Teasing apart office illumination

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Teasing apart office illumination: Isolating the effects of task illuminance on office workers

Short title: Teasing apart office illumination

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Task illuminance is one of the most used parameters in office lighting design and is often used as a 'single number criterion' to verify that a lighting design meets the requirements. Although other parameters, such as wall luminance, are often highly correlated with task illuminance, not taking these explicitly into account means critical user criteria such as comfort and satisfaction are left to chance. In this study, we investigated the effect of varying desk illuminance (150 to 1500 lx) while keeping wall luminance constant, isolating the effects of illuminance on the desk and eye on office users' overall perception of the space, their mental state and their performance (visual and cognitive). While both visual acuity (paper-based) and perceived brightness increased significantly with higher desk illuminance, the room's attractiveness did not. Even though illuminance at the eye increased considerably with desk illuminance (from 118 lx to 796 lx), only minor effects were found on subjective alertness and cognitive performance. This suggests that focusing on horizontal task illuminance as a design parameter is appropriate in view of visual acuity but has little to no effect on the space's attractiveness, nor on cognitive performance or mental state of the office worker.

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1. Introduction

While lighting design ideally should focus on creating an environment that satisfies relevant user needs, in practice, lighting installations are quite often specified to simply meet a given set of (numerical) requirements without assessing the impact on the actual user. This practice, sometimes referred to as 'compliance chasing', is characterized by a pass-or-fail approach where the absolute value that results from the calculations is leading (e.g., if the requirement states an average horizontal illuminance of 500 lx is needed, an average of 499 lx would fail the requirement, whereas an average of exactly 500 lx would result in a 'pass'). With this focus on single numeric values, and the traditional focus on the illuminance at the horizontal task surface, many offices today are designed to meet only the required average horizontal illuminance assigned to the space based on the primary task.

These lighting requirements usually do originate from standards or norms that have the user in mind. However, the nuances and additional requirements that these standards also provide (e.g., uniformities, ratios between the different surfaces, wall, ceiling or cylindrical illuminance requirements) are often ignored, despite the fact that several studies have shown that these other parameters too have a clear impact on the appraisal of spaces and the user satisfaction in office environments.[1–3] The luminous environment, which is an often recurring topic in literature, has been shown to affect user satisfaction via, for example, wall luminance and room brightness.[4–7] Although these parameters are part of the latest versions of leading workplace lighting standards such as the EN12464-1:2011[8] and the IES RP1-12[9], adoption has been slow[10], and they often are not listed in the design requirements in, for instance, tender documents, which tend to focus on horizontal (task) illuminance requirements only.

The result of a single-requirement design approach is that the overall resulting luminous environment is merely the by-product of the luminaire choice, which is selected mainly to reach the required horizontal illuminance. For example, a more narrow beam tends to result in a higher horizontal illuminance and as such would be perceived as a more economical and sustainable solution (i.e., lower cost and lower energy consumption to reach the same horizontal illuminance). However, the beam shape and width of a luminaire also have a large impact on the illuminance on vertical surfaces such as walls. Choosing a more narrow luminaire often results in lower vertical illuminance which, in turn, is a key component in perceived room brightness.[4] This is further amplified by the introduction of LED light sources, which allow for much more tailored beams. In principle, this opens up many opportunities to improve luminaires for optimal satisfaction of user needs, but also allows luminaires to be optimized for compliance chasing, which can easily result in dark spaces as most of the luminaires' output is utilized to comply with the horizontal illuminance requirements, not to optimize the luminous environment as a whole.

One of the consequences of the impact of the luminaire beam shape on the luminous environment is that causal relationships in studies in which only the horizontal illuminance as the independent variable is reported are quite difficult to interpret, particularly considering the different mechanisms via which lighting can affect the user's performance and well-being. For example, increased user satisfaction with higher horizontal illuminance can be the result of increased visual performance, as a higher illuminance on the task results in a higher visual acuity through improved contrast.[11–13] In addition, an increased horizontal illuminance quite often goes hand in hand with an increased illuminance on vertical surfaces and/or ceiling (depending on beam shape), potentially resulting in an increase in spatial brightness, which may lead to heightened room appraisal.[4,6,7,14] Moreover, with the increase in horizontal illuminance, illuminance on the eyes tends to increase as well, resulting in a stronger stimulus for the ipRGC's in the eyes.[15–17] This, in turn, has potential effects on (subjective) alertness, mood or task performance and may thereby lead to a higher user satisfaction.[18,19]

Given the complexity of the relationship between the luminous environment and the user response, a set of explorative experiments was designed to gain more insight into how different aspects of the luminous environment influence the office worker. The studies focused on separating the effects of the illuminance of the walls and that of the task surface, as they are often confounded in office lighting studies.[2,18,20] In the first experiment, reported elsewhere[21], wall illuminance was varied while keeping illuminance at the desk and the eye constant. It demonstrated a sustaining effect on subjective alertness when using a higher wall luminance.

