Ambiguities regarding the relationship between office lighting and subjective alertness: An exploratory field study in a Dutch office landscape

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\textbf{A R T I C L E I N F O}

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\textbf{A B S T R A C T}

The current field study investigated the ambiguities regarding the relationship between office lighting and subjective alertness. In laboratory studies, light-induced effects were demonstrated. Field studies are essential to prove the validity of these results and the potential recommendations for lighting in future buildings. Therefore, lighting measurements and subjective health data were gathered in a Dutch office environment. Health data was collected by questionnaires and includes data on functional health, wellbeing and alertness. Multiple general, environmental, and personal variables were identified as confounders for the relationship between light and alertness. For six out of the total 46 participants a statistically significant correlation was found between horizontal illuminance ($E_{ho}$) and subjective alertness. Further research needs to incorporate a larger sample size and more potential confounders for the relationship between $E_{ho}$ and alertness. Further research including these recommendations may explain why certain people respond to light while others do not.

\section{1. Introduction}

Light entering the eyes reaches the rods and cones on the retina which then stimulate vision. In addition to these two photoreceptors (i.e., rods and cones), a third photoreceptor was discovered approximately fifteen years ago [1], the so-called intrinsically photosensitive retinal ganglion cell (ipRGC). These ganglion cells capture light (i.e., effective irradiances) which has entered through the eyes and these cells initiate processes in both the Image-Forming (IF) and Non-Image-Forming (NIF) centres of the brain. Previous studies indicated effects of light on human’s health and well-being [2–5]. These effects can be acute (short-term) or circadian (long-term) effects. Acute effects are, for example, alerting effects or distraction due to glare or flicker. Circadian effects are caused due to exposure to a lighting condition for a certain period of time and are, for example, the regulation of hormones or the organisation of the biological clock. The production of the hormone melatonin is one example of a hormone which is influenced by light exposure. Zeitzer et al. [6] developed dose-response curves in order to determine a relation between light and melatonin. A mismatch between light exposure and individuals day/night rhythm can lead to a disrupted circadian system [3]. This disruption is associated with poor health and a lower work performance [3]. In addition, office lighting is often demonstrated to directly affect work performance [7–9]. Demonstrated direct and indirect effects of (office) lighting on health and work performance highlight the importance of the \textit{most appropriate light exposure at the right moment of time}.

An individual’s daily light exposure consists of contributions from daylight and electric light sources. One of the current challenges is to determine the individual’s need for light to enhance their health. Since individuals differ in experiences, sensitivity, and preferences, each individual has different responses to light exposure [10]. Therefore, it is recommended to investigate the relationship between light and health based on \textit{personal lighting conditions} [11,12]. The relationship between (either general or personal) light exposure and occupational health is investigated in multiple studies [7,13–16]. The experiments took place in laboratories, in simulated office rooms, or in realistic office buildings. The majority of the experimental studies included in the review of van Duijnhoven et al. [17], was performed under laboratory conditions whereas employees may react and behave differently in a real work environment. The actual effects of office light exposure on an employee’s health need to be investigated and validated in real office environments.

In order to investigate the relationship between office lighting and any outcome measure (e.g., occupational health, subjective alertness),
the lighting environment needs to be identified. Identifying a lighting environment comprises multiple lighting measurements. Illuminances and correlated colour temperatures are the most common measures to map a certain lighting situation [17]. Besides these two light parameters, the CIE proposed a protocol for describing lighting in an indoor environment including people, context, lighting systems and components, room surface light levels and distribution, task details, task area light distribution, high-luminance areas, modelling, colour appearance, and dynamic effects [18]. In addition, light measurements can be performed continuously (once per set interval, e.g., 1 s or 1 min) or at specific moments during the day. In addition, measurements can be performed person-bound or location-bound [11]. Furthermore, light measurements can be performed inside or outside.

To the authors’ knowledge and based on the literature review [17], this is the first field study which investigates the relationship between personal lighting conditions lighting and subjective alertness (SA), both measured at the same timestamp. No intervention to the lighting system was introduced in this study. All participants were exposed to their regular lighting environment.

