week of the study was not used. Furthermore, the governmental measures to control the outbreak of the COVID-19 pandemic led to a drastic drop in responses for the last week of the study.

2.2. Participants

Thirty participants (16 female, 12 male, 2 no answer) were recruited via their group managers based on their group’s location in one office building. With their managers’ permission, information sessions were organized for the employees after which potential participants had time to decide upon their participation. Table 1 shows the descriptive information of the participants that were included. Participation was voluntary and participants gave their written informed consent before the start of the data collection. During the data collection, participants could follow their regular routines (i.e., work consisting of computer-based tasks and live meetings), but were regularly prompted with questionnaires and tasks. Participants were compensated with € 50, if they responded to more than 80% of the experience sampling questionnaires, else they were paid proportionally.

2.3. Setting

This study was conducted in open office spaces in a recently renovated university building at the Eindhoven University of Technology campus. All participants received an extra desk luminaire that was positioned behind their computer screen. This extra desk luminaire was custom-made for this study, using dimmable and CCT adjustable LED panels of 46.5 W (Hue Aurelle Rectangular Ceiling Light, Signify, Eindhoven) and measured 120 by 30 cm (see Fig. 2A–B). The building is also standard fitted with suspended LED-based ceiling luminaires (TrueLine Pendel, Signify, Eindhoven). The windows in the building span the entire façade. The distance of the desks to the east-oriented or west-oriented windows varied from 1.20 to 4.80 m. The majority (25 out of 30) of the participants’ desks were placed perpendicular to the closest windows, with their main viewing directions parallel to the windows. Five participants had their desk parallel to the windows; three of them sat with their back towards the window, and the other two faced the window. Eleven participants sat closest to the east-oriented windows and nineteen to the west-oriented windows. In Fig. 2C–E, the floorplans of a few of the office areas are shown. The daylight in the office areas was measured on a 10-min interval near the east and west oriented windows. For each observation of each participant, we calculated the mean log-transformed illuminance from measurements taken vertically at a height of 1.30 m of the closest oriented window in the 30 min before the observation (Daylight illuminance at the window) and included these measurements in the analyses to account for variations in daylight exposure. The furniture and decoration throughout the building was identical, apart from yellow/grey accents (dividers and carpeting) in one part of the building and blue accents in the other. The indoor climate was maintained as constant as possible and monitored throughout the study period with a sampling rate of 10 min (mean air speed = 0.98 ± 0.06 m/s, relative air humidity = 32.3 ± 5.4%, air temperature = 22.0 ± 0.7°C and globe temperature = 22.0 ± 0.9°C).

2.4. Light manipulation

In the control scenario, illuminance (combination of daylight and electric light, ceiling and desk mounted combined) were roughly 500–600 lux measured horizontally on the desks and approximately 300 lux measured vertically at the eye. In the Noon scenario, this same light level was initially employed as the base setting, but light intensities of the desk and ceiling luminaires were increased (approximately +300 lux horizontally and +175 lux vertically) for 3.5 hr between 11:15 and 14:45. In the Skeleton scenario, this brighter light was used in the morning (before 10:15) and in the late afternoon (after 15:45; together amounting to about 3.5 hr when spending 9 hr in the office building), with the base setting in between these phases. The light settings were designed to clearly provide different light settings, with the brighter setting being as bright as possible without inducing glare. The light gradually transitioned from the base setting to the brighter setting, or vice versa, in 60 min. A schematic overview of the scenarios in which the timing of the transitions in the light scenarios is indicated can be found in Fig. 1. Table 2 provides a quantification of the light settings in a reference office space with and without daylight, in terms of aopic Equivalent Daylight Illuminance (EDI; measured vertically at the eye and horizontally on the desk).

2.5. Measurements

2.5.1. Questionnaires

Participants completed four different types of questionnaires. After enrollment, participants completed an intake questionnaire in which descriptive information was gathered. During the measurement period, participants received a daily morning questionnaire (the sleep diary), eight questionnaires throughout the day (experience sampling questionnaires) and a daily evening questionnaire (the day evaluation).

2.5.1.1. Intake questionnaire. In the intake questionnaire which participants completed before they started the experiment, information on participants’ age, gender, weight, height, medication use and travel behavior was gathered. Furthermore, participants completed the Munich Chronotype Questionnaire [65], the subjective sleep quality subscale from the Pittsburgh Sleep Quality Index [68], and five items on general health selected from the RAND-36 [69]. Last, participants judged their sensitivity to bright light on a five-point scale ranging from None (1) to A lot (5). These parameters were used to describe the sample and considered as control parameters in the analyses.

2.5.1.2. Sleep diary. Participants completed the Core Consensus Sleep Diary [70]; comments section excluded) in the morning of every measurement day on their smartphone. From these items, sleep duration,
midsleep and sleep quality were calculated, which were also considered as control parameters in the analyses.