The experiment described here investigated the effect of different levels of desk illuminance and, with it, vertical illuminance at eye position, while keeping wall luminance constant. A key aspect of both experiments was to employ a broad set of dependent variables, covering room appraisal, well-being and performance on a range of visual and cognitive tasks, to be able to identify possible effects covering both visual and non-visual effects.

Based on the aforementioned literature, our hypotheses were that an increase in horizontal desk illuminance would lead to improved visual acuity, as illumination of the visual task improved, and to increased alertness due to an increased illuminance on the eye inducing non-visual effects. In contrast, no effect on room appraisal was expected due to the constant wall luminance.

2. Method

2.1. Participants

Forty-eight individuals were recruited to take part in this experiment. Recruitment took place via an external agency who compensated the participants for their time, effort and travel cost in the form of a modest monetary reward. The study was conducted in accordance with the Helsinki declaration and approved by the internal ethics board. Participants were selected based on the following inclusion criteria: normal or corrected to normal vision, native Dutch-speaking, experience with office work, normal colour vision (which was tested during the experiment using the Ishihara colour vision test, concise edition).

The data from twelve participants were excluded from the analysis because they missed one or more of the scheduled sessions. The remaining 36 participants consisted of 19 female and 17 male participants between 18 and 36 years of age (mean age: 25.3, SD: 4.9) of which 10 evening types, 25 intermediate types and one morning type (see 2.4.1).

2.2. Settings

A space of 7.2 x 7.2 x 3.0 m (length x width x height) was furnished to resemble an open plan office setting using standard desks, chairs, dividers and storage cabinets in a symmetrical setup (see Figure 1). Daylight contribution was excluded using opaque screens. The walls were painted in a neutral white colour (reflection coefficient 90%). Four workstations were grouped in the centre of the space

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with the participants facing the opposing walls. A 40 cm high divider separated the participants sitting opposite each other. Each workstation was outfitted with a 22" display, keyboard and mouse to facilitate the questionnaires and cognitive tasks.

Whereas the space and interior were similar to the one as used in de Vries et al.[21], the lighting installation consisting of six standard 600 x 600 mm, low glare LED-based luminaires (type A in Figure 1; Philips PowerBalance, 3400lm, 4000K, $R_a > 80$, UGR < 16) was complemented by another 6 identical luminaires (marked with a '+' in Figure 1) to increase the upper limit of possible task illuminance levels to > 1500 lx on the desks. Uniformity on the desk with this new installation was estimated using Dialux simulation to be over 0.80 (the requirement for uniformity according to EN12464-1:2011 is $U_o \geq 0.60$). The 2x5 spots as used on either wall were left unchanged compared to the first experiment[21] (type B in Figure 1, Philips StyliD, 2700lm, 4000K, $R_a > 80$).

[Insert fig 1a and 1b]

Using this lighting installation, three levels of desk illuminance were set using a calibrated illuminance meter (Konica Minolta CL200) while keeping the wall luminance the same by correcting the output of the spots (measured using a calibrated LMK Color 5 luminance camera).

An overview of the room's lighting characteristics can be found in Table 1. Desk illuminance was manipulated at three levels: 150, 500 and 1500 lx. The 500 lx setting was identical to that in our first experiment[21] to allow for comparison of the results. With these settings, the vertical illuminance on the eyes increased from an average of 118 lx in the low desk illuminance condition to 292 lx in the medium desk illuminance condition and 795 lx in the high desk illuminance condition. This translates in a Melanopic Equivalent Daylight Illuminance (Melanopic EDI) of respectively 66, 163 and 442 lx according to CIE S026.[22]

The fixed wall luminance was selected based on limiting the ratios between desk and wall luminance to prevent extreme contrasts influencing the overall room appraisal. Based on this, the high wall luminance setting (72 cd/m^2) of the previous experiment was chosen as this resulted in the least extreme contrast differences between desk and walls in the three desk illuminance levels. The resulting luminance ratios using a wall luminance of 72 cd/m2 ranged from 0.4 for the low desk illuminance to 3.8 for the high desk luminance.

2.3. Experimental design

This study employed a within-subjects design using three levels of desk illuminance (approximately 150, 500 and 1500 lx – see Table 1 for more details). Per session one Desk Illuminance level was presented, every session taking place on a separate day with one week between sessions. Sessions always took place at the same time of day (15:00 – 16:30). Participants were invited in groups; Each group had a fixed composition and was assigned to a specific day of the week. The total test period

was divided into three blocks of three weeks (5 groups in the first block, 5 groups in the second block and, due to several absent participants in the first two blocks, another 2 groups in a third block). The order of the conditions was randomized over the groups for the original 10 groups. For the additional 2 groups, condition orders were selected to ensure a completely balanced design. As several dependent variables were measured at two time points per session, time of measurement was nested in each session as a second within-subject factor.

