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Lighting color temperature impacts effort-related cardiovascular response to an auditory short-term memory task

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ABSTRACT

To better understand the impact of environmental light on processes that underlie cognitive activity, Lasauskaite and Cajochen (2018) recently proposed a theoretical model that predicts how light's correlated color temperature (CCT) affects effort. Here we tested whether the effects of CCT of light on effort-related cardiovascular response also extend to another sensory input—hearing. In two experimental blocks, participants were exposed to either low (2800 K) or high correlated color temperature (6500 K) light with an illumination level of 500 lux for 15 min before and while they performed an auditory n-back task varying in difficulty level (low difficulty/1-back vs. moderate difficulty/2-back). Mental effort was indexed as sympathetic beta-adrenergic impact on the heart, measured via cardiac pre-ejection period and systolic blood pressure. Based on the theoretical model, we hypothesized that light with a high CCT should lead to lower mental effort compared to light with a low CCT in both the low and moderate task difficulty conditions. Moreover, moderate task difficulty should lead to stronger effort compared to an easy task. The results did not show expected differences in invested effort levels between the task difficulty conditions (1-back vs. 2-back task) measured by cardiac pre-ejection period and systolic blood pressure. However, in line with our prediction, the results indicated that higher CCT of light decreased effort during an auditory memory task. Task performance was higher in easy than moderate task difficulty but was not altered by lighting conditions. Furthermore, we found no significant associations between cardiovascular reactivity and changes in mood, sleepiness, light, task, or effort ratings. Taken together, our results provide first evidence that higher CCT of light reduces the amount of effort invested during cognitive tasks for which hearing is needed. Given that this study was conducted under controlled laboratory conditions and with healthy young participants, additional research is needed to demonstrate that our results generalize to real-life applications. Nevertheless, we recommend that lower CCT of light should be avoided in learning and work contexts, as it might lead to higher effort and cardiovascular reactivity that may contribute to the development of cardiovascular health problems. Instead, we recommend higher CCT of light during daytime for wellbeing and health.

Light at night can affect human physiology, cognition, and subjective states during the night (see Cho et al., 2015; Navara & Nelson, 2007) as it disrupts the natural light-dark rhythm. Furthermore, exposure to light during daytime, depending on its quantity and quality, can also have various non-visual effects such as brain and pupillary responses, cognitive functions, sleepiness, and fatigue (de Zeeuw et al., 2019; Grant et al., 2021; Hidayetoglu et al., 2012; Kang et al., 2019; Lok et al., 2022; Revell et al., 2006; Vandewalle et al., 2007; Viola et al., 2008). Even if some studies showed clear non-visual effects of daytime light exposure, other studies found only partial or no effects (Huiberts et al., 2016; Lok et al., 2018; Sahin et al., 2014; Smolders et al., 2018). Building on a recent demonstration (Lasauskaite & Cajochen, 2018) that light's correlated color temperature (CCT) affects mental effort, and the associated theoretical model, we sought to replicate light's impact on effort with an auditory—instead of a visual—short memory task with additional task difficulty levels.

Theoretical analysis suggests that light should affect mental effort (Lasauskaite & Cajochen, 2018), where effort is defined as the mobilization of resources to carry out instrumental behavior (Gendolla & Wright, 2009). In short, Lasauskaite and Cajochen's theoretical model explains that light, by inducing alertness, should influence mental effort through its effects on experienced task demand. The logic behind this

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model builds on three main points. First, it is based on the alerting properties of light (Cajochen, 2007), and that feeling alert is linked to higher attention and focus (Lindsley, 1988), and, therefore, to the readiness to perform a task. Second, alertness and readiness to perform a task should reduce experienced (subjective) task demand. Alertness is defined as the state of being awake, attentive, and prepared to act (VandenBos & American Psychological Association, 2007). Thus, we hypothesized that the state of feeling alert (in opposition to feeling sleepy) should diminish task difficulty appraisals. Third, light-induced changes in perceived task difficulty should result in corresponding effects on effort given that task difficulty is a main determinant of effort according to motivational intensity theory (Brehm & Self, 1989).

Motivational intensity theory builds on an energy conservation principle (i.e. we aim to avoid wasting resources and utilize only the necessary resources) (Gibson, 1900). It postulates that effort is proportional to experienced task difficulty as long as success is possible and justified. If experienced task demand suggests that the task requires more effort than justified, individuals should disengage and not invest any effort. For light-induced alertness effects on effort, this implies that lower alertness should lead to higher perceived task difficulty and effort than high alertness as long as the required effort seems justified. However, at high task difficulty levels, the high experienced task difficulty under low alertness should lead to disengagement. Under high alertness, experienced task difficulty should be lower, and the required effort correspondingly still be perceived as justified. Consequently, high alertness should lead to more effort than low alertness if task difficulty is high. At extremely high task difficulty levels, effort should not be justified under both low and high alertness and thus be low and independent of the level of alertness. In sum, this theoretical analysis suggests that high CCT, in comparison to low CCT, induces a state of alertness that leads to lower subjective task demand, which in turn reduces mobilized effort at lower task difficult levels, while the effect should be reversed in more difficult tasks.

The first study testing this model (Lasauskaite & Cajochen, 2018) showed that exposing people to higher CCT of light (containing larger proportion of short-wavelength light within the spectrum) for 15 min before and during task performance led to lower effort-related cardiac response compared to lower CCT. However, light exposure for only 4 min *during* task performance, without a dedicated exposure time beforehand, did not have this effect (Lasauskaite et al., 2019). Another study (Zauner et al., 2020) that used a slightly different procedure could not confirm the linear relationship between CCT of light and effort as it found a U-shaped relationship. In all these studies, Sternberg or modified Sternberg tasks were used in which participants had to memorize letter stimuli displayed on a computer screen. Given that vision is required for this kind of tasks, one can argue that lighting conditions, even when holding photopic illuminance constant among different CCT scenarios, might still have played a role in the effects on effort. It is possible, that differences in the spectral power distribution of light affect visual properties of the text displayed on the screen, which, consequently, impacts processes that underlie task performance. Furthermore, in contrast to standard ceiling lighting, having the light behind the screen may influence the perception of what is displayed on the screen in terms of contrast or luminosity. Therefore, in the present study, we were interested whether CCT of light can also affect effort during performance of a task requiring another sensory process–hearing–instead of relying on visual memory.