### 2.5.1.3. Experience sampling questionnaire

Participants received eight experience sampling questionnaires (ESQ) on their smartphones per day, in which they reported their experiences concerning their environment, current feelings and recent behavior. Four items were used to assess visual experience, as in Refs. [46,52]. Participants judged whether the lighting was 'Acceptable' or 'Unacceptable' on a binary scale (AcceptanceV). Participants’ experience of the intensity (SensationVI) and color of the light (SensationVC) were assessed separately, both on seven-point scales: ranging from Very low (−3) to Very high (+3) and

![Fig. 2. The setting and luminaires. A) Desks in the yellow/grey accented area with desks perpendicular to the east-oriented windows (monitors were removed for the photo); B) Example setting with one monitor in a blue accented area; C-E) Floorplans with the position of a selection of the participants using [x]: in blue accented area with desks parallel (C) or perpendicular (D) to the west-oriented windows and in yellow/grey accented areas with desks perpendicular to the west-oriented windows (E: the floorplan of the photo in A). (For interpretation of the references to color in this figure legend, the reader is referred to the Web version of this article.)](image)

### Table 2

<table>
<thead>
<tr>
<th>Light setting</th>
<th>With Daylight</th>
<th></th>
<th>Without Daylight</th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Brighter setting</td>
<td>Base setting</td>
<td>Brighter setting</td>
<td>Base setting</td>
</tr>
<tr>
<td></td>
<td>Vertical</td>
<td>Horizontal</td>
<td>Vertical</td>
<td>Horizontal</td>
</tr>
<tr>
<td>Illuminance (lux)</td>
<td>502</td>
<td>919</td>
<td>333</td>
<td>595</td>
</tr>
<tr>
<td>Irradiance in 380–780 nm (W/m²)</td>
<td>1.68</td>
<td>3.10</td>
<td>1.16</td>
<td>2.11</td>
</tr>
<tr>
<td>CCT (K)</td>
<td>4689</td>
<td>4706</td>
<td>5105</td>
<td>5175</td>
</tr>
<tr>
<td>S-cone-opic EDI (E_{v,sc} in lux)</td>
<td>360</td>
<td>661</td>
<td>257</td>
<td>462</td>
</tr>
<tr>
<td>M-cone-opic EDI (E_{v,mc} in lux)</td>
<td>461</td>
<td>847</td>
<td>313</td>
<td>564</td>
</tr>
<tr>
<td>L-cone-opic EDI (E_{v,lc} in lux)</td>
<td>500</td>
<td>916</td>
<td>331</td>
<td>593</td>
</tr>
<tr>
<td>Rhodopic EDI (E_{v,r} in lux)</td>
<td>394</td>
<td>729</td>
<td>279</td>
<td>509</td>
</tr>
<tr>
<td>Melanopic EDI (E_{v,mel} in lux)</td>
<td>367</td>
<td>684</td>
<td>264</td>
<td>487</td>
</tr>
</tbody>
</table>

Note: The measurements were conducted both in vertical (at the eye level) and horizontal orientation (on the desk level) in a reference office highly similar to the offices that were included in the study (in one of the blue-accented areas, with a monitor on the desk, both perpendicular to the window, at 1.4 m from the west-oriented window). The measurements with daylight were done on a cloudy day at the January 24, 2020, around 12:30 in Eindhoven. The normalized spectral power distribution of the light settings without daylight can be found in Supplementary Materials S3.
from Very cold (−3) to Very warm (+3) respectively. Furthermore, participants assessed comfort regarding the visual environment (Comfort Vision) using the following response options: Very uncomfortable (−2), Uncomfortable (−1), Just uncomfortable (0), Just comfortable (1), Comfortable (2) and Very comfortable (3). Moreover, three items on thermal experience were included in the ESD, as in Refs. [52,50]. The data of these three items are reported elsewhere.

The Karolinska Sleepiness Scale was used to measure momentary sleepiness, with a response scale ranging from Very alert (1) to Sleepy, difficulties to remain awake (9) [71]. Additionally, participants’ eating and drinking behavior of the last half hour before completing the day and 2:00 the day after was calculated as well as the mean timing thereof (MLIT100) according to the methods employed in Ref. [73]. The threshold of 100 lux was chosen as in nighttime dose-response curves 100 lux has been identified as the 50 % suppression point [74]. As the current study was conducted during daytime, we also considered higher thresholds. Analyses with a threshold of 200 lux are presented in Supplementary Materials S2. The number of observations exceeding the threshold of 500 lux were considered too few to run analyses with. In addition, the disparity index (DI) was calculated according to Ref. [75] to quantify the temporal variation in personal illuminance within each day while taking into account the chronological order of the values. The index assesses the variability by summing the natural logarithm of the ratio between subsequent measurements using Formula 1.

\[ DI = \frac{1}{n-1} \sum_{i=1}^{n-1} \ln \left( \frac{E_{i+1} + k}{E_i + k} \right) \]  

In this formula, \( E_i \) is the illuminance at time \( i \), \( n \) is the series length and constant \( k \) is 1, which is added to avoid zero values. This measure is independent of the mean of the series and incorporates the timing of different illuminance levels throughout the day.

