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NIF effects of illuminance and correlated color temperature of office light on alertness, mood, and performance across cognitive domains

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Abstract:

Research has explored acute effects of light level and correlated color temperature (CCT) of indoor lighting on subjective measures of alertness and task performance during daytime. Yet, these investigations did not render a conclusive or consistent finding on the relative contribution of illuminance and CCT on various cognitive domains. The current study (N = 57) investigated diurnal effects of illuminance level (100 lx vs. 1000 lx at eye level) and correlated color temperature (3000 K vs. 6500 K) in a simulated office environment on subjective alertness and performance in sustained attention, response inhibition, conflict monitoring, and working memory. Moreover, effects on mood and appraisals were explored. The findings revealed that the high vs. low CCT manipulation elicited no statistically significant benefits on subjective alertness and task performance, but revealed an increase in negative affect. Exposure to high vs. low illuminance rendered subtle benefits on participants' mood and selectively improved performance. Reaction speed in the Go/No-go task and Flanker task (only incongruent trials) were significantly enhanced with 1000 lx compared to 100 lx lighting, but not statistically significant in the PVT task or the PVSAT task. Effects are discussed in consideration of task type and melanopic activation under the various light conditions.

Keywords: Lighting, Illuminance, Correlated color temperature; Alertness; Cognitive domain

1. Introduction

Since the discovery of the intrinsically photosensitive retinal ganglion cells (ipRGCs) in the human eye [1–4], an increasing number of studies have been performed to investigate the non-image forming (NIF) effects of ocular light exposure on human functioning during the biological night and day. Research has established that light does not only have the potential to produce phase-shifting effects on

the human circadian rhythm, but can also exert instantaneous effects on physiological arousal, neural activity, hormone production, and subjective alertness [5–14]. In addition, light has also been shown to impact cognitive ability [15–18], including attention [19–24], inhibitory control [11,25], and working memory [26–29].

Whereas nocturnal effects of light on alertness and performance may be attributed to melatonin suppression, this mechanism is not likely to underlie daytime effects, as circulating melatonin concentrations are generally negligible then [30,31]. Alternative explanations offered in the literature pertain to potential modulation of alertness and mood-related pathways (e.g., in brainstem, thalamus, amygdala and or hippocampus) [17,32–36]; or to psychological mechanisms including appraisal and motivation, beliefs or expectations regarding effects of blue-enriched or bright light (e.g., [18–20,37,38]).

Light's effect on cognition is determined by many factors, chief among them are parameters of light (i.e., illuminance level and spectral composition), timing characteristics (exposure duration, time of day and year) as well as task type [17,39]. Previous studies on monochromatic light have established that the NIF effect of light on alertness is most pronounced at short wavelengths (i.e., about 460-480nm) [10,17,29,40]. But research employing polychromatic light has revealed rather inconsistent alerting and cognitive effects of exposure to varying levels or spectra of white light, especially during daytime [16,18,19,27,36]. In addition to properties of the light itself, research suggests that different cognitive tasks may also be differentially sensitive to a manipulation of the light level or the spectrum of white light, as was indicated by previous studies [19,26,41–43]. However, these earlier investigations did not explore the relative contribution of illuminance vs. spectral composition of polychromatic light, which are both vital characteristic determining the human NIF response to polychromatic light. Note that the correlated

color temperature of polychromatic light would generally rise with increasing power in the blue part of the spectrum. Thus, the current study aimed at systemically investigating the individual and combined effects of illuminance level and spectral composition of polychromatic light on subjective alertness, mood, and different cognitive domains during daytime working hours. Exploration of the individual and combined effects of illuminance and spectral composition on different cognitive domains may provide crucial insights into whether differentially manipulating office light level and correlated color temperature (CCT) would be essential to optimize alertness, mood, and cognitive performance.

1.1. The effects of light illuminance on cognition

Reported diurnal effects of illumination on cognition are quite equivocal (see also [16,36]). Multiple studies revealed beneficial effects of illuminance on cognition, such as sustained attention [19,20,22], response inhibition [25], and working memory [26,27]. However, other studies found no statistically significant improvement of sustained attention performance [24,27,43–45] and working memory [28]. Besides that, a few investigations revealed that participants even performed worse while being exposed to a higher illuminance level in terms of impaired sustained attention, auditory response inhibition, and working memory, suggesting performance-undermining effects of illuminance on cognition [19,26,46,47].

1.2. The effects of CCT on cognition

It is widely accepted that the ipRGCs contain the photopigment melanopsin, and are primarily responsible for the non-image forming effects of light [3,4,48]. The ipRGCs differ from the classical rods and cones in their sensitivity to light characteristics [1,4]. Higher light levels, i.e., more photons, are necessary to induce melanopsin photoreception. In addition, the peak sensitivity of the photopigment melanopsin in ipRGCs to light is in the blue part of the spectrum (around 460~480 nm) [1,4,49,50]. The

NIF effect of the spectral composition of light on human functioning has therefore also been partially investigated, sometimes by comparing effects of monochromatic or small-bandwidth lighting, or by comparing white light that is or is not enhanced in the blue part of the spectrum. Note that the correlated color temperature (CCT) of polychromatic light generally increases when it contains more power in the blue part of the spectrum. It is expected that exposure to either monochromatic blue light or polychromatic light of high CCT would have stronger NIF effects [10,11,40,49–52]. However, the advantage of high CCT on cognition is not always confirmed during daytime [18] -- as was also the case for illuminance level [16,36]. Positive effects of CCT were found on sustained attention [53] and subjective measurement of performance [53,54]. For instance, 17000 K light improved subjective alertness and performance more strongly than 4000 K or 2900 K [54,55]. Yet, some studies showed no advantage of CCT level on sustained attention [18], alerting attention, orienting, and executive control [18], or working memory [29].