We quantified effort as cardiovascular reactivity. This is based on work by Wright (1996), who integrated the motivational intensity theory (Brehm & Self, 1989) with Obrist's work on active coping (1981) and proposed that effort intensity should be reflected in the sympathetic impact on the heart. Non-invasively, this impact is best measured as the cardiac pre-ejection period (PEP)—the time period between left ventricular depolarization and the opening of the aortic valve (Berntson et al., 2004). Shorter PEP indicates stronger heart contractility, higher sympathetic activity, and thus stronger effort. Systolic blood pressure (SBP) is mainly affected by sympathetic activation and also a good indicator of invested effort (Richter et al., 2008; Wright, 1996).

The present study tested the effects of light's CCT and task difficulty on effort-related cardiac response to an auditory memory task. Participants performed an auditory 1-back and 2-back tasks (Kirchner, 1958) in two identical experimental blocks, being exposed to light of either low (2800 K) or high (6500 K) CCT for 15 min before and 5 min during each task. Given that this was the first study on light effects on listening effort, we decided to only include two difficulty levels and to focus on lower difficulty levels where task difficulty and lighting condition should not interact.[1] Consequently, we predicted two additive main effects: a CCT effect, that is, higher cardiovascular reactivity in the 2800 K condition compared to 6500 K condition, and a task difficulty effect, that is, higher cardiovascular reactivity in the 2-back task than in the 1-back task.

1. Method

1.1. Participants and study design

Eighty-six[2] volunteers participated in our study for a monetary reward (ca. USD 33). They were recruited through an online announcement board of the university. We invited people who indicated having no artificial cardiac pacemaker, no cardiovascular diseases, and not taking antidepressants as well as not having participated in previous studies on light and effort in our laboratory. Participants were instructed to refrain from coffee, nicotine, sports, and heavy meals for at least 2 h before the experimental session. None of participants had a color deficiency, which was assessed with Ishihara's color deficiency test (Ishihara, 2016). We run the experiment in individual sessions. The participants were randomly assigned to one of the lighting conditions (between-persons) and completed 2 blocks of an auditory n-back task (Kirchner, 1958) varying in difficulty (low difficulty/1-back vs. moderate difficulty/2-back, within-persons). Allocation of participants to the experimental conditions was counterbalanced in terms of sex, time of day (morning vs. afternoon), and order of 1-back and 2-back tasks. We discarded 11 participants from the final analysis: in 9 participants' ICG recordings were too noisy due to technical failure, and 2 participants did not follow or did not completely understand the experimental instructions (one participant had a success rate of only 16% in 1-back and 51% in 2-back tasks, while the other only obtained 51% accuracy rate in both 1-back and 2-back tasks). This left 77 participants for the final sample (mean age = 23.38, *SD* = 3.52, age range 18–35 years; 47 women and 30 men).

1.2. Lighting conditions

Lighting conditions were presented by a lighting panel (width 220 cm, height 140 cm), which was mounted vertically on a wall at height of 80 cm from floor. It consisted of 24 LED panels (RGB + White) each

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[1] The decision to refrain from examining task difficulty levels where an interaction between the two variables would be expected was based on the fact that it requires extensive pre-testing to find the "sweet spot" where low CCT/alertness results in disengagement, but high CCT/alertness still leads to effort investment.

[2] We aimed at testing 94 persons, but due to limited project duration and several no-shows, we could test only a total of 86 participants. Our sample size calculation was based on our power analysis executed using G*Power software, choosing F test family and an ANOVA statistical test. Effect size f was set to 0.255 (effect size from previous study on light effects (Lasauskaite & Cajochen, 2018)), alpha error probability to 0.05, power to 0.80, and correlation between repeated measures 0.5. Sample size calculations for task difficulty effects on effort, based on effect size from Richter et al. (2008) ($f = 0.562$) suggested a sample size of 22 participants. We opted for the higher sample size that the light effects power analysis indicated. The final sample of 77 participants used for data analysis had a power of 0.60.

containing 144 LEDs (i.e., a total of 3456 LEDs) and was covered by a diffuser. We aimed at analogous experimental settings and lighting conditions as in previous studies (Lasauskaite & Cajochen, 2018; Lasauskaite et al., 2019). Lighting scenarios of 2800 K and 6500 K were used as experimental conditions. The spectral power distributions for both conditions are presented in Fig. 1. Light with a correlated color temperature of 2800 K contains fewer short wavelength light components within the spectrum. Thus, the light appears to be more yellowish and is described in the everyday language as “warm”. On the contrary, 6500 K color temperature contains more short wavelength (blue) light components within the light spectrum, this way appears to be more bluish, and in everyday language is described as “cool”. Thus, low correlated color temperature (2800 K) refers to “warm” appearing white light, while high correlated color temperature (6500 K) refers to “cool” appearing white light. The lighting conditions chosen for this study were the two most extreme conditions in the previous study by Lasauskaite and Cajochen (2018) regarding CCT. According to our theoretical predictions, the active component within the light spectrum is short wavelength (blue) light proportion. Thus, for the baseline, we used the condition with the least of this component, and then, for the experimental light, we aimed at comparing low and high proportions of this component, using low and high CCT spectra. This implied that for the low CCT experimental group, the light did not change. Parameters of lighting conditions are listed in Table 1, and the values of the spectral measurements are provided in the Supplement 1. We took the measurements vertically at 120 cm height from floor and 100 cm distance from the panel corresponding to the eye level of a sitting person (Fig. 2). During the experimental session, lighting scenarios were manipulated from the experimenter’s room using DMXControl software (version 2.12.2, DMXControl Projects e.V., Berlin, Germany).

1.3. Measurements and apparatus

To determine cardiac PEP, an impedance cardiogram (ICG) and an electrocardiogram (ECG) were simultaneously recorded non-invasively via a Cardioscreen apparatus (medis. Medizinische Messtechnik GmbH, Ilmenau, Germany) with a sampling rate of 1000 Hz. For the assessment, electrodes were attached to the base of the left side of the neck and on the left middle axillary line at the height of xiphoid.