2.5.3.2. Sleep-wake parameters. Participants wore an Activity tracker [76] to measure their personal movement to estimate their sleep-wake rhythms. Participants were instructed to wear the tracker around the non-dominant wrist for 24 hr, starting in the morning of each measurement day until the next morning. The tracker measured acceleration (0–5 g) in the x-, y- and z-direction with a frequency of 50 Hz. The raw data were processed using 0.5 Hz and 15 Hz as cut-off frequencies and according to Formula 2 the Signal Vector Magnitude (SVM) in g was calculated.

\[ SVM = \sqrt{x^2 + y^2 + z^2} - 1 \]  

The SVM was resampled to 32 Hz and the highest acceleration within each second was taken as the score for this second (\( \text{max}(SVM_{n,i}) \), in line with the Actiwatch User Manual [77]. Subsequently, the activity count per minute (ACm) was calculated by summing the \( \text{max}(SVM_{n,i}) \) for each minute and adding the activity count of the surrounding minutes reduced by a factor of 5 and the activity count of the surrounding two minutes reduced by a factor of 25 as shown in Formula 3.

\[ ACm = \frac{\sum_{i=1}^{60} \text{max}(SVM_{n,i}) + \sum_{i=1}^{60} \sum_{j=1}^{60} \text{max}(SVM_{n-1,i,j})}{5} + \frac{\sum_{i=1}^{60} \sum_{j=1}^{60} \text{max}(SVM_{n-2,i,j}) + \sum_{i=1}^{60} \sum_{j=1}^{60} \sum_{k=1}^{60} \text{max}(SVM_{n-3,i,j,k})}{25} \]  

The data was scored as mobile if \( ACm > 40 \), and immobile otherwise. Sleep onset was defined as the start of the first 10-min period in which a maximum of 1 min had an \( ACm > 14 \). Sleep offset was defined as the end of the last period of 10 min during which a maximum of 2 min had an \( ACm > 18 \). The total number of inactive minutes per night was calculated by summing the immobile minutes between sleep onset and sleep offset and used as a proxy for sleep duration. Sleep efficiency was calculated by dividing the number of inactive minutes by the time difference between estimated sleep onset and offset, and multiplying this by 100. In the...
analyses, sleep efficiency, sleep onset and sleep duration were used as sleep-related outcome parameters.

Furthermore, participants wore an ActiGraph [78] to measure the intensity of their physical activity and two temperature sensors (iButton DS1925 and DS1922L data loggers) – one on the back of the hand palm and one on the forearm – to measure the skin temperature gradient during the entire working day which was used as an indicator for vasomotion. The data of these parameters are reported elsewhere.

2.6. Procedure

After an information session, potential participants were provided with an information brochure with detailed information about the procedure of the study based on which they could decide to participate in the study. In order to participate, they had to return the signed informed consent form that was attached to the information brochure. Before the actual start of the study, participants were invited to an instruction session during which the full procedure was explained and there was an opportunity to ask questions. All questions in the questionnaires were discussed, the cognitive task was practiced and the intake questionnaire was completed.

Subjects participated on two measurement days per week for six weeks. During a measurement day, they were doing their regular jobs and were asked to complete one sleep diary, eight ESQs, and one day evaluation questionnaire as shown in Fig. 3. The sleep diary was sent at 7:30 in the morning and could be completed until noon. The ESQs were randomly spread over the day between 9:00 and 17:00, with at least 30 min in between notifications. The day evaluation was sent at 17:30 and could be completed all evening. Furthermore, they completed the spatial planning task twice, once in the morning (~10:30) and once in the afternoon (~15:00). The light sensor was worn from getting up until going to bed, and the Axivity tracker was worn for 24 hr. Last, they wore the hip-worn ActiGraph and temperature sensors during the entire working day. After the study, participants were debriefed, thanked and compensated for the time spent.

2.7. Statistical analysis

All data were first processed and formatted into one dataset. Next, the distributions of the main study parameters were plotted, and observations that deviated more than three standard deviations from the mean were identified as outliers and coded to missing. In the analysis, only the observations during which participants indicated to be present behind their desk were used.

Separate multilevel models were run for all different dependent variables (visual experience, sleepiness, performance and sleep). The data for visual experience and sleepiness were structured as observations nested within measurement days (Day 1–12), which were nested within participants. Thus, a three-level model with ‘Participant’ and ‘Day nested within Participant’ as random intercepts was used. Task performance was analysed using ‘Participant’ and ‘Week nested within Participant’ as random intercepts, due to the limited number of observations per day (maximum of 2). The sleep metrics were analysed using only ‘Participant’ as random intercept, due to the limited number of observations per week (maximum of 2).

The measured personal illuminance did not significantly deviate between the scenarios (see Supplementary Materials S3), presumably due to daylight contribution in the office and the behavior of the participants. As the scenarios did result in difference in the visual field, both ‘Scenario’ and the mean personal illuminance in the 30 min prior to the questionnaire or task (which we will refer to as ‘Personal illuminance’) were included as main predictors in the models of visual experience, sleepiness and task performance. Additionally, ‘Daylight illuminance at the window’ in the 30 min prior to the observation was added in these models to consider the large daylight contribution in the offices due to the façade spanning windows (no multicollinearity with Personal illuminance). Furthermore, ‘Time of day’ was included as categorical predictor variable in the models for visual experience and sleepiness (labeled as Morning (9:00–10:45), Noon (10:45–15:15) and Afternoon (15:15–17:00), i.e. aligning with the phases in the scenarios). In the model predicting task performance, we added a categorical variable describing the notification number of the email within each measurement day (First notification, Second notification). Furthermore, we examined the interactions ‘Light * Time of day’ and ‘Scenario * Time of day’ for the models with visual experience and sleepiness as outcome parameters. If the interaction ‘Scenario * Time of day’ was significant, additional contrast analyses (as shown in Fig. 4) were done to test the effects of the scenarios during morning (M), noon (N) and afternoon (A) separately. The first set of contrasts (MC) covers the difference between the three scenarios (Control – C, Noon – N, and Skeleton – S) in the