The study described in this research paper included continuous location-bound measurements to identify the indoor lighting environment and questionnaires to gather information about the health outcomes (e.g., SA). The study was conducted as part of a larger research project investigating the potential impact of office lighting on occupational health in office landscapes. The aim of this experiment was to investigate the ambiguities regarding the relationship between office lighting and SA. It was expected that the investigation of this relationship in a field study would be challenging due to multiple potential confounders. Another aim of this study was to search for aspects which potentially explain the relationship between horizontal illuminance ($E_{h0}$) and SA in order to be taken into account for future (field) studies.

All considered variables in this study were categorized into general, environmental, and personal variables. General variables consisted of day and time of the day, environmental variables were light, temperature and relative humidity, and the personal variables were user characteristics, self-reported sleep quality and health scores. It was expected that SA was related to all three types of variables. In addition, since individuals respond differently to changes in lighting conditions, it was expected that the correlation between SA and $E_{h0}$ differed between the participants (i.e., that the correlation was significant for a percentage of the participant sample size). Finally, it was expected that differences in correlations (i.e., between SA and $E_{h0}$) between the participants could be explained through the personal variables.

2. Methods

The field experiment was performed during one 5-day work week in May 2016 in a two-floor office building in the Netherlands. The weather conditions varied from an overcast sky on Monday, Tuesday, and Wednesday towards a clear sky on Thursday and Friday. The dawn and dusk times were around the local times 5:30 and 21:45 respectively. The local times related to the daylight saving time in the Netherlands (March, 27th till October 30th, 2016). The office hours of all the participants fell in this daylight period.

2.1. Office environment

The study location was a two-floor office building in the West of the Netherlands (Hendrik-Ido-Ambacht) (see Fig. 1). This building was renovated in 2015 and transformed from a closed structure to an open structure with office landscapes. This office transformation is part of the new Flexible Working Arrangements (FWA) [19]. Companies increasingly support this working practice in order to improve employee’s productivity at work. The office building of the current study consists of two floors, each consisting one large office landscape. On the first floor there is one separate office landscape on the North side and there are four office spaces enclosed with glass throughout the whole office building. The first floor contains 52 desks and the ground floor contains 31 desks.

2.2. Office lighting

The west façade on the ground floor contained daylight openings without sun shading devices. In contrast, on the first floor, the building façade was more open and this façade consisted of sun shading devices (see Fig. 2 and Fig. 3). It was not recorded when the shading devices were open or closed.

In addition to the presence of daylight, electric lights were installed. The office landscapes were lit by dimmable suspended luminaires (Prolicht, Glorius, 01400 7x14/24 W DALI, see Fig. 4) and dimmable LED spots (Quadro LED reflector 31 W 2100 l m 3000 K or Quadro LED Reflector 53 W 2400 l m, see Fig. 5). The electric lighting in the office landscapes was on during office hours and dimmed based on the amount of daylight. The dimming levels (0–100%) were logged in the lighting system. There were no desk lights available at the desks.

Most lighting recommendations for Dutch office buildings are horizontally focused [20]. In earlier times, when most offices were paper-based, it was important to focus on the horizontal light levels. Recently, the vertical lighting conditions (e.g., vertical illuminance) are more important due to the digital world the office workers are currently working in. However, due to practical reasons, only $E_{h0}$ at desk level were measured in this study.

In order to gather continuously measured $E_{h0}$ at all work places throughout the office building, the non-obtrusive method (location-bound estimations, i.e., LBE) developed by van Duijnhoven et al. [11,12] was applied. This method consists of reference locations at which continuous measurements are performed and predictive models between the reference locations and all other workplaces (i.e., outcome locations) inside the office in order to estimate the lighting conditions at all workplaces. Between two-and four relation measurements (between reference and outcome locations) [11] were performed per outcome location to create the predictive models. During the relation...
measurements, an overcast sky prevented direct sunlight entering the office building. The average fit (i.e., $R^2$) between the relation measurements and the developed predictive models was 0.98 with the best at 0.99 and the worst at 0.89. The predictive models were applied using inter- and extrapolation of the relation measurement data points (more information regarding the LBE method can be found in other papers of van Duijnhoven et al.\textsuperscript{11,12}). The continuous estimated lighting conditions at all workplaces were used for the analysis of the relationship between light and subjective alertness in this study.

In this study, $E_{hor}$ was continuously (once per minute) measured at three reference locations throughout the office building. Fig. 1 shows the floor plans of the office building in which the red dots indicate the three measurement locations. Two measurement locations (0.1 and 0.2, see Fig. 1) were situated on the ground floor, respectively at a distance of 6 m and 2 m from the facade, one (1.1) was located on the first floor, at a distance of 6.5 m from the facade. The three locations were spread throughout the office building and chosen based on a prior observation before the start of the study regarding the occupancy of the desks during the experiment period. $E_{hor}$ at desk level was measured using Hagner SD2 photometers.