In order to control for potential preload (ventricular filling) or afterload (arterial pressure) effects on PEP (Krohova et al., 2017; Sherwood et al., 1990), we also measured systolic blood pressure (SBP), diastolic blood pressure (DBP), and heart rate (HR). Blood pressure was measured continuously beat-to-beat and non-invasively using a SOMNOtouch-NIPB device (SOMNOmedics GmbH, Randersacker, Germany) using pulse transit time technique (see Bilo et al., 2015 for a validation). For this device, a set of four disposable electrodes was attached to the torso and a soft silicone finger sensor for photoplethysmography was mounted.

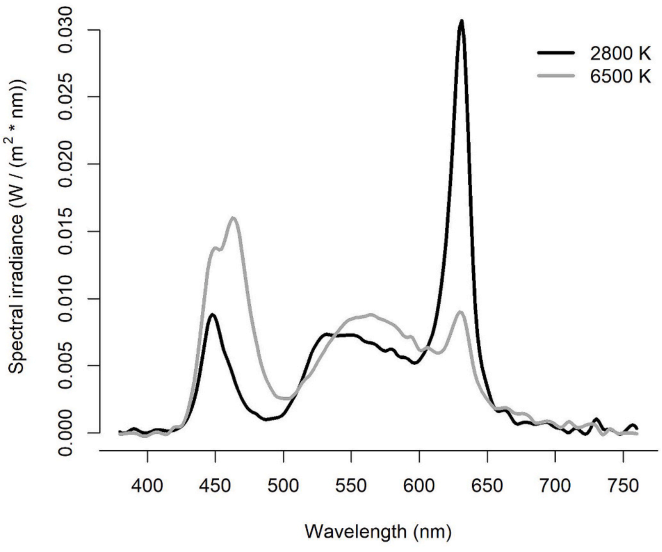

Fig. 1. Spectral power distributions for the experimental lighting conditions. Baseline lighting was identical to the 2800 K condition. Spectral power distribution values are presented in the Supplement.

1.4. Procedure

The study was run in a sound-attenuated room under light, temperature, and humidity-controlled conditions. Experimental sessions were scheduled in the morning (at 9am, 10am, or 11 a.m.) and afternoon (1:30pm, 2:30pm, or 3:30pm) with equal distribution by sex and experimental lighting conditions between morning and afternoon slots. The experimental procedure closely corresponded to a study by Lasauskaite and Cajochen (2018) and was approved by the corresponding review board. After arriving at the lab, participants were seated in a comfortable chair and read and signed the consent form. Afterwards, the experimenter applied the electrodes and went to the control room with closed doors. The experimental procedure was fully computerized (Inquisit 4 Lab, Millisecond Software, Seattle, WA) and consisted of two identical blocks. Before starting the first block, participants were given the possibility to practice for both task difficulty levels with 15 task items—1-back and 2-back tasks. For the n-back task, different tones from a set of 11 tones of frequencies from 290 Hz to 590 Hz, in steps of 30 Hz, were presented. For the 1-back task, participants had to decide whether the presented tone corresponded to the preceding tone. For the 2-back task, participants had to decide whether the presented tone corresponded to the tone presented two tones before. The total trial duration was 2000 ms. It consisted of a tone presentation (500 ms) and a time for response (1500 ms). In total, 150 tones were presented during 5 min. Each of the blocks started with a habituation phase of 10 min under 2800 K lighting conditions, which was announced as “the first part of the relaxation phase”. After this phase, participants were informed through the message on the computer screen that the light at the workplace will be adjusted, and they will continue with the “second relaxation phase”, which lasted 15 min. At this point, the light was immediately switched to the experimental condition–either 2800 K (meaning no change from the baseline level) or 6500 K–for the exposure phase and the subsequent task performance. During the habituation and exposure periods, participants were offered some popular magazines to read. Participants rated their subjective sleepiness levels on the Karolinska Sleepiness Scale (KSS; Åkerstedt & Gillberg, 1990; Kaida et al., 2006) and reported their current mood with two positive (*cheerful* and *happy*) and two negative (*sad* and *depressed*) hedonic tones from the Matthews et al. UWIST Mood Adjective Checklist (UMAC; Matthews et al., 1990) on a scale from 1 (*not at all*) to 7 (*very much*) five times throughout the session: at the beginning of the experiment, after each of the exposure phases, and after each of the tasks, as mood can affect effort investment (Gendolla, 2000; Gendolla et al., 2006; Richter & Knappe, 2014). After each experimental blocks, participants provided subjective ratings on task difficulty, amount of invested effort, and their capability to perform the task (we used the same items that were successfully used by Lasauskaite and Cajochen and numerous other studies on effort investment)—as they can moderate effort investment (Wright, 1998). At the end of the session, participants rated the lighting conditions in terms of perceived glare, visual comfort, color temperature of light, and preference of color temperature. The four items were adapted from the German questionnaire for evaluation of lighting situations (Moosmann & Vandahl, 2015) on a scale from 1 to 7. The timeline of the experimental procedure is outlined in Fig. 3. After the experiment, participants were thanked, debriefed, and received their monetary remuneration. The experimenter was not aware of the allocated experimental condition, and the light was set to the baseline level before the experimenter

Table 1
Parameters for lighting conditions.

Lighting condition	Illuminance (lux)	CCT (K)	CIE 1931 xy Chromaticity		CRI	α-opic equivalent daylight (D65) illuminance (lux)(CIE S 026 α-OpicToolbox, 2020; CIE S 026/E, 2018)				
			x	y		Melanopic	S-cone-opic	M-cone-opic	L-cone-opic	Rhodopic
2800 K	502.80	2814	0.43	0.37	81.80	246.17	261.85	397.00	511.56	286.87
6500 K	502.97	6454	0.30	0.30	86.06	462.20	577.69	479.58	504.55	452.50

Note. CCT correlated color temperature, *CRI* color rendering index.