Fig. 3. Schematic overview of one measurement day. The timing of the Experience Sampling Questionnaires (ESQ) is an example as a random-sampling strategy was employed in which notifications were sent between 9:00 and 17:00 with a minimum of 30 min in between notifications.
morning. In MC – C/S, the response during the morning in the Control scenario (base setting) was compared to the Skeleton scenario (brighter setting). In MC – C/N, the response during the morning in the Control scenario (base setting) was compared to the Noon scenario (base setting). In MC – N/S, the response during the morning in the Noon scenario (base setting) was compared to the Skeleton scenario (brighter setting). Similarly, the NC contrasts described the contrasts between the three scenarios during noon. In NC – C/N, the Control scenario (base setting) was compared to the Noon scenario (brighter setting) during noon. In NC – C/S, the Control scenario (base setting) was compared to the Skeleton scenario (base setting) during noon. In NC – C/N, the Noon scenario (brighter setting) was compared with the Skeleton scenario (base setting) during noon. The last contrast set (AC) tested the difference between the Noon scenario (base setting) in the afternoon and 2:00 the day after. In NC – C/S, the Control scenario (base setting) was tested against the Noon scenario (base setting) in the afternoon. In AC – C/N, the Control scenario (base setting) was tested against the Noon scenario (base setting) in the afternoon. The last contrast AC – N/S tested the difference between the Noon (base setting) and Skeleton (brighter setting) scenarios in the afternoon.

Control variables that showed a significant, medium to high correlation ($r > 0.4$) with the dependent variable as assessed with multilevel modelling, and did not show multicollinearity with other predictors as examined using the variance inflation factors (VIF $< 5$) were included as covariates. This resulted in the inclusion of ‘Caffeine’ (Yes/No) for the model for sleepiness, and of ‘Task number’ (i.e., how often the participant had performed the task already since the practice session) for the model for task performance.

In the multilevel models for the sleep metrics, the effects of Scenario and measured personal light levels were tested. The measured personal light levels were quantified using the ‘TaT$_{100}$’, ‘MLiT$_{100}$’, the interaction ‘TaT$_{100}$ * MLiT$_{100}$’, and the ‘Disparity index’. ‘Chronotype’ was additionally included as covariate in the model for sleep offset. In the other models, no covariates were included based on the preliminary correlational analyses.

All preparatory and main analyses were done in RStudio 1.1.463. Plots were made using the ‘ggplot 2’ and ‘ggpubr’ packages. The ‘lme4’ and ‘lmerTest’ packages were used to run the multilevel models. Post-hoc analyses were done using the ‘emmeans’ package. The linear mixed models were run using the restricted maximum likelihood approach (REML). Degrees of freedom were estimated using the Satterthwaite-methods, Tukey method was used to adjust p-values for multiple comparisons, and p-values < 0.05 were reported as statistically significant results.

3. Results

There were 30 participants, who together participated on 198 measurement days and in total completed 1074 questionnaires. The summary statistics of all dependent variables are presented in Table 3. Additionally, the summary statistics of the measured light-related parameters as used in the different models are given in this table to provide reference and facilitate interpretation. In the subsequent sections, the results of the effect of the different scenarios and the measured light on the visual experience, sleepiness, task performance and sleep metrics are described.

### Table 3
Summary statistics for the dependent and light-related variables.

<table>
<thead>
<tr>
<th>Variable</th>
<th>Mean (median)</th>
<th>Range</th>
</tr>
</thead>
<tbody>
<tr>
<td>Experience of the light intensity (Sensation$_V$)</td>
<td>0.04 (0.00)</td>
<td>[-3, 3]</td>
</tr>
<tr>
<td>Experience of the light color (Sensation$_C$)</td>
<td>0.19 (0.00)</td>
<td>[-2, 2]</td>
</tr>
<tr>
<td>Visual comfort (Comfort$_V$)</td>
<td>1.59 (2.00)</td>
<td>[-1, 3]</td>
</tr>
<tr>
<td>Sleepiness (KSS)</td>
<td>3.42 (3.00)</td>
<td>[1, 7]</td>
</tr>
<tr>
<td>Task performance</td>
<td>49.74 (50.00)</td>
<td>[13, 103]</td>
</tr>
<tr>
<td>Sleep onset (in hr)</td>
<td>23.10 (22.88)</td>
<td>[20.68, 27.83]</td>
</tr>
<tr>
<td>Sleep duration (in min)</td>
<td>384.30 (385.50)</td>
<td>[167, 564]</td>
</tr>
<tr>
<td>Sleep efficiency (in %)</td>
<td>88.69 (90.35)</td>
<td>[62.46, 99.30]</td>
</tr>
</tbody>
</table>