1.3. Interactions of illuminance and correlated color temperature on cognition

Most studies have tested effects of illuminance level at one specific CCT level, and vice versa. Previous studies investigating the interaction effect of illuminance and correlated color temperature of polychromatic light are relatively scarce. It is, however, interesting to investigate this nonetheless in order to optimize daytime lighting regimes, as it may shed light on underlying mechanisms. In line with the most common hypothesis today, one might expect that the essence of both an illuminance and a CCT manipulation is their differential activation of melanopsin-driven photic transduction. Both may result in more intense ipRGC activity, and hence stronger NIF effects. But in fact, the extent to which the remaining photoreceptors contribute to these effects is still under investigation [56,57], and recent studies have suggested potential complex interactions (inhibition and facilitation) between activation of

different photoreceptors [58,59]. If the activation of the traditional photoreceptors also adds to NIF effects [60,61], one might perhaps expect CCT manipulations to show fewer effects on performance and alertness than illuminance manipulations. Also, we cannot discard the fact that the altered visual experience – through psychological, image forming pathways – may impact performance and alertness [19,38]. In that sense, CCT manipulations may result in equally strong, but perhaps different effects. In other words, based on melanopsin-driven NIF effects one would expect purely additive effects of a combined increase in CCT and illuminance, but if other receptors play a part via NIF or IF effects, interactions might also emerge. To date, there is uncertainty regarding the relative contribution of the different photoreceptors in NIF effects, but some contribution of non-melanopsin driven photoreceptors is often acknowledged, and this interaction may depend on the illuminance levels (e.g., see [56,57,62,63]).

Only a few studies investigated interaction effects between CCT and illuminance. One earlier study by Noguchi and Sakaguchi [64] reported that CCT (5000 vs. 3000 K) influenced physiological activity more than illuminance levels (150 vs. 50 lx) with higher values of EEG alpha attenuation coefficient and higher mean EEG frequency of the theta-beta ratio under 5000 K vs. 3000 K in the afternoon. Moreover, participants in 5000 K light subjectively reported less drowsiness than in 3000 K light, whereas no statistically significant effect of illuminance was observed [64]. In contrast, Min et al. [47] found that exposure to a higher illuminance (700 vs. 150 lx) did decrease response speed on a sustained attention task, regardless of the CCT level (7100 vs. 3000 K). Park and colleagues [28] also suggested that the NIF effect of polychromatic light on cognitive function may depend more strongly on illuminance than on CCT. They reported no statistically significant effects of illuminance level and CCT on behavioral performance of working memory task, but exposure to a higher illuminance (700 vs. 150 lx) delayed the

onset latency of N1 and decreased the amplitude of theta component in frontal brain regions, again regardless of CCT (7100 K vs. 3000 K). The above studies testing effects of illuminance and CCT in one study paradigm have restricted their tests to a limited range of cognitive domains; it is still unclear whether the above findings would be evidenced in other cognitive functions as well. In addition, a recent study revealed enhanced mood and alertness, but impaired sustained attention with intense illumination at a relatively high CCT in the morning [46]. In their study, however, they failed to match the color temperature between the 5000 lx (6500 K) and 400 lx (4000 K) conditions appropriately. Due to this confound, it is impossible to attribute the effect to illuminance levels or CCT alone. Thus, the aim of the present study was to systemically explore the independent and combined effects of illuminance and CCT of polychromatic light on performance in a set of tasks probing various cognitive domains.

As was argued before, task type and task complexity may also be important moderators of light effects on cognition [19,26,27,41,42]. Hence, the current study employed a factorial design to manipulate illuminance and CCT independently and used a simple sustained attention task (psychomotor vigilance task; PVT), two more complex executive control tasks (Go/No-go and Flanker test), and a working memory task (paced visual serial addition task, PVSAT) to explore the contribution of illumination and CCT of polychromatic light across different cognitive domains during daytime. To achieve above aims, healthy adults were assigned to either high or low illuminance light (1000 lx vs. 100 lx at the eye) of either high or low CCT (6500 K vs. 3000 K). In addition, the effect of illuminance and CCT on the development of participants' subjective mood and alertness, subjective appraisals, preference for a work-related context and beliefs of the light conditions were also investigated.

2. Methods

2.1. Design

The study employed a 2 within (Illuminance level: 1000 lx vs. 100 lx) by 2 between (CCT: 6500 K vs. 3000 K) mixed model design. Participants came to the lab on two separate days with an interval of at least three days in between experimental sessions. The study was carried out during daytime hours (10:00~17:00) and participants were scheduled at the same local clock time for both experiment days.

2.2. Participants

Fifty-seven healthy undergraduates (38 females, $M = 20.23$; $SD = 1.58$) participated in the laboratory study. Twenty-eight participants (19 females) were randomly assigned to the low CCT (3000 K) condition, while the others (19 females) were assigned to the high CCT (6500 K) condition. Participants were randomly assigned to receive either 1000 lx light exposure or 100 lx light exposure first.

All volunteers were screened and reported no visual impairments other than myopia or hyperopia, which were corrected by wearing contact lenses or glasses, and none of them indicated that they suffered from color blindness. Potential candidates were screened for physical and mental health problems, according to their self-reports and responses on the General Medical Questionnaire [65]. Other exclusion criteria included (1) smoking, medication or drug consumption, (2) recent travel to a different time zone or shift-work in the last three months, (3) less than 7 hours or more than 9 hours spent in bed at night, (4) Pittsburgh Sleep Quality Index score > 5 [66], and (5) extremely late or extremely early chronotype on the Munich Chronotype questionnaire (MCTQ) [67].

All participants gave their written informed consent before the start of the study, and followed the complete experimental protocol.