The estimated $E_{hor}$ at all desks used by participants during the study, varied between 219 lx and 4831 lx throughout the work week. Two days (Monday and Wednesday) the maximum $E_{hor}$ was around 2200 lx whereas the maximum $E_{hor}$ on the other three days reached over 4000 lx. On the first floor, the sun shading devices caused fast decreases in $E_{hor}$ whereas a more closed façade on the ground floor led to a lower variation in $E_{hor}$ compared to the measurements on the first floor (Fig. 6).

2.3. Subjective alertness

The lighting measurements were accompanied by questionnaires completed by employees. Participants received a unique participant number after signing the informed consent form, in order to analyse all data anonymously. Four questionnaires were distributed during the day via participants’ work email addresses. The participant number and desk number were asked at the beginning of each questionnaire. Desk numbers were asked because of a flexible workplaces policy in the office building. In reality, there were only limited changes of workplaces. The 46 participants worked at 49 different desks throughout the experiment period.

Within the questionnaires, the Karolinska Sleepiness Scale \textsuperscript{[21]} (KSS) was applied to measure SA. The KSS measures on a scale from 1 to 10 providing 1 = extremely alert and 10 = extremely sleepy \textsuperscript{[21]}. The KSS questionnaire refers to the sleepiness level the last 5 min before completing the questionnaire and is a non-obtrusive way to investigate office workers’ alertness. The four questionnaires were distributed at 9 a.m., 11:15 a.m., 2 p.m., and 4:15 p.m.
2.4. Additional measures

Besides the E_hor and SA, additional aspects were objectively and subjectively measured in order to obtain more information about the work environment and the participant's conditions.

2.5. Objective measures

In addition to the objective lighting measurements, temperature and relative humidity were continuously measured at the three reference locations. Rense HT-732 transmitters were used for measuring.

Throughout the experiment period (i.e., five consecutive days between 8:30 h and 17:30 h), the temperature measured at the three reference locations varied between 21.8 °C and 24.8 °C (X ± s = 2.7 ± 0.402 °C). The temperatures on Tuesday varied the most (s = 0.439 °C). The mean temperature measured at the first floor was slightly higher (X = 22.91 °C) compared to the two reference locations at the ground floor (X = 22.85 °C and 22.32 °C, respectively). Relative humidity measured at the three reference locations varied between 32.9% and 57.5% (X ± s = 46.7 ± 5.52%). The variation in relative humidity was the highest on Friday (s = 4.83%). Measurements on the first floor showed a lower mean relative humidity (X = 42.7%) compared to the two measurements on the ground floor (X = 44.4% and 52.9%, respectively). The standard deviation for the three measurement locations was approximately 3%.

2.5.1. Subjective measures

The subjective KSS data was also extended with more survey results. The Short-Form 36 items (SF-36) [22] is a set of easily administered quality-of-life measures and was used to measure functional health and wellbeing from the individual’s perspective [22,23]. This questionnaire was distributed only once, at the beginning of the study period. The health of employees is described by the World Health Organisation in the definition of occupational health: a combined term which includes all aspects of health and safety in the workplace, ranging from prevention of hazards to working conditions [24]. The health data from the SF-36 health questionnaire resulted into eight aspects: physical functioning (PF), role physical (RP), bodily pain (BP), general health (GH), vitality (VT), social functioning (SF), role emotional (RE), and mental health (MH). All aspects were assessed using a 0–100 score, 100 indicating the healthiest. An extra question concerning sleep quality was added to every questionnaire at 9am. The statement ‘I slept well last night’ with a 5-point scale answer possibility (completely agree – agree – neither agree nor disagree – disagree – completely disagree) was added to the questionnaire to include self-reported sleep quality.

In addition to the regular (i.e., four times a day) questionnaires, a general questionnaire was distributed to obtain participant’s user characteristics (i.e., gender, age, corrective lenses, working days, and working hours). Age of the participant was asked with the answer options ‘younger than 25’, ‘25–34 years’, ‘35–44 years’, ‘45–54 years’, ‘55–65 years’, and ‘older than 65’.