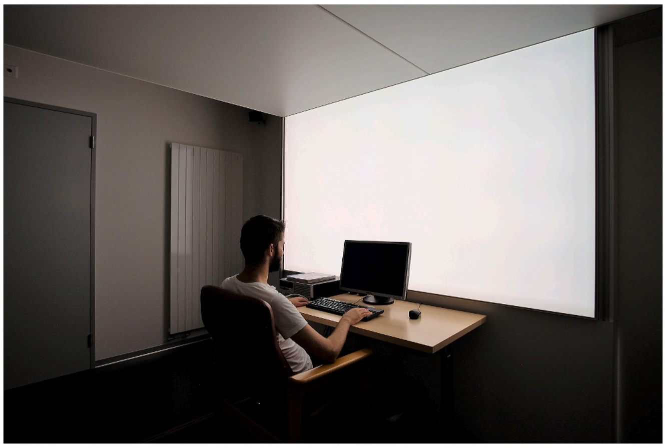

Fig. 2. Laboratory setting. From "Four minutes might not be enough for color temperature of light to affect subjective sleepiness, mental effort, and light ratings," by R. Lasauskaite, E.M. Hazelhoff, and C. Cajochen, 2019, *Lighting Research & Technology*, 51, p. 1128–1138. Copyright 2019 by SAGE. Reprinted with permission.

entered the room for debriefing.

1.5. Data analysis

The ECG and ICG signals were processed offline with a software developed by Richter (2010). Valid heartbeat cycles were selected and averaged over 1-min periods. Cardiac PEP (in ms) was determined as the time interval between the R-onset of the ECG and B-point of the ICG (Berntson et al., 2004). The B-point was visually detected and manually marked for each averaged minute of each period for every participant without access to information about experimental conditions. Physiological reactivity scores were calculated individually by subtracting the average of the measures obtained during the last 4 min of baseline from the scores obtained during the exposure (15 min) and the task performance (5 min) period, respectively. This procedure was applied for each block separately, considering the respective baseline. More negative PEP reactivity scores indicate stronger contractility and higher sympathetic activity in reference to baseline. We used Levene's test of equality of variance. Data were inspected for potential outliers by plotting descriptives for each experimental condition. The values were judged from the physiological point of view. For PEP, values ranged from 66 to 100 ms, SBP from 81 to 178 mm/Hg, DBP from 47 to 112 mm/Hg, and HR from 48 to 93 bpm. We judged these values as plausible and therefore included them into analyses. To test our hypotheses concerning task difficulty and light effects on cardiovascular reactivity during task performance, we employed mixed ANOVAs with task difficulty (1-back vs. 2-back) and light (2800 K vs. 6500 K) factors. We also ran the same test on task performance and self-reported measures. To control for potential confounding variables, we also ran separate ANCOVAs on cardiovascular reactivity scores including (1) respective cardiovascular baseline scores, (2) sleepiness baseline and change scores, (3) mood baseline and change scores, and (4) light ratings as covariates. The results of these ANCOVAs are reported in the respective sections. Given that light had effects during the light exposure period (experimental phase prior to task performance, see Fig. 3) in a previous study (Lasauskaite & Cajochen, 2018), we also ran the same analysis for exposure phase for exploratory purposes. Sleepiness and mood ratings at baseline were subtracted from the ratings before and after the task in order to create difference scores. Subsequently, they were analysed with mixed 2 (difficulty) × 2 (light) × 2 (time: before task, after task) ANOVA. Task ratings were analysed using 2 (difficulty) × 2 (light) mixed ANOVAs and effects on light ratings were tested using Student t-tests. Analyses were performed with R package "afex" (Singmann et al., 2021) and base functions.

2. Results

2.1. Cardiovascular baseline scores

Cardiovascular baselines scores for PEP, SBP, DBP, and HR were calculated as averages of the last 4 min of the baseline period, which provided stable values (McDonald's ωs > 0.97). Cell means and standard errors appear in Table 2. The 2 (task difficulty) × 2 (light) ANCOVAs, with baseline values as covariates, did not yield any significant associations between baseline scores and reactivity scores ($ps > .09$). None of the main effects of CCT and task difficulty were significant in ANCOVAs (cardiac PEP task difficulty effect, $F(1, 73) = 0.15$, $p = .695$, $\eta^2_G < 0.001$, CCT effect, $F(1, 73) = 0.16$, $p = .663$, $\eta^2_G = 0.002$, SBP task difficulty effect, $F(1, 67) = 0.74$, $p = .392$, $\eta^2_G = 0.005$, CCT effect, $F(1, 67) = 0.05$, $p = .828$, $\eta^2_G < 0.001$, DBP task difficulty effect, $F(1, 61) = 1.57$, $p = .215$, $\eta^2_G = 0.012$, CCT effect, $F(1, 61) = 0.17$, $p = .680$, $\eta^2_G = 0.002$, HR task difficulty effect, $F(1, 72) = 3.35$, $p = .071$, $\eta^2_G = 0.017$, CCT effect, $F(1, 72) = 0.95$, $p = .333$, $\eta^2_G = 0.008$).

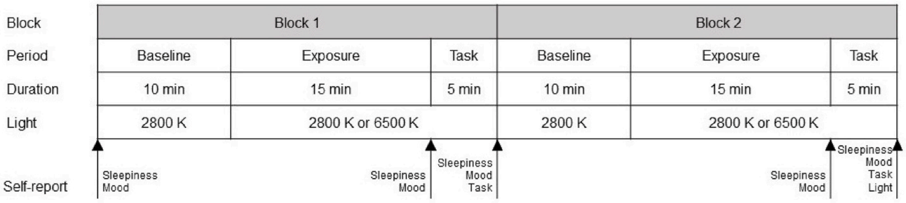

Fig. 3. The experimental procedure consisted of two identical blocks with the only difference of task difficulty (1-back or 2-back, in a randomized counterbalanced order, within-persons) under 2800 K or 6500 K experimental light conditions (between-persons).

Table 2
Cell means and standard errors (in brackets) of cardiovascular baseline scores.

	N	2800 K		*N*	6500 K	
		1-back	2-back		1-back	2-back
PEP	37	98.99 (1.72)	99.36 (1.67)	40	99.71 (2.01)	100.03 (1.97)
SBP	33	116.92 (2.47)	116.91 (2.36)	38	112.53 (2.31)	112.36 (2.36)
DBP	30	71.25 (1.38)	71.33 (1.45)	35	68.68 (1.84)	68.70 (1.77)
HR	37	71.31 (1.26)	70.45 (1.21)	39	73.14 (1.58)	72.39 (1.64)

Note. PEP: pre-ejection period (in ms); SBP: systolic blood pressure (in mmHg); DBP: diastolic blood pressure (in mmHg); HR: heart rate (in beats per minute).