2.3. Setting and light manipulation

1 The lab room (Fig.1) where the experiment was conducted was a simulated office environment of
 2 3.6m by 3.6m. Four separate workstations with a pure white desk (1.2m by 0.8m) and one black chair
 3 were created. One white All-in-One PC (Lenovo C260, 19.5 inch) with the white headphone, keyboard
 4 and mouse was placed on each of the desks.

5
 6 **Fig. 1.** Simulated office room where the ambient light parameters were manipulated and other physical variables
 7 were controlled.

8 The room was equipped with six ceiling mounted luminaires of 1.2m by 0.8m containing three
 9 Philips LED tubes (either T8-28W/865 or T8-28W/830) and three additional ceiling mounted
 10 luminaires of 1.2m by 0.6m containing two Philips LED tubes (T8-28W). Using a calibrated
 11 spectroradiometer (JETI Specbos1201), the illuminance level, spectral power distribution (SPD) and
 12 color-rendering index (CRI) were measured at eye level aimed at the wall in the gaze direction of
 13 participants. The CRI at 6500 K was $R_a = 81$, and the CRI at 3000 K was $R_a = 83$. Fig. 2 shows the SPD
 14 at 6500 K and 3000 K of the 1000 lx and 100 lx conditions.

Fig. 2. Spectral power distribution measured at eye level in the four lighting conditions.

During the baseline phase, the ceiling mounted luminaires provided illumination of approximately 100 lx on the table surface (70 lx at eye level at 3000 K in low CCT conditions, 73 lx at eye level at 6500 K in high CCT conditions). After the baseline phase, lighting was set to either 100 lx at 3000 K at eye level (photon density: 9.07×10^{13} photons* s⁻¹*cm⁻²; irradiance: 31 μ W/cm²; 118 lx on the table surface), to 1000 lx at 3000 K at eye level (photon density: 9.54×10^{14} photons*s⁻¹*cm⁻²; irradiance: 324 μ W/cm²; 1620 lx on the table surface), to 100 lx at 6500 K at eye level (photon density: 8.99×10^{13} photons*s⁻¹*cm⁻²; irradiance: 33 μ W/cm²; 116 lx on the table surface), or to 1000 lx at 6500 K at eye level (photon density: 9.28×10^{14} photons* s⁻¹*cm⁻²; irradiance: 341 μ W/cm²; 2190 lx on the table surface). See Table 1 for additional information about the lighting conditions based on the spectral sensitivity of the various photoreceptors.

Table 1.

Spectrally-weighted α -Opic lux level at eye levels for each lighting condition based on calculations of Lucas et al. (2014) [56].

	λ max	α -Opic lux value			
		(3000K, 100lx)	(3000K, 1000lx)	(6500K, 100lx)	(6500K, 1000lx)
Lux		99	1037	102	1040
CCT		3069	3088	6589	6666
Melanopsin	480	56	534	96	998
S-cone	419	47	385	105	1081
M-scone	530	85	872	102	1044
L-cone	558	97	1022	99	1003
Rods	496	66	643	98	1026

Note: α -Opic lux values for corneal spectral irradiance determined using the calculation toolbox developed by Lucas et al. (2014)[56]. These values are based on healthy human eyes (32 years old, dilated pupils, 7 min).). Based on this model, light's

non-visual responses are initiated by one or more of five distinct biological representations of irradiance: melanopic, rhodopic, cyanopic, chloropic, and erythropic illuminance.

2.4. Assessment of subjective ratings

Subjective alertness was assessed with the Karolinska Sleepiness Scale (KSS) [68], while the Positive and Negative Affect Scale (PANAS) [69] was used to assess subjective mood.

2.5. Cognitive performance measurement

Four tasks were employed to assess the light's effect on different aspects of cognitive functioning. Simple sustained attention was measured by the psychomotor vigilance task [70]. We used a 10-minute auditory PVT, with intervals randomly varying from 1 to 9s. A visual Go/No-go task measured the capacity for sustained attention and response inhibitory [11,71]. In this test, participants had to press the key button within 1 second if the letter "M" was shown on the screen, and withhold response to the letter "W". The interval between trials was varying from 1s to 1.5s, and a total of 70% of "M" letters were shown in a random sequence. The letters "M" and "W" were printed in black and with size of 30pt on purely white screen. The Eriksen flanker task is an executive function test used to assess selective attention and inhibition of conflicting irrelevant information [72]. In the task, a directional response was made to a central target stimulus by striking the left or right arrow on the computer keyboard. The target was randomly flanked by non-target stimuli, which corresponded either with the same (congruent flankers) or the opposite (incongruent flankers) directional response as the target. All 50 stimuli were black-and-white pictures that had been processed through Photoshop and the size of the picture was 500*375 pixels. The average accuracy and reaction times for both the congruent and incongruent presentations were separately recorded for the analyses. PVSAT is an addition task that engages with the executive aspect of working memory [73]. Single digits (1 to 20) colored in black (30pt) appear on the white screen and each digit must be added to the digit that preceded it. The resulting answer ("sum" of

adjacent pairs, not a total across all digits presented) is keyed in with the numerical keyboard. Digits were presented for 1 s, and then responses were allowed within a 5 s maximum, followed by a 1-s interval before the next stimulus appeared.

2.6. Evaluation of the lighting

At the end of the session, participants were asked to evaluate the lighting environment in the lab using six 5-point Likert-scale items adopted from Flynn et al. [74], including appraisals of the lighting in terms of brightness (dim – bright), color temperature (warm – cool), pleasant (unpleasant – pleasant), comfortable (uncomfortable – comfortable), disturbing (not distributed – distributed), and soft (not soft – soft). In addition, three 9-point Likert-scale items on participants' subjective beliefs of the current lighting effects on energy, mood, and work performance (i.e. whether the lighting benefited your performance, “1” does not benefit, “9” benefit) were administered as well as one item to probe participants' preference to work under the current lighting in daily life was evaluated on a 7-point scale ranging from (1) extremely inadequate to (7) extremely adequate.