### Table 4

<table>
<thead>
<tr>
<th></th>
<th>Sensation$_V$ (n = 567)</th>
<th>Sensation$_C$ (n = 567)</th>
<th>Comfort$_V$ (n = 567)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>F</td>
<td>p</td>
<td>F</td>
</tr>
<tr>
<td>Fixed effects</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Scenario</td>
<td>F$_{2,152}$ = 0.99</td>
<td>0.38</td>
<td>F$_{2,144}$ = 1.05</td>
</tr>
<tr>
<td>Personal illuminance</td>
<td>F$_{1,532}$ = 0.01</td>
<td>0.93</td>
<td>F$_{1,491}$ = 0.23</td>
</tr>
<tr>
<td>Daylight illuminance</td>
<td>F$_{1,542}$ = 0.06</td>
<td>0.80</td>
<td>F$_{1,246}$ = 0.02</td>
</tr>
<tr>
<td>Time of day</td>
<td>F$_{2,491}$ = 4.60</td>
<td>0.01</td>
<td>F$_{2,205}$ = 1.99</td>
</tr>
<tr>
<td>Time of day * Scenario</td>
<td>F$_{2,485}$ = 10.88</td>
<td>&lt; 0.001</td>
<td>F$_{2,002}$ = 1.13</td>
</tr>
<tr>
<td>Time of day * Personal illuminance</td>
<td>F$_{2,505}$ = 2.24</td>
<td>0.11</td>
<td>F$_{2,319}$ = 1.29</td>
</tr>
</tbody>
</table>

R$^2$ full-model | 0.36 | 0.40 | 0.33 |
R$^2$ fixed-effects | 0.08 | 0.02 | 0.05 |

Note: Personal illuminance was centered in all models. Statistically significant effects are presented in bold. F: F-value and p: p-value.
Noon scenario was perceived significantly brighter compared to both the morning. During noon, the brighter setting that was applied in the Noon scenario, which was at the base setting in the morning (MC scenario was statistically significant (p = 0.09) was perceived slightly more comfortable than the Noon scenario (1.61 ± 0.08; p = 0.008) and the Skeleton scenario (1.58 ± 0.09; p = 0.005), as can be seen in Fig. 6. Overall, the Noon and Skeleton scenarios did not differ significantly with respect to the experienced visual comfort (p = 0.94). Additionally, there was a non-significant trend for a relation between Daylight illuminance at the window and participants’ visual comfort votes (B ±SE = 0.16 ± 0.08).

3.1. Visual experience

Visual intensity sensation was significantly affected by the Time of day and the Time of day * Scenario interaction (Table 4). Independent of the scenario, the light settings in the morning (Estimated Marginal Mean (EMM) ± Standard Error (SE) = 0.31 ± 0.10) were perceived as significantly brighter compared to the settings during noon (0.05 ± 0.08; p = 0.01) and in the afternoon (0.05 ± 0.10; p = 0.04). No significant differences existed between the perceived brightness during noon and afternoon (p = 0.99). Fig. 5 visualizes the contrast analyses: in the morning, the Skeleton scenario was set to the brighter setting and this was perceived as significantly brighter compared to the Noon scenario, which was at the base setting in the morning (MC – N/S = 0.29 ± 0.11; p = 0.007). The Control scenario, also in the base setting, did not significantly differ from either the Noon (MC – C/N = −0.18 ± 0.10; p = 0.07) or the Skeleton (MC – C/S = 0.11 ± 0.11; p = 0.33) scenario in the morning. During noon, the brighter setting that was applied in the Noon scenario was perceived significantly brighter compared to both the Control (NC – C/N = 0.23 ± 0.07; p = 0.002) and the Skeleton (NC – N/S = −0.26 ± 0.07; p < 0.001) scenario, which were both set to the base setting. No significant differences existed between the Control and Skeleton scenarios around noon (NC – C/S = −0.03 ± 0.08; p = 0.66). Last, the brighter setting in the Skeleton scenario in the afternoon was perceived as significantly brighter compared to the base setting that was applied in both the Control (AC – C/S = 0.21 ± 0.10; p = 0.05) and Noon Scenarios (AC – N/S = 0.20 ± 0.10; p = 0.04). In the afternoon, no statistically significant differences existed between the perceived brightness of the Control and Noon Scenario (AC – C/N = 0.00 ± 0.10; p = 0.98). No statistically significant main effects of Scenario, Personal or Daylight illuminance occurred for the brightness sensation, nor was the interaction term between Personal illuminance and Time of day a significant predictor for SensationVI. Color sensation was not significantly affected by the Scenario, Time of day, Personal or Daylight illuminance (see Table 4).

Table 4 shows that Scenario affected the visual comfort significantly, whereas the Personal illuminance was not significantly related to visual comfort. Post-hoc comparisons for the main effect of Scenario showed that, at all times of day, the Control scenario (1.86 ± 0.09) was perceived slightly more comfortable than the Noon scenario (1.61 ± 0.08; p = 0.008) and the Skeleton scenario (1.58 ± 0.09; p = 0.005), as can be seen in Fig. 6. Overall, the Noon and Skeleton scenarios did not differ significantly with respect to the experienced visual comfort (p = 0.94). Additionally, there was a non-significant trend for a relation between Daylight illuminance at the window and participants’ visual comfort votes (B ±SE = 0.16 ± 0.08).