2.2. Cardiovascular reactivity

The 1-min reactivity scores for PEP, SBP, DBP, and HR were averaged throughout the exposure and task periods for each block (McDonald's $\omega s > .97$). Cell means and standard errors for each cardiovascular measure are provided in Table 3.

2.3. Cardiac PEP reactivity

Firstly, we ran a 2 (task difficulty) × 2 (light) mixed ANOVA on PEP reactivity scores during task performance. As predicted, there was a significant light effect, $F(1, 75) = 4.20$, $p = .044$, $\eta_G^2 = 0.044$, due to a stronger reactivity under 2800 K light ($M = -2.40$, $SE = 0.61$, 95% CI [−3.61, −1.9]) than under 6500 K light ($M = -0.54$, $SE = 0.39$, 95% CI [−1.32, 0.25]). The main effect for task difficulty and the interaction of factors (CCT × task difficulty) were not significant ($ps > .068$). The same analysis for the light exposure period did not show any significant effects ($ps > .308$).[3] A full report of statistical tests can be found in Supplement 2. Reactivity scores for each period and for each of lighting conditions, averaged for both task difficulty levels, are depicted in Fig. 4 (left panel). Cell means and standard errors measure for light exposure and task periods are provided in Table 3.

Table 3
Cell means and standard errors (in brackets) of cardiovascular reactivity scores during light exposure and during task performance period.

	2800 K			6500 K		
	N	1-back	2-back	*N*	1-back	2-back
Exposure						
PEP	37	−0.20 (0.31)	−0.40 (0.32)	40	−0.37 (0.30)	0.02 (0.29)
SBP	33	−0.02 (0.26)	−0.22 (0.35)	38	0.09 (0.30)	−0.12 (0.22)
DBP	30	−0.05 (0.20)	−0.31 (0.21)	35	0.03 (0.22)	−0.15 (0.19)
HR	37	−0.32 (0.39)	0.09 (0.37)	39	−0.93 (0.41)	−0.30 (0.36)
Task						
PEP	37	−2.26 (0.82)	−2.55 (0.91)	40	−1.20 (0.54)	0.12 (0.57)
SBP	33	2.53 (0.51)	2.53 (0.71)	38	0.79 (0.45)	0.74 (0.54)
DBP	30	1.38 (0.38)	1.55 (0.49)	35	0.82 (0.34)	0.85 (0.39)
HR	37	−0.05 (0.75)	1.67 (0.77)	39	−0.75 (0.55)	0.86 (0.51)

Note. PEP: pre-ejection period (in ms); SBP: systolic blood pressure (in mmHg); DBP: diastolic blood pressure (in mmHg); HR: heart rate (in beats per minute).

2.4. SBP reactivity

A 2 (task difficulty) × 2 (light) mixed ANOVA showed a significant main effect of light, $F(1, 69) = 7.33$, $p = .009$, $\eta_G^2 = 0.068$, where, corresponding to cardiac PEP, reactivity was again stronger for the 2800 K lighting condition ($M = 2.53$, $SE = 0.43$, 95% CI [1.66, 3.39]) than the 6500 K condition ($M = 0.77$, $SE = 0.35$, 95% CI [0.07, 1.46]). The main effects of task difficulty and interaction factor were not significant ($ps > .950$). The same analysis for light exposure period did not show any significant effects ($ps > .479$).[4] A full report of statistical tests can be found in Supplement 2. The reactivity scores for each period and for each of lighting conditions are depicted in Fig. 4 (right panel). Cell means and standard errors measure for light exposure and task periods are provided in Table 3.

2.5. DBP reactivity

There were no significant effects running 2 (task difficulty) × 2 (light) mixed ANOVA on DBP reactivity scores during task performance ($ps > .204$) nor during light exposure ($ps > .350$).[5] A full report of statistical tests can be found in Supplement 2. Cell means and standard errors measure for light exposure and task periods are provided in Table 3.

2.6. HR reactivity

The same 2 (task difficulty) × 2 (light) mixed ANOVA of HR reactivity scores during task performance showed a significant effect for task difficulty, $F(1, 74) = 13.05$, $p < .001$, $\eta_G^2 = 0.043$, with higher reactivity during the 2-back task ($M = 1.25$, $SE = 0.45$, 95% CI [0.5, 2.16]) compared to 1-back task ($M = -0.41$, $SE = 0.46$, 95% CI [−1.32, 0.51]). The main effect of light and the interaction factor were not significant ($ps > .345$). A 2-way mixed ANOVA of HR reactivity during light exposure did not show any significant effects ($ps > .169$).[6] A full report of statistical tests can be found in Supplement 2. Cell means and standard errors measure for light exposure and task periods are provided in Table 3.

2.7. Task performance

A 2 (light) × 2 (task difficulty) mixed ANOVA on n-back accuracy scores showed a significant main effect of task difficulty, $F(1, 75) = 85.42$, $p < .001$, $\eta_G^2 = 0.298$. Participants were more accurate in the 1-back ($M = 0.98$, $SE = 0.04$, 95% CI [0.98, 0.99]) than in the 2-back condition ($M = 0.87$, $SE = 0.12$, 95% CI [0.84, 0.90]), which demonstrates a successful task difficulty manipulation. The main effect of light and the interaction factor did not yield significances ($ps > .623$). A full report of statistical tests can be found in Supplement 2.

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[3] For readers, who are interested in a combined analysis including exposure and task periods into one design, we report that 2 (period: exposure, task) × 2 (task difficulty) × 2 (light) mixed ANOVA of cardiac PEP reactivity scores showed a significant main effect of period, $F\ (1, 150) = 6.20$, $p = .014$, $\eta_G^2 = 0.031$, significant light effect, $F(1, 150) = 4.27$, $p = .041$, $\eta_G^2 = 0.022$, and significant light × task difficulty interaction, $F(1, 150) = 4.45$, $p = .037$, $\eta_G^2 = 0.007$. Other effects and factor interactions were not significant ($ps > .074$).