2.6. Participant sample

Participants were recruited after providing general information about the study. 54 out of 70 employees (i.e., response rate = 77%) agreed to participate and signed the informed consent form. Participation was voluntary and anonymous. In total, 570 completed questionnaires were collected. 46 (22 male and 24 female) participants filled in at least three questionnaires. The average number of completed questionnaires was 12 with a maximum of 20 (four questionnaires per day for 5 consecutive days). The median age was “35–44 years”, approximately 65% of the participants reported to have a 5-day work week and the average working hours regarding all participants were 7.7 hours per work day. The majority (56.5%) of the participants used corrective lenses (glasses or contacts) and that was most of the time (57.7%) due to myopia. Nearly all (i.e., 93.5%) participants rated their general health as good, very good, or excellent.

2.7. Data analysis

The objective and subjective data were analysed using MATLAB R2015a and SPSS Statistics 22. The data analysis consisted of four steps.

First, Kendall’s tau correlation coefficients were calculated between SA and other variables potentially being a confounder in the relationship between E_hor and SA. All subjective alertness scores from the data set were included in these correlation analyses. These non-parametric correlations were used because the majority of the data was not normally distributed and because the SA values in the analysis were ordinal variables. All the tests were two-sided using a significance (p) level of 0.05 to indicate statistical significance.

Secondly, the relationship between E_hor and SA was investigated. The estimated E_hor at the specific desks (i.e., where the participants were working) for the same time of the day as filling in the questionnaires were selected to perform the statistical analysis. All E_hor, together with the KSS data were tested on significant correlations. Individual differences for filling in the KSS required a within-subject statistical analysis.

Thirdly, partial correlations were calculated for the relationship between E_hor and SA including all variables identified as confounder in the first step of the data analysis.

The last step was to investigate the differences between two groups: the participants with a significant correlation between E_hor and SA and the participants without this significant correlation. The non-parametric Mann-Whitney test was applied to test whether these differences between both groups were significant. Exact significance levels were used due to relatively small sample sizes.

3. Results

This section provides results regarding aspects correlating with SA (section 3.1), the relationship between E_hor and SA with and without confounders (section 3.2), and the differences between participants with a significant correlation between E_hor and SA and the participants where this correlation was not significant (section 3.3).

3.1. Aspects correlating with SA

In this paper, the tested variables which potentially predict SA were categorized into general, environmental, and personal variables (see Fig. 7 and Fig. 8). Day of the week and time of the day were the included general variables. Light (i.e., E_hor), temperature, and relative humidity were the environmental variables. User characteristics, self-reported sleep quality, and health scores (i.e., determined with the SF-36) were the personal variables. All general, environmental, and personal variables which correlate significantly with SA were included as

Fig. 7. General overview of variables which potentially predict SA (measured with the KSS)
confounding variables when investigating the relationship between Ehor and SA.

3.1.1. General variables

A significant correlation between KSS and day of the week indicated a slightly higher sleepiness in the beginning of the week ($\tau = -0.13, p < .001$) compared to the end of the week. In addition, a significant correlation between KSS and time of the day demonstrated higher subjective sleepiness towards the end of the day compared to the beginning of the day ($\tau = 0.11, p = .002$). Although the correlations were low to medium, they were significant and both day and time should be included as potential confounders for SA.

3.1.2. Environmental variables

The correlations between Ehor and SA ($\tau = 0.02, p = .526$) and between temperature and SA ($\tau = 0.02, p = .526$) were not significant. The correlation between relative humidity and SA, however, was significant ($\tau = 0.07, p = .027$). Again, although the correlation was weak, relative humidity should also be considered as a potential confounder for SA.

3.1.3. Personal variables

Personal variables were subdivided into user characteristics, self-reported sleep quality, and health scores obtained from the SF-36 questionnaire.

3.1.3.1. User characteristics. In this paragraph, the relationships between multiple user characteristics and SA were determined based on correlations. A negative significant correlation ($\tau = -0.14 p < .001$) between gender (1 = male and 2 = female) and SA indicated that the female participants reported to be slightly more alert compared to the male participants. In addition, the use of corrective lenses correlated significantly with SA ($\tau = 0.08 p = .027$). The correlation between age category and SA was not significant ($\tau = 0.04 p = .256$).