3.2. Sleepiness

Table 5 shows that participants’ sleepiness was significantly associated with Scenario and Time of day, but not associated with the Personal or Daylight illuminance. Post-hoc analyses showed that sleepiness was not significantly different in the Control scenario (3.42 ± 0.20) compared to the Noon scenario (3.15 ± 0.19; p = 0.21) or the Skeleton scenario (3.70 ± 0.20; p = 0.24). Yet, the difference between the Noon and Skeleton scenario was statistically significant (p = 0.003), with lower sleepiness in the Noon scenario compared to the Skeleton scenario (Fig. 7). Participants’ sleepiness showed an increasing trend over the day within

![Fig. 5. Estimated marginal means (EMMs) of visual intensity sensation per time of day (M = Morning, N= Noon, A = Afternoon) per condition. The solid lines represent morning contrasts, the longdashed lines represente noon contrasts, and the twodashed lines represent the afternoon contrasts. The errorbars represent the standard error (SE). The colors indicate whether the light was set to the base (grey) or the brighter (white) light setting. ** indicates p < 0.001, *: p < 0.01, and #: p < 0.05.](image)

![Fig. 6. Estimated marginal means (EMMs) of visual comfort per condition. The error bars represent the standard error. ** indicates p < 0.01 and NS: p > 0.05.](image)
office hours. In the afternoon, participants felt sleepier (3.70 ± 0.19) compared to the morning (3.22 ± 0.19; p < 0.001) and noon ratings (3.36 ± 0.18; p = 0.002). Sleepiness in the morning vs. around noon did not significantly differ (p = 0.31). Lastly, participants felt significantly less sleepy when they had consumed a caffeinated drink in the 30 min before completing the questionnaire (3.30 ± 0.19) compared to the morning (3.22 ± 0.11) and longer sleep duration (BMLIT ± SE = 217.65 ± 103.22 and BMLIT ± SE = 14.92 ± 6.50). Neither TaT nor the TaT * MLiT interaction were significantly related to any of the assessed sleep metrics. Last, sleep onset was significantly related to Chronotype, confirming that earlier chronotypes had an earlier sleep onset (B ± SE = 0.78 ± 0.19).

4. Discussion

In this field study, we tested two different dynamic scenarios against a control scenario to examine their potential in an operational office environment. Dynamic scenarios, offered through a diffuse vertical luminaire on the desk and suspended ceiling mounted luminaires, added approximately 175 lux at the eye (300 lux on the work plane) to regular lighting conditions for ~3.5 hr either around noon (Noon scenario), or in the early morning and late afternoon (Skeleton scenario). A counterbalanced crossover design was employed in which participants were exposed to each scenario for two weeks. Using highly frequent assessments of visual experience, sleepiness, performance and sleep, we aimed to gain insight in the visual, acute and circadian responses of office occupants to light in a real office environment. The data showed that self-reported sleepiness was lower in the Noon scenario than in the Skeleton scenario, although the differences between sleepiness across scenarios were small and participants’ sleepiness levels in neither dynamic scenario differed significantly from the control scenario. Visual comfort was highest in the control scenario with a constant electric light setting, whereas participants’ task performance, sleep onset, duration and efficiency did not significantly differ between the scheduled scenarios.

4.1. Effects of the electric light scenarios

Unexpectedly, the personal illuminance pattern as measured by the personal light sensors – the amount of light actually received as a result of the specific scenario and naturalistic conditions – did not significantly reflect the brighter light periods in the dynamic light scenarios. The absence of systematic differences in personal illuminance between the scenarios is likely due to the substantial and quite variable daylight contribution and the spatial behavior of the participants (movements through the building for coffee, lunch, meetings etc.). However, the

Table 6
Model statistics for sleep onset, inactive minutes and sleep efficiency.

<table>
<thead>
<tr>
<th></th>
<th>Sleep onset (n = 115)</th>
<th>Sleep duration (n = 115)</th>
<th>Sleep efficiency (n = 115)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>F</td>
<td>p</td>
<td>F</td>
</tr>
<tr>
<td>Fixed effects</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Scenario</td>
<td>F2,21 = 0.04</td>
<td>0.97</td>
<td>F2,24 = 0.08</td>
</tr>
<tr>
<td>Chronotype</td>
<td>F1,25 = 16.98</td>
<td>&lt; 0.001</td>
<td>F1,24 = 4.45</td>
</tr>
<tr>
<td>Disparity Index</td>
<td>F1,106 = 13.12</td>
<td>&lt; 0.001</td>
<td>F1,106 = 0.66</td>
</tr>
<tr>
<td>TaT</td>
<td>F1,106 = 0.02</td>
<td>0.88</td>
<td>F1,106 = 5.27</td>
</tr>
<tr>
<td>MLiT</td>
<td>F1,106 = 6.07</td>
<td>0.02</td>
<td>F1,106 = 0.01</td>
</tr>
<tr>
<td>TaT * MLiT</td>
<td>F1,107 = 0.07</td>
<td>0.79</td>
<td>F1,107 = 0.49</td>
</tr>
<tr>
<td>R² fixed-effects</td>
<td>0.67</td>
<td></td>
<td>0.49</td>
</tr>
<tr>
<td>R² full-model</td>
<td>0.49</td>
<td></td>
<td>0.26</td>
</tr>
</tbody>
</table>