2.7. Procedure

All potential participants were required to fill in online questionnaires, including questions about demographics, physical and mental health, general sleep quality and chronotype after their registration. Participants were instructed to comply with their regular night sleep schedule (± 30 min as they reported in the MCTQ) for at least one week before the laboratory study and kept it until they completed all the experiments, and to abstain from drinking beverages containing alcohol or caffeine on both the experiment days.

Fig. 3. Overview experimental condition and schematic representation of one full session. PVT: Psychomotor Vigilance test; KSS: Karolinska Sleepiness Scale; PANAS: Positive and Negative Affect Scale. Tasks were run in two orders (PVT-PVSAT-Flanker-Go/No-go or PVT- Go/No-go -Flanker- PVSAT)

After arriving in the laboratory, participants were asked to complete a brief interview including questions on their sleep-wake timing and sleep quality that day, whether they drank beverages containing alcohol or caffeine, or had vigorous exercise or long-term (more than 2h) outdoor activities before arriving in the lab. Participants who reported bad sleep quality or did not adhere to the sleep-wake schedule during the night preceding an experimental session, and/or those participants who did not adhere to the other instructions (e.g., drank alcoholic beverages) were rescheduled to another day.

Subsequently, participants were guided to the workstation and asked to assess their baseline sleepiness and mood with questionnaires. After that, participants were informed about the general procedure and started the formal experimental phase. The experiment started always with a 10-minute light adaption (Block 1) and then four computerized task blocks (Blocks 2, 3, 4, and 5: PVT, Go/No-go, Flanker and PVSAT task respectively) programmed with one of the two fixed task orders (either PVT-Go/No-go - Flanker - PVSAT or PVT - PVSAT - Flanker - Go/No-go). The task order was identical for each participant on two experiment days. Participants reported on their current alertness and mood at baseline (T0), twice during the test session (at T1 and T2) and once more at the end of the test session (T3). At T3, participants also completed the mood questionnaire and a questionnaire evaluating the

lighting environment in the laboratory. A schematic representation of one full experimental session is depicted in Fig. 3.

2.8. Data analysis

The scores of the positive subscale and the negative subscale of the PANAS were averaged for each participant respectively. Reaction times (RT) on error trials (omissions, false starts and trials following incorrect responses) and outliers (more than three standard deviations from the mean) were removed per participant for the various performance tasks before calculating the averages. All RT data were inverted before further analysis to increase normality. For the PVT data, the average reaction speed ($1/RT$) for overall trials, the average speed for the 10% fastest and the 10% slowest responses were separately investigated. Lapses in the PVT task were not investigated since the number of lapses was quite low and not normally distributed.

For all analyses, SPSS version 19.0 (IBM, USA) was used. In order to test whether the baseline alertness and mood were different across four experiment conditions, two-way repeated measures ANOVAs with within-subject factor Illuminance (1000 lx vs. 100 lx) and between-subject factor CCT (6500 K vs. 3000 K) were performed for baseline alertness and mood. Since subjective sleepiness was assessed multiple times, Testing time (T1, T2 vs. T3) was added as a within-subjects factor in the analysis of effects of light on changes (Δ) of subjective alertness. Two-way repeated measures ANOVAs with within-subject factor Illuminance and between-subject factor CCT were also performed to test the effect of the lighting conditions on subjective mood and appraisals of lighting. For task performance, two-way repeated measures ANOVAs with within-subject factor Illuminance and between-subject factor CCT were performed. Congruency (congruent/incongruent) was added as an additional within-subject factor in the repeated-measures ANOVAs for accuracy and reaction speed in the Flanker task. Note that

reported contrasts for main effects and interaction effects always refer to post-hoc analyses using Bonferroni correction.

3. Results

3.1. Subjective measurement

3.1.1 Baseline comparisons

Repeated measures ANOVAs with the factors Illuminance (within: 1000 lx vs. 100 lx) and CCT (between: 6500 K vs. 3000 K) was performed first on baseline data for alertness and mood. The results indicated that – at baseline (T0) - there were no significant main or interaction effects of illuminance and CCT conditions on subjective alertness [100 lx at 6500 K : $M = 3.34 \pm SE = .24$; 1000 lx at 6500 K : $3.31 \pm .20$; 100 lx at 3000 K : $3.39 \pm .25$; 1000 lx at 3000 K: $3.32 \pm .26$], positive mood [100 lx at 6500 K: $2.00 \pm .11$; 1000 lx at 6500 K: $1.80 \pm .12$; 100 lx at 3000 K: $1.77 \pm .11$; 1000 lx at 6500 K: $1.74 \pm .13$] or negative mood [100 lx at 6500 K: $1.21 \pm .05$; 1000 lx at 6500 K: $1.20 \pm .06$; 100 lx at 3000 K: $1.42 \pm .06$; 1000 lx at 3000 K: $1.42 \pm .05$] (all p values $> .05$).

3.1.2. Effects of lighting manipulations on subjective alertness

Fig. 4. The changes in KSS score relative to baseline for different light conditions during the experimental session. Error bars indicate ± 1 standard error of the mean. ** $p < .01$.

The development of the average change in KSS score relative to T0 (Δ KSS) during the lighting session is shown in Fig. 4. A repeated ANOVA with within factors Illuminance level and Test time, and between factor CCT on Δ KSS showed a significant main effect of Test time [$F(2, 110) = 9.81, p < .01, \eta^2 = .15$]. Post-hoc comparisons showed that the increase in KSS score (i.e., lower alertness compared to baseline) was significantly larger at Time2 and Time3 than that at Time1 [*all* $p < .01$], no statistically significant differences emerged between Time2 and Time3 [$p > .05$]. The lighting conditions revealed no significant main or interactions effects (all p values $> .05$).