2.4. Measures

A combination of self-report scales, objective performance measures and appraisal questionnaires was used to analyse the impact of desk illuminance. All questionnaires were administered using the workstations (display, keyboard, mouse) whereas the performance tasks were either fully on paper (Visual acuity), a combination of paper and screen (Alternate uses task, Remote Associates task) or fully on the screen (Stroop task, Navon task, on-screen visual performance task). All screen-based elements were presented as white text (Arial font) on a light grey background to prevent high exposure by the screen (see Table 1; display luminance, $L_{display}$, was measured using this background with a single, representative question presented in white text).

2.4.1. Self-report scales

The following self-report scales were administered:

- *Chronotype* was evaluated using the Morningness-Eveningness Questionnaire (MEQ[23], modified to fit modern-day language[24]). Note that this variable was tested each session for protocol consistency. No significant differences emerged between Desk Illuminance levels.

- *Emotional state* was assessed using the pleasure-arousal-dominance emotional state model (PAD [25]), which was administered using 6 semantic differentials per dimension measured on 7-point scales (1 indicating low pleasure/arousal/dominance, 7 indicating high pleasure/arousal/dominance.

- *Subjective alertness* was measured using the Karolinska Sleepiness Scale (KSS[26]) with scores ranging from "1: extremely alert' to "9: extremely sleepy – fighting sleep".

- *Room appraisal* was assessed using a modified version of the room appearance scale developed by Veitch and Newsham[27] using a set of 8 semantic differentials (measured on a visual analog scale of 0-1). The semantic differentials are Unattractive – Attractive, Ugly – Beautiful, Unpleasant – Pleasant, Dislike – Like, Sombre – Cheerful, Vague – Distinct, Gloomy – Radiant and Dim – Bright. The original questionnaire used only two dimensions: Attractiveness (based on the first five pairs) and Illumination (based on the last three). However, upon analysis of the consistency of the items within these two dimensions, we found that the Dim – Bright scale showed a different behaviour compared to the other two items in the Illumination dimension and as such this item was analysed separately (improving Cronbach's alpha for the remaining

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two items from 0.5 to 0.77). We refer to the scale with the latter two pairs as Distinctiveness/Radiance. This change will be further discussed in the discussion section.

- *Ego depletion* was measured using the State Self-control Capacity Scale (ED[28]), which was added as a control variable to monitor possible exhaustive effects of the performance tasks. The possible total score ranged from 25 (low ego depletion) to 175 (high ego depletion).

2.4.2. Objective task performance

The following performance measures were employed:

- *Visual acuity on paper* was measured using a modified Landolt-C test consisting of a single A4 paper panel with rows of optotypes, decreasing in size per row (gap size ranging from 1.73 to 0.42 arc minutes). Visual acuity was estimated based on the last line of optotype sizes for which the orientation could still be accurately identified for all 8 optotypes. No chin rest was used, the panel was roughly 70 cm from the eyes of the participant. Participants were instructed to sit still and not to lean towards the panel. Participants used glasses for the visual acuity task if they habitually wore those during everyday life.

- *Visual acuity on screen* was measured using a tumbling-E test adapted for screen use (at approximately 60 cm distance from the participant). The optotype sizes were defined in number of screen pixels (to accurately display the optotype) in 5, 10, and 15 pixels height and width resulting in gap sizes (i.e., distances between lines) from 1.62 to 6.48 arc minutes. Additionally, the optotypes were shown in several different opacity values (5, 10, 25, 50, 100%), to increase the difficulty of the task (Michelson contrast ranging from 0.10 for the 5% opacity to 0.89 for the 100% opacity setting). Reaction time and error rate were recorded.

- *Divergent thinking performance* was measured using the Alternate Uses Task (AUT[29,30]) which asks participants to write down as many (realistic) uses of two provided household items as possible in a time span of 5 minutes. Scoring is based on the 'flexibility' of the participant which is represented by the number of different classes of answers the participant comes up with. Scoring was performed by the first author and an independent rater who was blind to the experimental condition. Inter-rater reliability was tested using the intra-class correlation coefficient (ICC). Based on a two-way model testing for consistency, an ICC of .747 was found which, according to the guidelines by Cicchetti, on the border between 'good' and 'excellent'.[31]

- *Convergent thinking performance* was measured using the Dutch version of the Remote Associates Task (RAT[32,33]) which presents participants with 10 word-problems where each problem consists of a set of 3 words to which a fourth word, associated with the first three needs to be found. The total number of correct answers in a time span of 5 minutes was recorded.

- *Digital Stroop task* was employed as one of the more classical cognitive performance tasks. The Stroop task consists of congruent (25%) and non-congruent (75%) stimuli where

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participants are asked to indicate the presented font colour of colour names as quickly as possible (no time limit). Response times (RT) are reported. Response times below 200 ms or above 2500 ms were considered as artefacts and excluded from the analysis. Median RTs were calculated and then transformed using a reciprocal transformation to improve normality.