Note: Chronotype was only added in the model for sleep onset. TaT and MLiT were centered in all models. Statistically significant effects are presented in bold. F: F-value and p: p-value.
manipulation did affect the visual experience, as the brightness sensation varied largely according to the planned scenarios. As expected, participants assessed the brighter light periods in the dynamic scenarios significantly brighter than the base-level light periods. It therefore appears that the scenarios provided a quite apparent visual stimulus, though not necessarily a non-visual one, as illuminance at the eye as measured by the personal sensors was not significantly different between the scenarios. In general, participants assessed all scenarios as visually (just) comfortable, although the control scenario with constant base lighting was perceived slightly, yet significantly, more comfortable than the two dynamic scenarios. As the transitions between the different light settings spanned a full hour, it is unlikely that this slightly lower comfort was induced by fast light transitions [52,50,79]. Instead, the data seem to suggest a preference for constant electric light, even though people generally appreciate variable daylight [59,80]. This is in line with the fact that participants in the study by Ref. [81] also appear to have selected quite constant electric light settings, on top of the naturally varying daylight curve. Furthermore, the lower comfort experienced in the dynamic light scenarios compared to the control scenario may be due to other light parameters such as uniformity, contrast or glare [15–18,82] or contextual parameters such as the visual task difficulty and time of day [83].

Across the entire day, self-reported sleepiness was lowest in the Noon scenario. Given the fact that the scenarios did not significantly differ in the amount of light measured at the eye, it is unlikely that the reduced sleepiness in the Noon scenario was caused by non-image forming processes. Instead, as differences in visual sensation were detected, the alerting effect was more likely induced by the differences in what the participants saw (e.g., brighter ceiling or desk), comparable to the effect of wall luminance reported by Ref. [84]. However, no conclusive answer on the underlying process can currently be given, as alerting effects may (also) be driven by cognitive associations between brighter settings and arousal/activity related concepts (e.g., Ref. [85]). Furthermore, a similar associative effect would have also been expected in the Skeleton scenario, which offered a brighter light setting at the start and ending of the work day, but this was not found in the current data. Evidence for a motivational pathway as also suggested by Ref. [84] (see also [86]) was not detected in the current study, as participants preferred the (dimmer) control scenario rather than the Noon scenario.

4.2. Acute effects of varying illuminance levels at the eye

Despite the fact that the personal illuminance did not vary systematically with the dynamic scenarios, there was a lot of variation in the measured vertical light levels between and within participants. This is likely due to movements through the building, movements of the head and the eye [56]. As the personal light sensors are the most accurate measure of the illuminance they received throughout the study, we examined the relationships between the ESQ items and average personal illuminance in the 30 min prior to the questionnaires and tasks as well. Neither the visual sensation, the visual comfort, the self-reported sleepiness nor the task performance were significantly associated with the luminous exposure in the 30 min before the observation. The non-significant relationships between the average personal illuminance in the prior 30 min and visual sensation and comfort are likely related to the employed metric to quantify the light. Apart from the quantity of light as assessed by the illuminance measurements, sensation and comfort are influenced by the luminance, uniformity, quality and color rendering quality of light (e.g. Ref. [82]), requiring additional parameters describing the visual environment. Moreover, visual comfort is greatly influenced by momentary lighting and very recent transitions [46,52], which are not reflected in the averages over the past 30 min.

The personal illuminance measured at the clavicula in the 30 min before the ESQ was expected to acutely relate to self-reported sleepiness and objective task performance. Even though melanicp irradiance would likely be a better predictor for subjective sleepiness [87] and inconsistent results have been reported in prior work [25,29,31,32,88], we had expected to be able to find a negative relationship between the personal illuminance and subjective sleepiness, as the study lasted six weeks, and repeated measurements throughout each day and week were taken. Such a design including 30 participants rendered more than 80% power to detect a difference of 0.5 on the KSS scale, yet no such alerting effects of light were identified. Especially in an operational office as the current study was conducted in, the potential acute alerting effects of the lighting may have remained hidden due to alerting effects of other parameters (e.g., social interactions, work engagement) that were not all controlled for in the current study [89–91]. Moreover, participants’ mean sleepiness during office hours was rather low in the current study, and therefore possibly left little room for further reduction by the light conditions [45,92]. The finding that illuminance at the eye did not relate to subjective sleepiness or performance is corroborated by results of earlier field studies [31,32,53], although some others did report significant associations [25,29]. It appears that a definitive verdict on this relation is at least as hard to reach in field studies as in controlled experiments (e.g., Refs. [11,12]). As this study is not the first that was not able to establish a relationship between personal illuminance and acute alerting effects of light, future research should strive to establish the circumstances under which these effects do occur, or at least are substantial enough to be detectable and meaningful in a real-life context.