3.1.3. Mood

Fig. 5. Changes in PANAS scores (negative and positive affect) relative to baseline for different light conditions over the experimental session. Delta negative means PANAS scores decreased and vice versa. Error bars indicate ± 1 standard error of the mean. * $p < .05$. ** $p < .01$.

The average changes in PANAS scores during the test session are shown in Fig. 5. A repeated measures ANOVA with the factors Illuminance and CCT on the changes in subjective mood revealed that participants' negative mood decreased more in the 1000 lx vs. 100 lx condition [$-0.14 \pm .03$ vs. $0.02 \pm .05$, $F(1, 55) = 6.10, p < .05, \eta^2 = .10$], as well as in the 3000 K vs. 6500 K condition [$-0.18 \pm .04$ vs. $0.06 \pm .04$, $F(1, 55) = 16.32, p < .01, \eta^2 = .22$]. No significant Illuminance $\times$ CCT interaction was found [$F(1, 55) = .32$; $F(1, 55) = .17$; all $p > .05, \eta^2 < .01$]. In contrast, the repeated measures ANOVA for positive affect did not reveal any significant effects on the changes in subjective positive mood [main effect

1 Illuminance: $F(1, 55) = .53$; main effect CCT: $F(1, 55) = .98$; interaction effect: $F(1, 55) = 2.26$; all
2 $p > .05$, $\eta^2 = .1$].

3 3.2 Task performance measurement

4 3.2.1 Effects of lighting manipulations on sustained attention

5
6 **Fig. 6.** PVT performance of speed on overall trials (left panel) and 10% fastest trials (middle panel) and 10% slowest trials (right
7 panel) in 100 lx vs. 1000 lx at 6500 K (dark bars) vs. 3000 K (light bars) condition. Error bars indicate ± 1 standard error of the mean.
8 + $p = .05$.

9 A repeated-measures ANOVA computed on PVT performance (speed) revealed no significant main
10 effects of Illuminance or CCT on overall reaction speed [$F(1, 55) = 3.21$, $p = .08$, $\eta^2 = .06$; $F(1, 55) = .77$,
11 $p > .05$, $\eta^2 = .01$, respectively]. The average speed on the 10% fastest trials also revealed no significant
12 effects of Illuminance or CCT [$F(1, 55) = .91$, $p > .05$, $\eta^2 = .02$; $F(1, 55) = .13$, $p > .05$, $\eta^2 < .01$,
13 respectively], while the main effect of Illuminance (not CCT) on the 10% slowest trials bordered on
14 significance [Illuminance: $F(1, 55) = 3.98$, $p = .05$, $\eta^2 = .07$; CCT: $F(1, 55) = .65$, $p > .05$, $\eta^2 = .01$]. In
15 addition, no significant Illuminance $\times$ CCT interaction effects were found for PVT performance [all F
16 < 1 , ns , $\eta^2 < .01$] (see Fig. 6). 3.2.2. Effects of lighting manipulations on response inhibition (Go/No-go)

17 Results on the Go/No-go accuracy (Figure 6) revealed no significant effect of Illuminance or CCT
18 [$F(1, 55) = 2.65$, $p > .05$, $\eta^2 = .05$; $F < 1$, ns , $\eta^2 < .01$, respectively], or of their interaction [$F(1, 55) = 2.42$,
19 $p > .05$, $\eta^2 = .04$]. However, the main effect of Illuminance on reaction speed in this task did reach
20 significance. Reaction speed was higher in the 1000 lx vs. 100 lx condition [$2.62 \pm .03$ vs. $2.56 \pm .02$, $F(1,$

55) = 6.13, $p = .02$, $\eta^2 = .10$]. The main effect of CCT and the Illuminance x CCT interaction effect did not reach significance [$F(1, 55) = 1.14$, $p > .05$, $\eta^2 = .02$; $F < 1$, ns , $\eta^2 < .01$, respectively] (see Fig. 7).

Fig. 7. Go/No-go accuracy (left panel) and reaction times (right panel) in 100 lx vs. 1000 lx at 6500 K (dark bars) vs. 3000 K (light bars). Error bars indicate ± 1 standard error of the mean. * $p < .05$.

3.2.3. Effects of lighting manipulations on conflict monitoring (Flanker)

Fig. 8. Flanker accuracy (left panel) and reaction times (right panel) in 100 lx vs. 1000 lx at 6500 K (dark bars) vs. 3000 K (light bars) condition. Error bars indicate ± 1 standard error of the mean. * $p < .05$.

A three-way repeated measures ANOVA on Flanker accuracy revealed no significant main effects of Illuminance or CCT (Fig. 8) [$F(1, 55) = 2.24$, $p > .05$, $\eta^2 = .04$; $F < 1$, ns , $\eta^2 = .02$, respectively] (see Fig. 8). The main effect of Congruency was significant: participants performed better for the congruent vs. incongruent trials [$.99 \pm .002$ vs. $.93 \pm .007$, $F(1, 55) = 118.88$, $p < .01$, $\eta^2 = .68$]. No significant interactions were found for Flanker accuracy (all p values $> .05$).

The average reaction speed (Fig. 8b) also disclosed a significant main effect of Congruency, with reaction speed significantly higher for the congruent vs. incongruent trials [2.30 ± 0.02 vs. $2.06 \pm .02$, $F(1,$

55) = 964.52, $p < .01$, $\eta^2 = .95$]. Main effects of Illuminance and CCT did not reach significance [$F(1, 55) = 2.30$, $p > .05$, $\eta^2 = .04$; $F < 1$, ns , $\eta^2 = .02$, respectively]. However, the interaction between Illuminance and Congruency did reach significance [$F(1, 55) = 15.61$, $p < .01$, $\eta^2 = .22$]. The post-hoc tests revealed that participants' reaction speed for the incongruent Flanker trials was significantly higher under 1000 lx vs. 100 lx condition [$2.10 \pm .03$ vs. $2.05 \pm .02$, $p < .05$], while reaction speed for the congruent Flanker trials did not significantly differ between 1000 lx vs. 100 lx conditions [$2.31 \pm .03$ vs. $2.32 \pm .03$, $p > .05$]. No other interactions reached significance (all p values $> .05$).