[4] For readers, who are interested in a combined analysis including exposure and task periods into one design, we report that 2 (period: exposure, task) × 2 (task difficulty) × 2 (light) mixed ANOVA of SBP reactivity scores showed a significant period main effect, $F(1, 138) = 21.61$, $p < .001$, $\eta_G^2 = 0.092$, significant light main effect, $F(1, 138) = 5.47$, $p = .021$, $\eta_G^2 = 0.025$, and significant period × light interaction, $F(1, 138) = 6.90$, $p = .010$, $\eta_G^2 = 0.092$. Other main effects and interactions were not significant ($ps > .658$).

[5] For readers, who are interested in a combined analysis including exposure and task periods into one design, we report that 2 (period: exposure, task) × 2 (task difficulty) × 2 (light) mixed ANOVA of DBP reactivity scores showed significant period main effect, $F(1, 126) = 22.73$, $p > .001$, $\eta_G^2 = 0.108$. Other effects and interactions were not significant ($ps > .157$).

[6] For readers, who are interested in a combined analysis including exposure and task periods into one design, we report that 2 (period: exposure, task) × 2 (task difficulty) × 2 (light) mixed ANOVA of HR reactivity scores showed significant task difficulty main effect, $F(1, 148) = 13.51$, $p < .001$, $\eta_G^2 = 0.028$. Other effects and interactions were not significant ($ps > .057$).

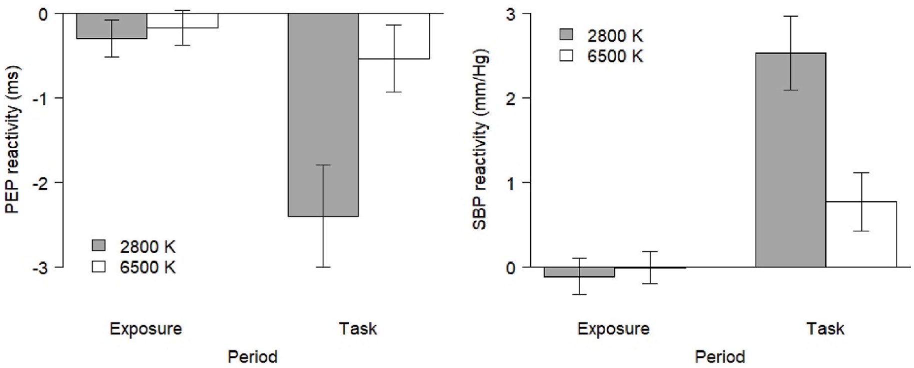

Fig. 4. Reactivity scores and standard errors for cardiac PEP (left panel) and SBP (right panel) for each lighting condition during exposure and task performance periods, averaged over both task difficulty levels.

2.8. Self-report measures

Sleepiness. KSS baseline ratings (Table 4) were subtracted from the ratings before and after the task in order to create difference scores. A preliminary 2 (light) × 2 (task difficulty) × (time) mixed ANCOVA of these difference scores with KSS baseline ratings as covariate found a significant association with baseline scores ($p < .001$). Thus, we employed an ANCOVA as main analysis of difference scores with the baseline as covariate. A 2 (light) × 2 (task difficulty) × (time) mixed ANCOVA of KSS difference scores showed significant time effect, $F(1, 74) = 8.06$, $p = .006$, $\eta^2_G = 0.015$, as participants were less sleepy after the task performance ($M = 1.22$, $SE = 0.15$, 95% CI [0.92, 1.52]) than before ($M = 1.66$, $SE = 0.15$, 95% CI [1.36, 1.95]). Furthermore, task difficulty × time factor interaction yielded significance, $F(1, 74) = 9.41$, $p = .003$, $\eta^2_G = 0.011$ (1-back: before task $M = 1.60$, $SE = 0.22$, 95% CI [1.6, 2.04], after task $M = 1.53$, $SE = 0.23$, 95% CI [1.08, 1.98]; 2-back: before task $M = 1.71$, $SE = 0.21$, 95% CI [1.30, 2.12], after task $M = 0.91$, $SE = 0.20$, 95% CI [0.50, 1.31]), meaning that the alerting effect of the task was more pronounced in the 2-back task (moderate difficulty level) condition than in the 1-back (easy) task condition. A full report of statistical tests can be found in Supplement 2. Cell means and standard errors for difference scores are presented in Table 5.

In order to explore whether the observed cardiovascular effects can be explained by subjective sleepiness, we performed 2 (light) × 2 (task difficulty) ANCOVAs of cardiovascular measures with KSS ratings (baseline and change scores) as covariates. We found no associations for PEP and HR reactivity ($ps > .056$). A significant association with change in sleepiness before the 2-back task was found for SBP reactivity ($p = .036$) but adding these scores as covariates to the analysis did not change the results. Finally, sleepiness change score before 2-back task was significantly associated with DBP reactivity during the task ($p = .007$), without changing results on DBP reactivity by adding this sleepiness difference score as a covariate.

Task ratings. We performed corresponding 2 (light) × 2 (task difficulty) mixed ANOVAs on task difficulty, capability to perform, and invested effort ratings. Task difficulty was rated as higher in 2-back task condition ($M = 5.34$, $SE = 0.14$, 95% CI [5.07, 5.61]) compared to 1-back task condition ($M = 2.57$, $SE = 0.17$, 95% CI [2.23, 2.92]), $F(1, 75) = 377.41$, $p < .001$, $\eta^2_G = 0.514$, indicating successful task difficulty manipulation. Also, interaction between task difficulty and light condition was significant, $F(1, 75) = 4.29$, $p = .042$, $\eta^2_G = 0.012$ (2800 K 1-back $M = 2.78$, $SE = 0.29$, 2-back $M = 5.24$, $SE = 0.21$, 6500 K 1-back $M = 2.38$, $SE = 0.19$, 2-back $M = 5.43$, $SE = 0.17$), as the difference in subjective task difficulty between 1-back and 2-back tasks was more pronounced in the 6500 K than 2800 K condition. Main effect of light was not significant ($p = .682$). Ratings of the capability to perform also showed a significant main effect of task difficulty, $F(1, 75) = 160.12$, $p < .001$, $\eta^2_G = 0.375$, as participants regarded their capability to perform as higher for 1-back task ($M = 5.35$, $SE = 0.17$, 95% CI [5.01, 5.70]) compared to 2-back task ($M = 3.27$, $SE = 0.15$, 95% CI [2.98, 3.56]). The main effect of light and the light × task difficulty interaction were not significant ($ps > .355$). Finally, a 2-way mixed ANOVA of invested effort ratings also revealed significant task difficulty effect (1-back $M = 3.45$, $SE = 0.19$, 95% CI [3.08, 3.83]; 2-back $M = 5.64$, $SE = 0.13$, 95% CI [5.38, 5.90]), $F(1, 75) = 165.08$, $p < .001$, $\eta^2_G = 0.373$. The main effect of light and interaction factor were not significant ($ps > .141$). A full report of statistical tests can be found in Supplement 2. Cell means and standard errors for each condition are presented in Table 6.