- *Global Local task* was used to determine whether the participants were in a more global or local processing mode. This was measured using a nested letter identification task (Navon task[34]). In this task, a large character (either S or H) is displayed consisting of small characters (either S or H). The participants are asked to identify the small characters by pressing the corresponding key. Response times (RT) are reported. Response times below 200ms or above 2500 ms were considered as artefacts and excluded from the analysis. Median RTs were calculated and then transformed using a reciprocal transformation to improve normality.

2.5. Procedure

Within each group, each participant was assigned to a specific desk to ensure consistency between conditions. Upon entry, the participants were given brief instructions (both in written and verbal form) followed by the colour blindness test and a paper-based visual acuity task before starting the session procedure as depicted in Figure 2. With the exception of the visual acuity task (for which participants were instructed to keep a static position/posture), participants were given no further instructions concerning their posture. The procedure was programmed to run automatically using the Psychopy software package developed at the University of Nottingham.[35]

Participants started with a set of questionnaires to determine chronotype (MEQ) and to establish a baseline for emotional state (PAD1) and subjective alertness (KSS1). This was followed by the three cognitive tasks (alternate uses task, Remote Associates Task, Stroop task), each repeated twice (two blocks). The first block of trials was intended to mitigate learning effects, the second one intended for data analysis. The Alternate Uses Task (AUT) and Remote Associates Task (RAT) each consisted of 2 blocks of 5 minutes, whereas the Stroop task (ST) consisted of 1 block of 80 trials, followed by a second block of 112 trials. The three tasks were separated by the room appraisal questionnaire (RA1) between the AUT and RAT and the ego depletion questionnaire (ED) between the RAT and Stroop task. After the third cognitive task, the questionnaires administered at the start of the session were administered again to determine the effects of Desk Illuminance on emotional state (PAD2), subjective alertness (KSS2) and room appraisal (RA2). Last, the Global Local task (GL) and on-screen visual acuity tasks (VA-Sc) were performed. The total procedure took about 90 min.

[Insert fig. 2]

2.6. Statistical analysis

Statistical analyses were performed using the software package R (version 3.5.3[36]). Due to the presence of the nested factor (time) regular repeated-measures ANOVA analyses were not feasible. As

such, Linear mixed models (LMMs) were employed to analyse the main effects using the *lme4* package.[37] All p-values derived from the LMMs were based on Satterthwaite approximation for degrees of freedom using the *lmerTest* package[38] (significance level set at $p < 0.05$). For the parameters which were measured multiple times per session, time was nested in the model under Desk Illuminance. In all cases, the repeated measures aspect was taken into account by including participant ID as a random variable. Post hoc analysis was performed on the LMM models using the *emmeans* package[39] employing Tukey corrections for multiple comparisons and Satterthwaite approximation for degrees of freedom. Finally, the *irr* package[40] was used to determine the intraclass correlation coefficient (ICC).

3. Results

3.1. Room appraisal – attractiveness, distinctiveness/radiance, brightness

As mentioned in 2.4.1, we analysed the room appraisal ratings in three dimensions: attractiveness, distinctiveness/radiance and brightness. Figure 3 shows the participants' ratings in the three Desk Illuminance conditions (see Table 2 for details). LMM analyses were performed for all three dimensions separately, with Desk Illuminance, Time and their interaction as factors. The results showed a significant effect of Desk illuminance on brightness ($F (1,70) = 30.07$, $p < 0.001$), but not on the attractiveness or the distinctiveness/radiance dimensions (respectively $p = 0.54$ and $p = 0.09$). Post hoc analyses showed that both the medium and high Desk Illuminance conditions were considered significantly brighter compared to the low Desk Illuminance condition (respectively $\Delta = 0.19$, $SE = 0.04$, $p < 0.001$ and $\Delta = 0.28$, $SE = 0.04$, $p < 0.001$). The increase in brightness between medium and high Desk Illuminance conditions was near significant ($\Delta = 0.09$, $SE = 0.04$, $p = 0.06$).

The effect of Time was significant for both attractiveness ($F (1,105) = 9.19$, $p < 0.01$) and brightness ($F (1,105) = 7.73$, $p < 0.01$) – both showed a slight decline over time – but not for the distinctiveness/radiance dimension ($p = 0.11$). There were no interactions between Desk Illuminance and Time on attractiveness, distinctiveness/radiance or brightness (respectively $p = 0.51$, $p = 0.77$, $p = 0.42$).

[insert fig. 3]

3.2. Emotional state – PAD

LMM analyses were performed for each of the three dimensions of the emotional state questionnaire (pleasure, arousal, dominance, see Table 3 for details). For all three dimensions, Desk Illuminance, Time and their interaction were used as predictors. Desk Illuminance did not have a significant effect on any of the dimensions. However, a significant effect of Time was found was for pleasure ($F(1, 105) = 44.13$, $p < 0.001$) and dominance ($F(1, 105) = 20.80$, $p < 0.001$), in both cases reflecting lower ratings at the second measurement.