3.2.4. Effects of lighting manipulations on working memory (PVSAT)

Fig. 9. PVSAT accuracy (left panel) and reaction times (right panel) in 100 lx vs. 1000 lx at 6500 K (dark bars) vs. 3000 K condition (light bars). Error bars indicate ± 1 standard error of the mean. * $p < .05$.

Result for accuracy in the PVSAT task (Fig. 9) revealed a significant main effect of Illuminance. Participants' accuracy was average higher in the 1000 lx vs. 100 lx condition [$0.70 \pm .04$ vs. $0.53 \pm .03$, $F(1, 55) = 84.79$, $p < .01$, $\eta^2 = .61$]. The main effect of CCT and the Illuminance $\times$ CCT interaction did not reach significance [both $F < 1$, ns , $\eta^2 < .01$]. The reaction speed in PVSAT task, however, did not reveal any significant main effects nor interaction effect [main effects Illuminance and CCT: $F < 1$, ns , $\eta^2 < .01$; Interaction: $F(1, 55) = 2.65$, $p > .05$; $\eta^2 = .05$].

3.3. Evaluation of lighting

Fig. 10. Mean score on subjective appraisals of lighting in different experimental conditions

Repeated-measures ANOVA analyses with Illuminance (within) and CCT (between) were performed to examine effect on participants' subjective appraisals, beliefs and preference of the lighting conditions. The results for the lighting appraisals (see Fig. 10) revealed that the 1000 lx light was perceived as brighter ($4.44 \pm .10$ vs. $3.17 \pm .09$, $F(1, 55) = 113.00$, $p < .01$, $\eta^2 = .67$), but less soft ($2.38 \pm .13$ vs. $2.58 \pm .14$, $F(1, 55) = 14.03$, $p < .01$, $\eta^2 = .20$) and less comfortable ($2.68 \pm .13$ vs. $3.36 \pm .12$, $F(1, 55) = 11.18$, $p < .01$, $\eta^2 = .18$) than the 100 lx light. Meanwhile, light in the 6500 K condition was evaluated as softer ($3.18 \pm .11$ vs. $2.77 \pm .11$, $F(1, 55) = 6.62$, $p < .05$, $\eta^2 = .11$) and brighter ($3.98 \pm .13$ vs. $3.62 \pm .08$, $F(1, 55) = 5.42$, $p < .05$, $\eta^2 = .09$) than light of 3000 K. In addition, the results (see Fig. 11) showed that light of 1000 lx was judged as more beneficial for task performance than that of 100 lx ($6.67 \pm .16$ vs. $5.70 \pm .14$, $F(1, 60) = 22.58$, $p < .01$, $\eta^2 = .29$), however, lighting of 3000 K was believed to benefit subjective mood more than that of 6500 K ($5.44 \pm .18$ vs. $4.75 \pm .14$, $F(1, 55) = 9.53$, $p < .01$, $\eta^2 = .15$) than that of 6500 K. No significant interaction between illuminance level and CCT were found on subjective appraisals, beliefs and preference.

Fig. 11. Subjective beliefs and preference of lighting in different experimental conditions. ** $p < .01$.

4. Discussion

Previous studies have investigated and reported acute effects of illuminance and CCT of light on alertness, task performance, and physiological arousal during daytime. These investigations, however, did not draw a conclusive finding. Moreover, the relative contribution of illuminance and CCT on various cognitive domains was largely unknown. Thus, the current study was conducted in an effort to provide a more comprehensive picture of the potential diurnal effects of office lighting on subjective alertness, mood, and different cognitive domains, by studying both dimensions in parallel and through separating and comparing the relative contribution of illuminance and spectrum of polychromatic white light.

Overall, the current results revealed that the illuminance level of office lighting influenced individuals' subjective measures and cognitive process more than CCT level. Statistically significant interaction effects between illuminance and CCT did not emerge on any of the indicators for subjective experiences or performance. Manipulations of illuminance did impact several performance measures and mood, though not subjective alertness. Only subjective mood and appraisals of the lighting were

1 responsive to the CCT manipulation in the current study.

2 Although the current results revealed several benefits of illuminance level on task performance, the
3 manipulation of spectrum (via CCT level) did not produce any significant performance improvements. In
4 other words, our study did not render the advantage of light with high CCT reported in earlier studies
5 [11,54,55]. Two possible factors may explain the absence of advantage of a higher CCT level in the
6 current study. First, the melanopsin-expressing ipRGCs, which are primarily responsible for the NIF
7 effect, were less affected by the manipulation of CCT level than illuminance level. It is widely
8 documented that the ipRGCs differ from the classical photoreceptors (rods and cones) in their response
9 to light characteristics [1,4] particularly with regard to peak sensitivity (around 460~480 nm) [4,49,50].
10 With the manipulation of the lighting conditions in the current study, the melanopic alpha-opic lux level
11 increased quite modestly between CCT conditions (56 vs. 96 at 100 lx at eye level; 534 vs. 998 at 1000 lx
12 at eye level). In other words, it increased with almost a factor two, whereas the illuminance manipulation
13 implied a tenfold increase (melanopic lux at eye level: 56 vs. 534 at 3000 K; 96 vs. 998 at 6500 K).
14 Meanwhile, earlier field studies that reported activating effects of daytime exposure under high CCT on
15 participants' subjective performance, employed either longer exposure durations (i.e., several weeks)
16 and/or extremely high CCT levels (i.e., 17000 K vs. 4000 K) [53–55]. Together, these findings suggest
17 that an even higher CCT level and/or a longer exposure duration could be essential to induce
18 alertness-enhancing effects. Additional studies are required to examine whether exposure to extremely
19 higher CCT level (e.g., 17000 K) for short duration (i.e., 30-minutes or 1 hour) or to relatively high CCT
20 (i.e., 6500 K) level for long duration (i.e., 2 hours or 3 hours) could induce alertness-enhancing effects
21 during biological daytime. Moreover, additional research is required to establish thresholds for the
22 alerting potential of melanopic activation in terms of alertness and cognitive performance.