Table 4
Baseline scores and standard errors (in brackets) for sleepiness and summed mood ratings.

	N	2800 K	*N*	6500 K
Sleepiness	37	3.65 (0.26)	40	3.88 (0.27)
Mood	37	23.78 (0.47)	40	23.80 (0.45)

Table 5
Rating differences from baseline and standard errors (in brackets) for sleepiness and mood.

	2800 K			6500 K		
	N	1-back	2-back	*N*	1-back	2-back
Before task						
Sleepiness	37	1.73 (0.36)	1.89 (0.30)	40	1.48 (0.28)	1.55 (0.29)
Mood	37	−0.95 (0.47)	1.22 (0.61)	40	0.00 (0.30)	−0.12 (0.31)
After task						
Sleepiness	37	1.84 (0.35)	1.03 (0.31)	40	1.25 (0.28)	0.80 (0.27)
Mood	37	−0.84 (0.32)	−1.08 (0.48)	40	−0.10 (0.30)	−0.75 (0.38)

Mood. Mood scores were calculated by summing positive and inverse-coded negative affect items for each of measure points (McDonald's ωs > 0.80). Subsequently, mood baseline score (Table 4) was subtracted from the ratings before and after the task, in order to create difference scores. Cell means and standard errors appear in Table 5. Preliminary 2 (time: before task, after task) × 2 (light) × 2 (task

Table 6
Cell means and standard errors (in brackets) for task ratings.

	2800 K			6500 K		
	N	1-back	2-back	*N*	1-back	2-back
Task difficulty	37	2.78 (0.29)	5.24 (0.21)	40	2.38 (0.19)	5.43 (0.17)
Capability to perform	37	5.35 (0.26)	1.19 (0.20)	40	5.35 (0.23)	1.36 (0.22)
Invested effort	37	3.59 (0.30)	5.51 (0.21)	40	3.33 (0.24)	5.75 (1.56)

difficulty) mixed ANCOVA did not find significant association between mood baseline and change scores ($p = .062$). A 2 (light) × 2 (task difficulty) × 2 (time) mixed ANOVA of difference scores did not show any significant effects ($ps > .073$). A full report of statistical tests can be found in Supplement 2.

Light ratings. Light of 2800 K ($M = 3.59$, $SE = 0.22$, 95% CI [3.15, 4.04]) was rated warmer than 6500 K ($M = 2.50$, $SE = 0.18$, 95% CI [2.15, 2.85]), $t(71) = 3.92$, $p < .001$. Light color preference ratings, as well as light comfort and glare ratings, did not differ between the two lighting conditions ($ps > .06$). A full report of statistical tests can be found in Supplement 2. Cell means and standard errors are presented in Table 7. Also relevant, additional ANCOVAs for PEP and SBP scores did not find significant associations with light ratings ($ps > .17$), making it unlikely that light appraisals might have driven lighting effects. The only significant association was between SBP scores and light color ratings ($p < .001$), but even after controlling for color ratings, the light effect on SBP was still significant ($F(1, 65) = 18.37$, $p < .001$, $\eta^2_G = 0.157$).

3. Discussion

The present study tested hypotheses of the impact of CCT of light and task difficulty on effort. In support of our prediction and replicating previous findings (Lasauskaite & Cajochen, 2018), exposure to differential light color temperature (2800 K vs. 6500 K) affected cardiac PEP response, which was our primary indicator of effort mobilization (Kelsey, 2011; Wright, 1996). In addition, the light spectrum also affected SBP, which is systematically influenced by cardiac contractility. Participants invested more effort—that is, they had stronger PEP and SBP responses—after spending 15 min and subsequently working under low color temperature light (2800 K, appearing as warm light) compared to light of high color temperature (6500 K, appearing as cool light). This light effect occurred only during the cognitive task but not during the exposure period. On the other hand, contrary to our study's expectation that a moderately difficult task should lead to a stronger cardiac contractility than an easier task, task difficulty did not affect effort-related cardiovascular response. Taken together, these results support the main prediction of the theoretical model on light's impact on effort mobilization.

3.1. Task demand and mental effort

Based on both the motivational intensity theory (Brehm & Self, 1989), postulating that effort intensity is proportional to task demand, and the ample evidence that task difficulty affects cardiovascular reactivity (Brinkmann & Gendolla, 2008; Gendolla & Krüsken, 2002; Mazeres et al., 2019; Richter, 2016; Richter et al., 2008; Silvestrini & Gendolla, 2009, 2011; Wright et al., 1986, 2003), we expected a moderately difficult task to lead to stronger PEP and SBP reactivity than an easy task. Higher task accuracy scores indicated a successful difficulty manipulation for the1-back and 2-back task. Furthermore, participants also rated the task as more difficult, their work more effortful, and their ability to perform lower for the 2-back than the 1-back task. Nevertheless, and surprisingly, task difficulty effects on PEP and SBP did not yield significance, thus providing no evidence for task demand effects on effort in our study. Typically, one would expect self-report, task performance, and cardiovascular measures to show the same pattern. Previous work, however, frequently found dissociating results – diverging patterns of cardiovascular measures showing the predicted pattern, while self-report and/or performance scores did not (e.g., Brinkmann & Gendolla, 2008; Framorando & Gendolla, 2018; Richter & Gendolla, 2007). In the present study, task difficulty affected self-report and task performance, but not cardiac PEP or SBP. This divergence can have several reasons. For instance, even if we did not have any indications for insufficient data quality, the measures might have been affected by different amounts of noise ("noisy data") nevertheless. Also, the three kinds of measures assess different aspects of effort – cardiovascular measures capture momentary resource mobilization, self-report measures retrospective subjective judgments. At the same time, task performance shows behavioral outcomes affected by effort, but not exclusively. Although the task difficulty manipulation did not affect PEP and SBP reactivity—the main indicators of effort—task difficulty had an effect on HR during task performance, with stronger reactivity for the 2-back task compared to the 1-back task under both lighting conditions. This result is, however, not interpretable as a difficulty effect on effort, because HR is a more ambiguous indicator of sympathetic activity. For example, higher HR may be due to increased sympathetic autonomic nervous system activity, but also because of a decreased parasympathetic activity. As a next step, future experiments should test the interaction between CCT and task difficulty by including difficult tasks. Besides lower effort under higher CCT and higher effort under lower CCT light for easy and moderately difficult tasks, for difficult tasks, low effort under low CCT light (disengagement) and high effort under high CCT would be expected.