3.3. Subjective alertness – KSS

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For subjective alertness, an LMM was set up using Desk Illuminance, Time and their interaction (see Figure 4 and Table 4 for details). This model revealed that there was a significant effect of Time ($F(1, 105) = 7.35$, $p < 0.01$), but not of Desk Illuminance or their interaction. To further investigate how subjective sleepiness changed over time, the effect of time was analysed per Desk Illuminance condition using post-hoc testing. The analysis showed that a significant decrease in subjective alertness (increase in sleepiness) during the session only occurred in the low Desk Illuminance condition ($\Delta = 0.50$, $SE = 0.24$, $p = 0.042$) but not in the medium and high conditions (medium: $\Delta = 0.39$, $SE = 0.24$, $p = 0.11$; high: $\Delta = 0.25$, $SE = 0.24$, $p = 0.31$).

[Insert fig. 4]

3.4. Ego depletion – ED

Ego depletion was investigated as a function of Desk Illuminance using LMM, (see Table 4 for details). The results showed no significant effects of Desk Illuminance ($F(2, 70) = 1.11$, $p = 0.33$).

3.5. Cognitive performance tasks – AUT, RAT, Stroop, Navon

For the Alternate Uses Task (AUT), flexibility was analysed as a function of Desk Illuminance. However, no significant effects were found (see Table 5 for means and SD values). Also, for the Remote Associates Task (RAT) the same model was employed with the same result: no significant effects of the Desk Illuminance. For the Stroop and Navon task, the outcome was analysed based on the congruent and non-congruent inverted response times, the difference between these two parameters and the total number of errors. However, in none of the cases did Desk Illuminance have a significant effect.

3.6. Visual acuity tasks

Visual acuity was tested both on paper (Landolt C) and on the computer display (tumbling E). For the paper-based task an LMM analysis was conducted to analyse the effects of Desk Illuminance. This showed a significant effect on visual acuity ($F(2,70) = 13.18$, $p < 0.001$). Post-hoc analyses indicated that visual acuity significantly improved between the low and medium Desk Illuminance conditions ($\Delta = -0.10$, $SE = 0.038$, $p = 0.023$), medium and high conditions ($\Delta = -0.09$, $SE = 0.038$, $p < 0.046$) and low and high conditions ($\Delta = -0.19$, $SE = 0.038$, $p < 0.001$).

The LMM analysis on response speed (inverted response time) for screen-based visual acuity with Desk Illuminance, Size (of the optotype), and Opacity (of the optotype) as fixed factors indicated no effect of Desk Illuminance condition ($F(2,385) = 0.04$, $p = 0.96$. The test characteristics (Size and Opacity of the optotypes and their interaction) did impact the response speed, but the statistical results for these factors are not reported in detail as they are not relevant for the study goal.

4. Discussion

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We tested the impact of increased desk illuminance in a simulated office setting on visual performance, room appraisal, subjective ratings of alertness, ego depletion, emotional state, and on cognitive performance. Along with desk illuminance, the illuminance at the eye also increased substantially, as it would normally, due to the use of luminaires for general illumination and reflectance of the task area. Wall luminance, however, was kept constant in order to prevent the effects of higher illuminance on the desk and on the eye from being confounded with the effects of room appearance and/or brightness. As expected, increased desk illuminance resulted in improved visual acuity on the paper-based task. However, the remaining objective performance measures and the subjective scales related to performance (i.e., subjective alertness and ego depletion) showed only minimal, if any, effects of the lighting condition. Additionally, while the overall brightness perception of the space did increase with desk illuminance, neither the attractiveness and distinctiveness/radiance dimensions of room appraisal nor the emotional state did show any effects of the lighting condition.

Our starting hypothesis was that, given the almost seven-fold increase of vertical illumination on the eye, the KSS scores would significantly decrease from the low to the high desk illuminance condition. Although such an effect has been reported in several studies, there is also a large body of research which failed to find alerting effects of higher illumination levels (see Lok et al.,[41]; Souman et al.,[19] for overviews of both positive and negative findings). In the current study, no significant differences in subjective alertness could be established across the employed range of desk illuminance. This was the case despite the fact that our sample was considerably larger than that of most of the studies described in the reviews by Lok et al.[41] and Souman et al.[19] and despite the tenfold increase in desk illuminance (two methodological issues that were noted in these reviews to explain the inconsistent findings in the literature).

In our first study[21], which focused on the effects of wall luminance on the appearance of the space, we found that increasing the wall luminance (with only minimal changes in the illuminance on desk and eyes) resulted in a sustaining effect on subjective alertness. In contrast, subjective alertness was not maintained when wall luminance was too low, with a desk illuminance of 500 lx. This prompted us to investigate, in the current study, the effect of changing desk and eye illuminance on these time-dependent effects, with a constant wall luminance. No significant difference in subjective alertness was observed for the medium and high desk illuminances, whereas the low desk illuminance condition resulted in a minor decrease in subjective alertness over time. In other words, subjective alertness was not maintained when desk illuminance was too low, but wall luminance was still high. We should note, however, that this effect was very subtle and not reflected in a significant interaction effect.