4.3. Circadian effects of scenarios and light at the eye

With regard to the sleep-related metrics, no statistically significant effects of the scenarios were found, but the measured light exposure did significantly associate with sleep onset and duration. Rather than using the average illuminance throughout the day as a predictor for the sleep indicators, we investigated the applicability of metrics related to the duration and timing of luminous exposure (TaT and MLiT [73]), as well as a light-variability related metric (Disparity Index; [75]). We found that with a later timing of the light and more variation in the exposure, sleep onset was earlier and sleep duration longer. It may seem counterintuitive that a later timing of the luminous exposure was related to earlier and longer sleep, but it is important to consider the range of the light parameters when interpreting these results. Although illuminances over one full 24-hr day were used in the calculation of MLiT, the mean MLiT was just after 13:00 with a standard deviation of slightly over one hour. This indicates that light brighter than 100 lux was, on average, timed at the middle of the working day. Thus, this positive effect of MLiT on sleep onset and sleep duration may possibly be explained by a lowered sensitivity to evening light due to exposure to relatively bright light during the afternoon [66,67].

The results of the separate analyses of the 100 and 200 lux as threshold for TaT and MLiT showed similar trends, suggesting an absence of a step-shaped dose response relationship within these ranges. A more extensive sensitivity analysis (e.g., exploring also thresholds of 500 or 1000 lux) as performed in Ref. [88] would perhaps yield better insights in the relevant light thresholds for the circadian effects of light, but was not possible given participants’ scarce exposure to higher illuminance levels.

The positive relationship between the variability of personal light levels on sleep onset and duration may be explained by the luminous exposure being more effective when the circadian system has the opportunity to regenerate (part of) its sensitivity in between bright periods [93]. To our knowledge, this is the first study exploring metrics describing such variability by calculating the disparity index, which originates from the field of ecology [75]. It was designed to incorporate the chronological order of time series values, while assessing the rate of change between consecutive values. In the current study, the index seems a promising parameter to capture variability in dynamic light, but more research is required to gain in-depth understanding of this parameter and assess the predictive value for circadian effects of light. Likely, additional parameters are needed in parallel to comprehensively
describe and compare light scenarios with differently timed light exposure.

5. Conclusive reflection

In sum, visual sensation, comfort and subjective sleepiness were affected by the dynamic light scenarios in this field study, but task performance and actual sleep were not. Furthermore, personal illuminance did not relate to the visual experience, subjective sleepiness, or objective task performance, but the variation and timing of the measured personal illuminance did significantly relate to sleep onset and duration.

A field study such as the current one clearly illustrates the multitude of factors that should be considered and dealt with when studying and implementing novel lighting solutions in an operational office. For example, quantification of the entire light environment using multiple parameters is required as multiple processes underlie these different effects (e.g., Refs. [94–97]). Moreover, the current study emphasizes the attention that a light intervention demands to ensure an actual, meaningful change in personal luminous exposure. The indirect relationship between the personal illuminance and light in the visual field can be exploited to create integrative lighting scenarios in which the illuminance that falls on the eye is sufficient to generate positive circadian – and potentially acute – effects, while the visual environment is maintained comfortable. Yet, this study also showed that dynamic electric light led to lower comfort ratings than static light. Thus, researchers and lighting designers should be careful with introducing dynamic light scenarios as the natural preference for daylight and tolerance for – or even appreciation of – its variability [59,80,98] cannot be directly transferred to a preference for dynamic electric light.

We do note that it is questionable whether acute effects of light hold in real office environments. Possibly, the absence of acute effects can be attributed to the manipulation in the visual field rather than illuminance at the eye or the specific context of this study. The sample consisted of 30 healthy employees (administrative support staff and doctoral candidates) following largely self-chosen diurnal working schedules. Other samples with different occupations may have yielded different results. Yet, this sample of 30 - especially using a within-subject design with repeated measures and completely counterbalanced conditions – yields more than sufficient power to detect modest effects. Furthermore, the office in which this study was conducted consisted of an open office environment with abundant daylight openings, which resulted in a lot of additional light from surrounding areas and the large windows. The custom-made luminaires on the desk did provide a lot of local additional light, yet due to the use of two monitors in front of the luminaire by many employees their contribution was not always optimal as was also reflected in the personal illuminance measurements. Together, this has very likely resulted in a light manipulation that was more present in the visual field than at the eye.

To conclude, this study showed that the spatial and behavioral context in which a lighting intervention is applied are also important aspects to consider when implementing integrative lighting. However, in spite of the uncontrollable and unpredictable conditions in real life, the current study in an operational office did demonstrate that the overall light environment impacted visual sensation, comfort, and subjective sleepiness and that the personal light exposure related to sleep.

CRediT authorship contribution statement

M.E. Kompier: Writing – review & editing, Writing – original draft, Visualization, Software, Methodology, Investigation, Formal analysis, Data curation, Conceptualization. K.C.H.J. Smolders: Conceptualization, Investigation, Methodology, Supervision, Validation, Writing – original draft, Writing – review & editing. R.P. Kramer: Writing – review & editing. W.D. van Marken Lichtenbelt: Writing – review & editing. Y.A.W. de Kort: Writing – review & editing, Writing – original draft, Supervision, Resources, Project administration, Methodology, Funding acquisition, Conceptualization.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.buildenv.2022.108844.

References