Second, the illuminance levels were tested as a within-subject factor in the current study, while between-subjects manipulation was employed for CCT level. This may result in a potential (larger) influence of inter-individual differences in the dependent measures between CCT conditions. Although participants' baseline mental state (i.e., alertness, affect), chronotype, and total sleep duration of the preceding night were not significantly different across lighting conditions, we did not measure participants' performance ability at baseline, or other sleep parameters (i.e., onset, offset and also midsleep) across the lighting conditions. Moreover, participants were potentially not blind to the manipulation of illuminance level, but did not experience the CCT manipulation due to the mixed design. In addition, the statistical power was higher for Illuminance than CCT due to the repeated measures across the 1000 lx and 100 lx conditions within subjects

While task performance remained insensitive to the CCT level, the illuminance manipulation induced both positive and null effects on task performance. Various types of tasks were adopted in the current study to explore the individual or combined effect of daytime exposure to bright vs. dim white light and high vs. low CCT on different components of cognition. For the PVT task, measuring sustained attention, only subtle improvements of reaction speed for the 10% slowest trials emerged under high vs. low illuminance condition. For the other tasks probing more complex cognitive functions, the current results, however, suggested statistically significant benefits of exposure to bright light, although not on all indicators of every task. Working memory as assessed with the PVSAT improved in terms of accuracy, whereas response inhibition, assessed with the Go/No-Go task, and conflict monitoring, assessed with the Flanker task, improved in terms of response speed. It is notable that the current benefits of illuminance level emerged under both bright light at 6500 K and bright light at 3000 K. Moreover, the effect sizes for the significant effects of illuminance on Go/No-Go task and PVSAT performance ranged

from medium to large. Yet, additional research studying the effects of light on performance *in situ* is needed to establish the practical relevance of the obtained results.

The current finding on sustained attention did not confirm the expectation that, during daytime, performance on the relatively simple attention task would be significantly improved with high vs. low light levels [20,22]. Differences in study protocol may partly explain these contradictory findings, since participants were sleep deprived in the study by Phipps-Nelson et al. [22] studies. In contrast, participants who were not sleep-restricted in the study by Smolders et al. [20] study showed faster responses on the PVT under 1000 lx vs. 200 lx (at the eye) condition during regular working hours. However, this effect was only observed in the morning session, but not in the afternoon. In contrast, several studies also suggested no statistical significant effects of Illuminance or CCT level on vigilance (PVT) performance among healthy day activity participants during daytime [18,26,27,44–46]. It is notable that the non-significant improvement of sustained attention performance in the current study may also be traced back to the fact that the PVT task was always performed first during each session. In fact, Smolders et al. (2012) [20] and Smolders and de Kort (2014) [19] showed most pronounced effects of bright light on PVT response times after about 30 minutes of exposure. Regarding the effects on more complex cognitive tasks (i.e., executive functions), previous research reported inconsistent effects, including positive, null or even negative effects of daytime exposure to high illuminance level on Go/No-go tasks [19,42], as well as on working memory tasks [19,26,27,41,42]. The current results revealed that the illuminance manipulation during daytime elicited selective benefits on performance for executive control (speed) and working memory (accuracy). It is difficult to directly compare the findings from previous studies and the current one, due to differences in lighting properties and experimental paradigms across these studies. Besides, the task characteristics (i.e type of task or task difficulty) – can also partly explain

these contradictory findings, as some studies have reported differential benefits on tasks that varied either in cognitive type [19,42] or task difficulty level [26,27]. Yet, the current findings demonstrated rather consistent benefits of illuminance manipulation on relative difficult executive function, but not no significant effects on easier sustained attention. Although speed improvement was partially found on conflict monitoring (only for inconsistent trials), it was noted that incongruent Flanker trials could be more difficult to perform than congruent trials in which no or minimal demanding of executive conflict occurred. One recent study by Huiberts et al. [27] suggested that the benefits of an illuminance manipulation were evidenced on difficult but not on easy level of working memory task as assessed with neither BDST task nor relatively easy PVT task. Together with the current findings, these results suggest that the NIF effect of an illuminance manipulation is more strongly moderated by the difficulty level of task itself than the type of task. Nevertheless, additional studies are required to establish the potential moderating effect of the difficulty of task for various cognitive domains modulate on the diurnal effects of light exposure on cognitive functioning.

In addition to task performance, the current results did not reveal individual or combined benefits of high illuminance level and CCT level on participants' feeling of alertness. This result is comparable to two recent studies that revealed participants' subjective sleepiness also remained unaffected after 50 minutes exposure to 1000 lx vs. 200 lx [27] as well to 6000 K vs. 2700 K light [18]. In addition, these results are in line with two very recent studies investigating dose-response relationship between alertness and illuminance during daytime [44,45]. These studies revealed that daytime exposure to more intense light, at least for one hour of exposure, may not systematically benefit alertness or executive functioning. Moreover, as mentioned above, studies reporting positive effects of CCT level on daytime alertness employed either longer exposure periods or extremely high CCT levels [54,55,75,76]. In the current

study, participants showed overall deterioration of subjective alertness during the test session, such that larger increments in sleepiness occurred in the second as well as the third measurement block during the experimental phase (i.e., about 38 and 50 minutes after light manipulation onset), but regardless of light condition. This gradually increased sleepiness could be the result of the sustained cognitive load during the test session which may have induced mental fatigue. Together, the current findings underline the fact that exposure to higher illuminance or CCT level lighting does not always induce a positive effect on subjective alertness during daytime, at least not within 50 minutes.