The participants were all working for the same company and performed similar work tasks. However, the number of work days a week and work hours a day differed between participants. SA did not correlate significantly with the number of work days ($\tau = -0.03 p = .432$). However, the number of work hours during a work day correlated significantly with SA ($\tau = -0.17 p < .001$).

3.1.3.2. Self-reported sleep quality. Self-reported sleep quality was obtained via one question in the morning questionnaire (9am). A significant correlation between this statement and SA indicated that self-reported sleep quality was a potential predictor for SA ($\tau = 0.17 p < .001$). The positive correlation suggests that individuals who reported to disagree with the statement (i.e., “I slept well last night”) reported to feel sleepier in the morning (KSS evaluation 9:00).

3.1.3.3. Health. The associations between SA and the eight different health scores were tested. No significant correlation was found for SA and PF, RP, BP, or RE ($\tau = 0.05 p = .187$, $\tau = 0.04 p = .263$, $\tau = 0.06 p = .090$, and $\tau = -0.02 p = .534$, respectively).

Participants with a higher GH score reported to be more alert ($\tau = -0.21 p < .001$). The same applies for the VT, SF, and MH scores ($\tau = -0.26 p < .001$, $\tau = -0.15 p < .001$, and $\tau = -0.12 p < .001$, respectively).

3.1.4. Overview confounders

All variables which showed a significant correlation with SA were included as potential confounders in the analysis of the relationship between Ehor and SA (see Fig. 9). The general variables caused medium ($\tau = 0.30$) effects on the explanation of the total variance in SA. The effect of the environmental aspect relative humidity on SA was small ($\tau = 0.10$). The correlations between personal variables and SA were the strongest compared to the general and environmental variables. However, the correlations between personal variables and SA were still small to medium.
For all participants together, the correlation between Ehor and SA remained non-significant when all confounders were included in the analysis. For the determination of the partial correlations for the individual participants, the majority of personal variables identified as potential confounders were not used as confounder as they did not vary within subjects. The only personal confounder included in the calculation of the partial correlations was the self-reported sleep quality as this could have varied throughout the five experiment days. Table 1 shows the correlations when including none, one, or more groups of confounders.

3.3. Differences between groups with and without significant initial correlation between Ehor and SA

Differences were analysed between the two groups: group 1: the group of 40 participants in which no significant correlation was found between Ehor and SA and group 2: the group of 6 participants where this correlation (excluding confounders) was significant. SA in group 1 did not differ significantly from group 2 (U = 18274, z = -1.749, p = .08). The median SA was 3 in both groups; however, the mean in group 1 was slightly lower (3.46) compared to group 2 (3.89), which may suggest a slightly higher sleepiness in group 2. Ehor, by contrast, differed significantly between the two groups (U = 16166, z = -3.199, p = .001). The mean Ehor in group 1 was 981 lx whereas the mean Ehor in group 2 was 862 lx.

In addition to Ehor, the environmental parameter temperature differed significantly between both groups (U = 15274, z = -3.199, p = .001). The mean temperature for group 1 was 22.85 °C whereas the mean temperature for group 2 was slightly lower (22.69 °C). The third environmental parameter, relative humidity, did not differ significantly between both groups (U = 18222, z = -1.733, p = .083). The mean relative humidity for group 1 was 45.46% and for group 2 46.31%.

Group 2 included four male and two female participants, all aged between 25 and 44 years. They were working throughout the entire office building and their most performed task was ‘using the computer’. Four participants of these six used corrective lenses, mostly because of myopia. None suffered from colour vision problems, but one participant indicated an unspecified medical eye problem. No large differences were noticed between the groups for these categorical variables location of the office worker inside the office landscape, gender, age category, most performed task, job type, the use and reason of corrective lenses, colour vision problems, and medical eye problems. The number

3.2. Office lighting and subjective alertness

In section 3.1.2, a non-significant correlation was described between Ehor and SA (τ = .02, p = .526). Whereas this correlation was based on the data of all participants together, calculating correlations for each individual participant resulted in a group of six participants out of the total 46 for whom a significant correlation was found between Ehor and SA (see Fig. 10). Five of the six correlations were negative correlations indicating office workers being more alert when exposed to a higher Ehor. For one participant, a significant positive correlation was found. All negative correlations had a medium to large effect explaining the variance of SA and the effect regarding the positive correlation was medium (i.e., τ = -.59, τ = -.48, and τ = .42). For the calculation of these correlations the number of data points varied between 7 and 17 per participant.