It should be noted that in our setup, the luminaires that illuminated the desks, and that also were the main contributors to the vertical illuminance measured at eye height, were placed directly over the participants. As such, it is possible that vertical illuminance (measured using standard methods, as an

unobstructed measurement of a hemisphere) does not accurately portray the actual illuminance on the eye. Moreover, the spatial distribution of the ipRGC's in the retina is still under discussion (see CIE S 026 for a summary[22]), where current thinking is that some areas in the retina may be more relevant than others. Hence, the vertical illuminance measurement as reported in this study may not be an entirely accurate quantification of the stimulus to the non-visual pathway.

As reported above, we found that our desk illuminance manipulation only affected one item on the original brightness dimension of the room appraisal questionnaire. Scores on the brightness item did not correlate highly with the other two items, distinctiveness and radiance. These items did not show significant effects of desk illuminance, nor did the other items, which probed attractiveness of the room. In our previous study, we found that wall luminance did affect both brightness (including distinctiveness and radiance) and attractiveness. This latter result matches the results of van Ooyen *et al.*[4] and Loe *et al.*[14], who found that vertical surfaces and/or surfaces which are more dominant in the field of view (as in our first study[21]) have a higher effect on preference and appraisal than the horizontal task surface.

We did not find effects of desk illuminance on any of the cognitive performance tasks. This matches our results in the first experiment, which investigated wall luminance[21], but also numerous studies on effects of increased retinal illuminance (see Lok *et al.*,[41]; Souman *et al.*,[19]), and corroborates our suspicion that, in the current experiment, increased task illuminance and illuminance at the eye did not enhance cognitive functioning. We should note that, in our study, participants were only exposed to the lighting conditions for 1.5 hours. Hence, we cannot exclude the possibility that (stronger) effects on subjective alertness and cognitive performance may still emerge after longer exposure durations.

In conclusion, the results of our current study demonstrate very few, if any, additional beneficial effects of raising illuminance at the desk. Although this metric may accurately represent needs from a visual acuity perspective, it appears to be unsuitable as a predictor for room appraisal, as we failed to find effects on attractiveness. Moreover, despite a substantial increase in illuminance on the eye, we did not find effects on cognitive performance. These results indicate that focusing only on horizontal task illuminance as the single design parameter could lead to unattractive spaces due to low luminance on walls, which in turn may result in lower attractiveness as shown in de Vries *et al.*[21], with little to no benefits for alertness, cognitive performance or well-being of the office worker. A more comprehensive approach of office lighting design, taking all different aspects of the luminous environment into account, is needed. Or, as Peter Boyce recently put it in an editorial, "This approach requires a complete redrafting of lighting recommendations involving new metrics and the abolition of the horizontal working plane".[42]

Conflicts of interest

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List of figure captions:

Figure 1   Layout and impression of the experimental setup – Luminaire type A: General lighting luminaires, '+' indicates the added luminaires of the same type compared to de Vries et al. [21]. Luminaire type B: Spots.

Figure 2   Session procedure overview.

Figure 3   Effects of Desk Illuminance and Time of measurement on three dimensions of Room appraisal (EMM), · $p < 0.1$, *** $p < 0.001$, significant effects of time not displayed in plot due to absence of interactions with light conditions (see 3.1), whiskers represent the 95% confidence interval of the mean.

Figure 4   Effects of Desk Illuminance and Time of measurement on KSS (EMM). * $p < 0.05$, whiskers represent the 95% confidence interval of the mean.

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Table 1   Lighting conditions for each level of Desk Illuminance, mean (and SD) of 4 desks (one measurement per desk) or over the defined surface (e.g. the wall).

Desk illuminance level		Low		Medium		High		Ref [5]
		Mean	(SD)	Mean	(SD)	Mean	(SD)	Mean
L_{desk}	cd/m2	29.9	(0.7)	101.2	(2.8)	308.7	(9.0)	98.0
E_{desk}	lx	158	(0.8)	527	(8.2)	1596	(22.4)	538
$E_{v,eye}$	lx	118.0	(1.6)	291.8	(4.1)	796.3	(13.1)	254
$E_{landoltC}$	lx	156.3	(1.9)	413.3	(4.6)	1160.5	(11.8)	
$L_{wall,ref}$ [1]	cd/m2	76.1	(1.6)	76.9	(1.5)	82.2	(1.3)	72.0
L_{wall} [2]	cd/m2	95.3	(1.2)	94.7	(0.9)	96.8	(0.6)	
$L_{ceiling}$ [3]	cd/m2	21.9	(0.1)	35.9	(0.6)	77.0	(1.7)	36.0
$L_{divider}$	cd/m2	10.7	(0.4)	21.2	(1.3)	52.2	(4.2)	26.0
$L_{display}$ [4]	cd/m2	78.2	(3.2)	78.2	(2.9)	80.7	(3.0)	72.0
$L_{40° band}$	cd/m2	38.7	(0.5)	46.8	(0.8)	71.7	(2.4)	50.0
LMM_{wall}	--	2.61	(0.07)	2.23	(0.08)	1.95	(0.06)	1.83