In contrast to effects on alertness, results on subjective mood revealed significant effects of both illuminance and CCT levels. Participants' negative mood significantly decreased after 50 minutes of exposure to high vs. low illuminance (1000 lx vs. 100 lx) level, or to low vs. high CCT (3000 K vs. 6500 K) level. This finding was in line with earlier studies that reported positive effects of illuminance level on subjective mood [77], as well studies suggesting participants have less positive affect and more negative affect under high vs. low CCT (6000 K vs. 2700 K) conditions during daytime [18]. We should acknowledge that the changes in negative mood were relatively modest, particularly for the intensity manipulation. Whether this has practical relevance may depend on the specific application domain, but, perhaps more importantly, the question whether these effects gradually dissipate, are persistent, or even increase with exposure time should be answered first, before we recommend people select more bright or warm light at work or at home to relieve their negative mood.

Meanwhile, the effect of light on lighting appraisals was also investigated at end of the experimental session. The data revealed that lower CCT level (3000 K) was subjectively perceived as more beneficial for their subjective mood, which is consistent with the effect of CCT on subjective mood as assessed with the PANAS. Light of 1000 lx vs. 100 lx was reported to be brighter and to benefit their task performance,

but also less soft and less comfortable in the current study. This underlines the point that multiple indicators including subjective experience and objective performance should be taken account when applying these laboratory findings in actual working environment.

The mechanism underlying the relationship between diurnal light exposure and cognitive performance is still unclear, and the effects may operate through both the NIF and image forming system (e.g., [37]). While melatonin might play an important role at night, melatonin level is minimal during the subjective day for well-entrained individuals. This means that there is little room for suppression of melatonin by ipRGCs activation [78,79]. Nevertheless, multiple alternative hypotheses have been generated to speculate on the underlying mechanism of light-induced regulation of alertness and cognition. In addition to light's effects via regulation of the 24-h circadian rhythm, one possible mechanism is the light-induced activation of cortical networks involved in cognitive processing (i.e. the dorso-lateral prefrontal cortex, intraparietal sulcus (IPS) and superior parietal lobule, middle frontal gyrus, supramarginal gyrus and IPS) and subcortical networks (i.e. alertness-related brainstem, thalamus), such as impacting arousal, attention, and memory [17,32–36]. Moreover, lighting appraisals or expectations regarding effects of ambient light [37,38] as well as the regulation of mood-related brain regions (amygdala and hippocampus) [17,80] have been proposed to contribute to the potential effects of light on alertness and cognition. The current results on mood and appraisals do not provide support for the potential mediating role of positive appraisals, beliefs and/or affect in the effects of light level or spectrum on alertness and cognition. We did not assess brain activity, and additional research is required to determine which brain regions play a crucial role in the diurnal effects of light on alertness and cognition.

Some limitations of the current study should be mentioned before drawing conclusions. First, the

four tasks were presented in a fixed order (with two versions), and the PVT task was always presented first, which may have introduced a confounded change in arousal or mental fatigue across the different tasks. Moreover, effects of light might be more pronounced after longer exposure (e.g., 30 minutes) [19,20]. Secondly, although we measured participants' prior mental state, self-reported sleep duration and chronotype; we did not employ objective measures for participants' night sleep (i.e., sleep-wake pattern and quality) by means of, for instance, actigraphy on the day(s) before the experiment day. In addition, the performance tasks employed in the current study were visual tasks suggesting that we cannot eliminate potential effects of the lighting conditions on visual task performance. Having said this, the task stimuli were presented in such a way that it is unlikely that the conditions impeded the visibility of the task. The potential moderating role of task modality on the impact of light on alertness is, at least to our knowledge, as yet unknown. Furthermore, it should be noted that there were quite substantial differences in the timing of the lighting manipulations between participants in the current study. A few recent studies have revealed time-of-day dependent moderations in the effects of illuminance (e.g., [20,80]) and CCT (e.g., [18]) in effects of light on daytime performance. The current study, however, did not test time-of-day dependent moderations due to the relatively low number of observations per time interval for each condition and because of the fact that this was not purpose of the current study. Thus additional research is required to test time-of-day dependency of the individual and combined effect of illuminance and CCT on various cognitive performance tasks.

5. Conclusion

In sum, exposure to high vs. low illuminance selectively benefited task performance, and decreased participants' negative mood. Participants' reaction speed in response inhibition and conflict inhibition,

and accuracy in working memory were significantly enhanced with 1000 lx compared to 100 lx (at eye level) condition, while the remaining performance indicators showed no statistically significant effects. The current findings revealed that the manipulation of CCT elicited no statistically significant benefits on subjective sleepiness and task performance, but did affect participants' negative mood. It is important, in this respect, to note that the activation of the ipRGCs of the CCT manipulation we employed was substantially smaller than that of our illuminance manipulation.

Our findings contribute to the current studies suggesting that manipulation of office light during daytime does have the potential to optimal employees' subjective responses and ongoing task performance. Yet, in order to define optimal lighting settings, additional research is required.

Declaration of interest

The author declared no potential conflicts of interest with respect to the research, authorship, and/or publication of this article.

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Highlights

Manipulation of correlated color temperature of office light elicited no statistically significant benefits on subjective alertness and task performance

Exposure to high vs. low illuminance rendered subtle benefits on participants' mood and selectively improved performance

Diurnal non-visual effects of office light would depend on task type and melanopic activation