Although Fig. 10 showed significant initial correlations between Ehor and SA, the correlations needed to be calculated including the confounding variables identified in section 3.1.4. Partial correlations were calculated by inserting the confounding variables for all participants together and for the six specific participants for whom a significant correlation was found between Ehor and SA excluding confounding variables.

Fig. 10. Graphs demonstrating the significant correlations between Ehor and SA for the 6 participants. A low number on the KSS scale indicates alertness and a high number indicates sleepiness. The blue dotted lines are SA (KSS evaluations) and the orange lines are the Ehor to which the participants were exposed to at the exact moment of filling in the KSS questionnaire. (For interpretation of the references to colour in this figure legend, the reader is referred to the Web version of this article.)
of work days during one week was significantly lower for group 2 (MEAN = 3.95) compared to group 1 (MEAN = 4.41) (U = 27800, z = −8.802, p < .001). In addition, the number of work hours for group 1 (MEAN = 7.58) differed significantly from group 2 (MEAN = 8.17) (U = 34600, z = −5.186, p < .001).

The self-reported sleep quality in group 1 (mean = 2.41) did not significantly differ from group 2 (mean = 2.64). Regarding the eight health category scores, no significant differences were reported between both groups for PF, RP, SF, and MH. Bodily Pain (U = 36600, z = −4.506, p < .001), General Health (U = 34200, z = −5.106, p < .001), Vitality (U = 38000, z = −3.715, p < .001), and Role Emotional (U = 39600, z = −4.954, p < .001) differed significantly between both groups. Table 2 provides the health category means and standard deviations for both groups.

4. Discussion

The current study investigated the ambiguities regarding the relationship between Ehor and SA, based on findings from a Dutch field study.

The first step in the analysis was to identify aspects significantly correlating with SA in order to include these later as potential confounders while investigating the relationship between Ehor and SA. Both investigated general variables (i.e., time and day), one environmental variable (i.e., relative humidity), and eight personal variables (i.e., gender, corrective lenses, working hours, self-reported sleep quality, VT, GH, SF, and MH) were found to significantly correlate with SA. The clothing value (clo) of the participants was not included and this may explain the absence of significance for the relation between air temperature and SA. All of the significant correlations were of small to medium size. This was in accordance with the hypothesis that all three types of variables (i.e., general, environmental, and personal) would influence SA and need to be included as confounder.

The second step was to investigate the relationship between Ehor and SA. Initial correlations (excluding confounders) were calculated and this showed a significant correlation between Ehor and SA for six participants out of the total 46. However, including the confounders as identified in the first step, removed all the significance for the relation between Ehor and SA. Including the general or environmental confounders led to some differences in significance levels whereas including the personal confounders led to no significant correlations at all anymore. This may indicate that personal variables had more influence on the SA compared to the effect Ehor had. These results are in contradiction to multiple lab studies demonstrating beneficial effects of light on SA [7,16,25]. This discrepancy may be explained by the amount, duration or timing of the light exposure or the absence of confounders. In the current study the estimated Ehor varied throughout the entire office building at minimum between 232 lx and 2157 lx over a day and at maximum between 219 lx and 4831 lx throughout a week. However some lab studies [7,16,25] used vertical illuminances, this Ehor range falls within their applied (corresponding) ranges of vertical illuminances (i.e., in Smolders et al. [7,25] 1000 lx versus 200 lx and in Maierova et al. [16] 1000 lx versus 5 lx). Ehor in the current study changed gradually over the day whereas in the mentioned lab studies the contrast between the bright and dim light condition was more noticeable. The International Commission of Illumination (CIE) highlighted that the dose-response relationship between light exposure and daytime effects on alertness is essential information to determine whether or not illuminance recommendations during the day are adequate to support NIF functions (e.g., human health) [22].

In this study, six out of the total 46 participants had significant initial correlation between Ehor and SA, excluding the confounders. However, when the confounders were included in the statistical analysis, the correlations for those six participants were no longer significant. It is of high importance to include all potential confounders while investigating the relationship between light and health. Multiple laboratory studies demonstrated effects of different lighting conditions on SA and human health [7,25,26]. The advantage of performing a lab experiment is that the researchers are able to control potential confounders (e.g., temperature, relative humidity, time and duration of the light exposure) and to change only the independent variable to be investigated. The benefit of performing a field study is that the results of tests in controlled environments (laboratory studies) can be validated in a real office environment and this leads to realistic results. The major challenge of field studies is to investigate a specific relationship in a constantly varying office environment. This field study showed a significant correlation between Ehor and SA which is a ‘response-to-light percentage’ of ± 13%. Similar results were found in another pilot field study performed in the Netherlands, i.e. for one out of the eleven participants (± 9%) a significant correlation (excluding confounders) was found between light and alertness level [27]. These percentages may indicate that not all individuals are equally sensitive to changes in the light environment.