[1] Wall definition as used in de Vries *et al.* 2018 – area includes section of side walls

[2] Only backwall

[3] Visible part of the ceiling, excluding luminaires

[4] Display set to a representative setting in the experiment (see 2.4)

[5] Reference values from the '500 lx, high wall luminance' condition from de Vries *et al.*[21]

Abbreviations: Desk luminance (L_{desk}), Desk illuminance (E_{desk}), Vertical illuminance on the eye in viewing direction ($E_{v,eye}$), Landolt C card illuminance ($E_{landoltC}$), Wall luminance as defined in de Vries *et al.*[21] ($L_{wall,ref}$), Wall luminance of visible wall section (L_{wall}), Ceiling luminance ($L_{ceiling}$), Divider luminance ($L_{divider}$), Display luminance($L_{display}$), Luminance of the 40° band ($L_{40° band}$), Logarithm of ratio maximum to minimum luminance (LMM wall)

Table 2   Room Appraisal data overview & Cronbach's alpha

Desk Illuminance		Low			Medium			High			Cronbach's
Dimension	Time	EMM	SE*	95% CI	EMM	SE*	95% CI	EMM	SE*	95% CI	alpha
Attractiveness	Start	0.49	0.031	[0.43, 0.55]	0.47	0.031	[0.41, 0.53]	0.51	0,031	[0.45, 0.57]	0.90
	End	0.47	0.031	[0.41, 0.53]	0.46	0.031	[0.40, 0.52]	0.48	0,031	[0.42, 0.55]	0.92
Distinctiveness/ Radiance	Start	0.42	0.035	[0.35, 0.49]	0.43	0.035	[0.36, 0.50]	0.49	0,035	[0.42, 0.56]	0.77
	End	0.41	0.035	[0.34, 0.48]	0.41	0.035	[0.34, 0.48]	0.46	0,035	[0.39, 0.53]	0.82
Brightness	Start	0.54	0.032	[0.48, 0.61]	0.73	0.032	[0.66, 0.79]	0.83	0,032	[0.76, 0.89]	--
	End	0.51	0.032	[0.45, 0.57]	0.72	0.032	[0.65, 0.78]	0.79	0,032	[0.72, 0.85]	--

*SE of full model

Table 3 Emotional state data overview & Cronbach's alpha

Desk Illuminance		Low			Medium			High			Cronbach's
Dimension	Time	EMM	SE*	95% CI	EMM	SE*	95% CI	EMM	SE*	95% CI	alpha
Pleasure	Start	5.51	0.135	[5.25, 5.78]	5.45	0.135	[5.19, 5.72]	5.31	0.135	[5.04, 5.58]	0.8
	End	5.04	0.135	[4.77, 5.31]	4.97	0.135	[4.70, 5.24]	4.91	0.135	[4.64, 5.18]	0.88
Arousal	Start	3.92	0.114	[3.69, 4.14]	3.84	0.114	[3.61, 4.06]	3.95	0.114	[3.73, 4.18]	0.47
	End	3.76	0.114	[3.54, 3.99]	3.96	0.114	[3.74, 4.19]	4.04	0.114	[3.81, 4.26]	0.58
Dominance	Start	4.81	0.128	[4.55, 5.06]	4.70	0.128	[4.45, 4.96]	4.81	0.128	[4.56, 5.06]	0.74
	End	4.59	0.128	[4.34, 4.85]	4.47	0.128	[4.22, 4.73]	4.44	0.128	[4.18, 4.69]	0.77

*SE of full model

Table 4 Subjective alertness & Ego depletion data overview & Cronbach's alpha

Desk Illuminance		Low			Medium			High			Cronbach's alpha
Parameter	Time	EMM	SE*	95% CI	EMM	SE*	95% CI	EMM	SE*	95% CI	
Subjective alertness	Start	3.50	0.303	[2.90, 4.10]	3.86	0.303	[3.26, 4.46]	3.58	0.303	[2.98, 4.18]	--
	End	4.00	0.303	[3.40, 4.60]	4.25	0.303	[3.65, 4.85]	3.83	0.303	[3.23, 4.43]	--
Ego depletion	--	75.3	3.75	[67.8, 82.8]	70	3.75	[62.5, 77.5]	70.4	3.75	[62.9, 77.8]	0.94

*SE of full model

Table 5 Cognitive performance tasks data overview (RT = response time, in seconds)