The last step was to explore differences between the groups with and without a significant initial correlation between Ehor and SA. Remarkable was the significant lower Ehor in the group where a significant relation between Ehor and SA was found (i.e., group 2) compared to the other group (i.e. group 1). In addition, group 2 reported significantly less work days but more work hours per day compared to

Table 1
Kendall’s tau correlations between Ehor and SA including multiple control variables. Significance levels: * = p = .05, ** = p = .01, *** = p = .001, ns = not significant.

<table>
<thead>
<tr>
<th>Control variables</th>
<th>General (Day, time)</th>
<th>Environmental (RH)</th>
<th>Personal (self-reported sleep quality)</th>
<th>General + Environmental + Personal</th>
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Table 2
Means and standard deviations (X ± s) for the eight health category scores (i.e., PF, RP, BP, GH, VT, SF, RE, MH) for group 1 and group 2. Group 1 contains the 40 people without significant correlation between Ehor and SA whereas group 2 consists of 6 people with a significant correlation between Ehor and SA.

<table>
<thead>
<tr>
<th>SF-36 aspect</th>
<th>Group 1 (X ± s)</th>
<th>Group 2 (X ± s)</th>
</tr>
</thead>
<tbody>
<tr>
<td>PF</td>
<td>93.50 ± 16.37</td>
<td>93.33 ± 9.901</td>
</tr>
<tr>
<td>RP</td>
<td>89.38 ± 23.66</td>
<td>87.50 ± 28.07</td>
</tr>
<tr>
<td>BP</td>
<td>85.38 ± 19.80</td>
<td>77.00 ± 22.77</td>
</tr>
<tr>
<td>GH</td>
<td>78.70 ± 16.84</td>
<td>85.83 ± 11.82</td>
</tr>
<tr>
<td>VT</td>
<td>67.66 ± 20.02</td>
<td>64.58 ± 11.83</td>
</tr>
<tr>
<td>SF</td>
<td>91.88 ± 13.86</td>
<td>89.58 ± 18.34</td>
</tr>
<tr>
<td>RE</td>
<td>89.17 ± 26.25</td>
<td>100.0 ± 0.0</td>
</tr>
<tr>
<td>MH</td>
<td>81.13 ± 12.58</td>
<td>81.67 ± 6.90</td>
</tr>
</tbody>
</table>
group 1. More working hours per day may cause higher sleepiness (not a significant difference but group 2 showed a slightly higher sleepiness) and this may have increased the probability of responding to light. Regarding the personal health scores, there were significant differences between the two groups for BP, VT, GH, and RE. Notably, the BP and VT scores were significantly lower in group 2 compared to group 1, whereas the GH and RE scores were significantly higher in group 2 compared to group 1.

4.1. Limitations of the study

The relationship between light and health is often, as also done in this study, determined by measuring illuminance levels or correlated colour temperatures [17]. Illuminance levels are often reported in the forms of horizontally measured values at desk level or vertically measured at eye level. Lighting designs typically aim for recommended values for $E_{hor}$ as this parameter is included in standards [28]. In contrast, the amount and type of light entering human eyes is relevant since this light causes the light-related health effects. This amount is often expressed as the vertical illuminance measured at eye height. Khademagha et al. proposed a theoretical framework to integrate the non-visual effects of light (e.g., human health) into lighting designs [29]. They identified three luminous (spectrum, quantity, directionality) and three temporal (timing, duration, history) light factors to be relevant for triggering NIF effects. A limitation of the current study is that $E_{hor}$, as applied in this study, only covers the quantity light factor.

In addition, the non-obtrusive method (LBE) [11,12] was applied to estimate $E_{hor}$ at every participant’s workplace. This method consists of location-bound measurements (at workplaces) and does not include location changes and the corresponding light exposures (duration of light exposure and light history) for each office worker. Rea et al. [30] mentioned that duration of the light exposure is one of the aspects of lighting conditions which support the circadian system functions (e.g., human health) in addition to the visual system functions. In order to measure the light exposure per participant, the exact location and viewing direction of each participant is required in addition to continuous measurements throughout the entire office building (not only at the workplaces). Another method to measure individual’s light exposure is by using person-bound measurement devices. These devices, however, bring along practical and comfort issues [31] as well as certain measurement inaccuracies [32]. In order to be as unobtrusive as possible for the participants, the LBE method was applied in this study.

Finally, all health-related variables were subjectively measured. Individual’s sleep quality, functional health and wellbeing (SF-36), and alertness were all self-reported measured and may therefore deviate from objective health measures. Alertness, for example, was subjectively measured by including the KSS in the distributed questionnaires. The KSS was validated by a study of Kaida et al. [33] including sixteen female participants. The number of participants as well as the user characteristics may be questioned for correct validation. It is dubious how many participants are required to eliminate the potential disinterest of participants completing the questionnaire. In addition, it is uncertain how large a difference on the KSS needs to be in order to be relevant, for example, for human health or employee’s work performance. The potential relationship between lighting conditions and subjective alertness may be influenced by the circadian rhythm of subjective alertness as well. Regardless varying lighting conditions, subjective alertness was already proven to be influenced by time of the day [23]. This diurnal variation of subjective alertness was not included in this research.

4.2. Recommendations for further research

Based on limitations of this study, implications for theory and practice, several recommendations for further research were determined.

The differences between the groups with a significant initial correlation between $E_{hor}$ and SA may be questionable because of the limited sample size ($n = 40$ in group 1 and $n = 6$ in group 2). Further research needs to include more participants. A limitation potentially caused by this limited sample size is the absence of normality in the data. Therefore, the data analysis in this study was mostly performed based on correlation coefficients. The drawback of a correlation coefficient is that the direction of the correlation is uncertain. In this study, it is uncertain whether the health scores influenced participant’s SA or that SA influenced the health scores. Changes in lighting conditions may (indirectly via SA) have impacted human health. Aries et al. [34] also mentioned that physical conditions at work influence home life.

The small differences between the two groups may also be explained by the included (and excluded) variables (both environmental and personal). Further research should include light-dependent user characteristics such as light sensitivity, sensitivity to seasonal depressions, chronotype, sleep-wake rhythms, and activity patterns. Maierova et al. [28] found, for example, significant differences in SA between morning chronotypes and evening chronotypes. Although both chronotypes were more alert in the bright light condition compared to the dim light condition, these significant differences in SA may be of relevance while investigating the relationship between $E_{hor}$ and SA. In addition, the environmental physical aspects light, air temperature, and relative humidity were included in this study. Al Horr et al. discusses eight physical factors (i.e., indoor air quality and ventilation, thermal comfort, lighting and daylighting, noise and acoustics, office layout, biophilia and views, look and feel, and location and amenities) which affect occupant satisfaction and productivity in an office environment [35]. It is recommended to include these personal and environmental factors in further research investigating the relationship between light and alertness.

Adding the two above mentioned recommendations to further research may explain why certain individuals respond to light and why certain people do not.

5. Conclusions

This study investigated ambiguities regarding the relationship between $E_{hor}$ and SA based on findings from a Dutch field study. The results showed that multiple confounders (general, environmental, and personal variables) were identified suggesting they should be taken into account when investigating the relationship between office lighting and human health. In addition, the initial relationship (excluding confounders) between $E_{hor}$ and SA was established for six participants out of the total 46. Differences between the groups with and without the significant initial correlation between $E_{hor}$ and SA did not explain why certain individuals respond to changes in the light environment and others do not. The current study demonstrated discrepancies between this field study and previously executed laboratory studies. The benefit of performing a field study is that the results of tests in controlled environments (laboratory studies) can be validated in a real office environment and this leads to realistic results. This study highlights the importance of validating laboratory study results in field studies.

Further research should incorporate a larger sample size and additional potential confounders for the relationship between $E_{hor}$ and SA. Further research including these recommendations may explain individual variability in the response to light.

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References


[5] M. Aries, M. Aarts, J. van Hoof, Daylight and health: a review of the evidence and


ale in people during office hours; findings on subjective measures, task performance and heart rate measures, Physiol. Behav. 107 (2012) 7–16.