Desk Illuminance		Low			Medium			High		
Task	Parameter	EMM	SE*	95% CI	EMM	SE*	95% CI	EMM	SE*	95% CI
Alternate Uses Task	Flexibility	5.94	0.551	[4.84, 7.05]	6.08	0.551	[4.98, 7.19]	6.21	0.551	[5.10, 7.32]
Remote Associates Task	RAT	4.08	0.343	[4.40, 4.76]	4.03	0.343	[3.35, 4.71]	4.56	0.343	[3.88, 5.24]
Stroop task	Congruent RT	0.79	0.025	[0.75, 0.84]	0.81	0.025	[0.76, 0.86]	0.82	0.025	[0.77, 0.87]
(RT's in seconds)	Non-congruent RT	0.90	0.025	[0.85, 0.95]	0.91	0.025	[0.86, 0.95]	0.91	0.025	[0.86, 0.96]
	RT Delta	0.11	0.013	[0.08, 0.13]	0.10	0.013	[0.07, 0.12]	0.80	0.013	[0.06, 0.11]
	Total errors	2.19	0.351	[1.50, 2.89]	1.86	0.351	[1.16, 2.56]	2.56	0.351	[1.86, 3.25]
Navon task	Congruent RT	0.58	0.013	[0.56, 0.61]	0.59	0.013	[0.57, 0.62]	0.59	0.013	[0.57, 0.62]
(RT's in seconds)	Non-congruent RT	0.66	0.017	[0.63, 0.70]	0.66	0.017	[0.62, 0.69]	0.67	0.017	[0.63, 0.70]
	RT Delta	0.08	0.009	[0.06, 0.10]	0.06	0.009	[0.05, 0.08]	0.07	0.009	[0.06, 0.09]
	Total errors	4.19	0.68	[0.285, 5.54]	3.44	0.68	[2.10, 4.79]	3.97	0.68	[2.63, 5.32]

*SE of full model

Supplementary material – Full result table, Linear Mixed Models

		df	*F*	*p*
Room appraisal - Attractiveness	Desk Illuminance Time Desk Illuminance * Time	(2, 70) (1, 105) (2, 105)	0.61 9.19 0.68	0.548 0.003 0.509
Room appraisal - Distinctiveness/Radiance	Desk Illuminance Time Desk Illuminance * Time	(2, 70) (1, 105) (2, 105)	2.45 2.55 0.26	0.093 0.112 0.771
Room appraisal - Brightness	Desk Illuminance Time Desk Illuminance * Time	(2, 70) (1, 105) (2, 105)	30.07 7.73 0.87	3.75E-10 0.006 0.424
Emotional state - Pleasure	Desk Illuminance Time Desk Illuminance * Time	(2, 70) (1, 105) (2, 105)	1.03 44.13 0.13	0.361 1.39E-09 0.876
Emotional state - Arousal	Desk Illuminance Time Desk Illuminance * Time	(2, 70) (1, 105) (2, 105)	0.75 0.09 2.00	0.476 0.762 0.140
Emotional state - Dominance	Desk Illuminance Time Desk Illuminance * Time	(2, 70) (1, 105) (2, 105)	0.78 20.80 0.73	0.46 1.38E-05 0.484
Subjective alertness - KSS	Desk Illuminance Time Desk Illuminance * Time	(2, 70) (1, 105) (2, 105)	0.69 7.35 0.27	0.507 0.008 0.766
Ego depletion	Desk Illuminance	(2, 70)	1.11	0.334
Alternate Uses Task - Flexibility	Desk Illuminance	(2, 70)	0.16	0.855
Remote Associates task	Desk Illuminance	(2, 70)	0.84	0.435
Stroop - Congruent RT Stroop - Non-congruent RT Stroop - RT Delta Stroop - Total errors	Desk Illuminance Desk Illuminance Desk Illuminance Desk Illuminance	(2, 70) (2, 70) (2, 70) (2, 70)	1.16 0.05 1.82 1.61	0.319 0.947 0.170 0.208
Navon - Congruent RT (inv.) Navon - Non-congruent RT (inv.) Navon - RT Delta (inv.) Navon - Total errors	Desk Illuminance Desk Illuminance Desk Illuminance Desk Illuminance	(2, 70) (2, 70) (2, 70) (2, 70)	0.23 0.12 1.35 0.48	0.794 0.890 0.266 0.621
Visual acuity - paper	Desk Illuminance	(2, 70)	13.18	1.38E-05
Visual acuity - screen	Desk Illuminance Size (of Optotype) Opacity (of Optotype) Desk Illuminance * Size Desk Illuminance * Opacity Size * Opacity Desk Ill. * Size * Opacity	(2, 385) (1, 18092) (1, 18092) (2, 18092) (2, 18092) (1, 18092) (2, 18092)	0.04 2068 2001 0.54 0.22 491.9 0.09	0.96 2.00E-16 2.00E-16 0.583 0.801 2.00E-16 0.908