Table 7
Cell means and standard errors (in brackets) of light ratings.

	N	2800 K	*N*	6500 K
Light color	37	3.59 (0.22)	40	2.50 (0.18)
Light color preference	37	4.57 (0.20)	40	5.10 (0.19)
Light comfort	37	4.46 (0.28)	40	3.90 (0.25)
Glare	37	3.19 (0.32)	40	3.95 (0.31)

3.2. CCT and mental effort

As predicted, we found a significant effect of CCT on PEP reactivity. In addition, SBP responses were also significantly affected by the lighting conditions. Both cardiovascular markers indicated higher effort mobilization during task performance under 2800 K than 6500 K. Even though PEP is the most sensitive measure of effort (Kelsey, 2011), SBP is also largely influenced by the beta-adrenergic sympathetic impact on the heart. It has been used as effort indicator in numerous studies (see Gendolla et al., 2012; Richter et al., 2016), even though SBP is also influenced by peripheral vascular resistance. Not surprisingly, the light colour temperature had no significant effects on DBP and HR. DBP is less influenced by the beta-adrenergic sympathetic impact on the heart but more affected by total peripheral resistance. HR is influenced by both the sympathetic and parasympathetic nervous systems. Thus, influences by the sympathetic nervous system on HR might be masked. Importantly, decreases in PEP and increases in SBP were not accompanied by reductions in DBP and HR. This makes it unlikely that PEP and SBP were influenced by preload—ventricular filling, which can influence the force of myocardial contraction and thus affect PEP, or afterload—the pressure against which the heart must work to open the aortic valve and to eject blood into the aorta, which also influences PEP—effects (Sherwood et al., 1990). This allows us to interpret decreased PEP (and increased SBP) as reflecting increases in beta-adrenergic activity.

In contrast to the previous study by Lasauskaite and Cajochen (2018), there was no influence of the color of light on cardiovascular reactivity during the 15-min light exposure (relaxation) period; that is, reactivity scores did not differ from baseline. This suggests that the observed light effects on effort were specific for cognitive load, and solely changing the lighting color temperature might not be sufficient to affect cardiovascular reactivity. However, it is unclear why the results in the current and previous studies differ. One possible explanation might be that participants learned about the cognitive task and had practice trials before starting the baseline and exposure periods in the current study. This way, they already knew what to expect for the task period. On the contrary, in our previous study (Lasauskaite & Cajochen, 2018), participants only learned about the task after the exposure phase, which might have led to anticipation of a cognitive challenge during that period. If this led to additional mental load, then light might have influenced the higher or lower engagement. Having eliminated this, light did not have effects on cardiovascular activity during exposure phase in the current study, which could explain the difference of the results during the light exposure in our both studies.

An interesting research question would be to test how CCT of light would affect effort in the case of a difficult task. Low CCT of light should lead to higher perceived task difficulty, therefore resulting in disengagement for a difficult task. Effort should be higher under low CCT compared to high CCT when working on an easy or moderate difficulty task. In contrast, for a difficult task this effect should be reversed as people would be expected to disengage, which would mean high effort for high CCT light and low effort for low CCT light condition. The design of the present study did not allow us to test this hypothesis as participants worked on low and moderate difficulty tasks but not on a high difficulty task.

3.3. *CCT and task performance*

Lighting manipulations in our experiment did not affect task performance – participants in both lighting conditions performed as good. This is consistent with previous studies (Lasauskaite & Cajochen, 2018; Lasauskaite et al., 2019), in which neither response accuracy nor response time was affected by lighting conditions. To put it in context, findings of daytime effects of light on cognitive performance are mixed: some studies found effects (Baek & Min, 2015; Hawes et al., 2012; Viola et al., 2008) whereas others did not (Cajochen et al., 2019; Ru et al., 2019; Sahin et al., 2014). Thus, light may have effects on task performance in combination with other factors that are not apparent to date. To be clear, we did not anticipate performance effects accompanying changes in effort. Effort and performance are two different concepts. Performance can but does not always correspond to the amount of invested effort, as performance (behavioral outcome) depends not only on effort alone but also on other factors like ability and strategy (Locke & Latham, 1990).

3.4. *Subjective alertness and mental effort*

Subjective sleepiness (KSS) scores were higher before than after the task. A potential explanation for this could be that the activity (reading magazines) during light exposure was rather relaxing subsequently increasing sleepiness. The task itself was alerting, leading to lower sleepiness scores. The same logic explains the interaction with task difficulty: the 2-back task was more challenging than the 1-back task. The effects were mainly driven by decreased sleepiness after the 2-back task condition in comparison to before the task.

We theorized that light should affect effort mobilization by inducing alertness, affecting task difficulty appraisal and thus effort. Yet, in our study, there were no indications that light affected subjective alertness (assessed as self-reported sleepiness using KSS) or that sleepiness was associated with the effects on cardiovascular reactivity. Even if other studies showed that light could affect subjective sleepiness during daytime (Smolders et al., 2012; te Kulve et al., 2017), our results do not support this concept. Furthermore, task difficulty ratings did not differ between lighting conditions either, indicating the lack of support for this additional element in our predicted mechanism. Self-report measures are a limitation for testing the elements of our proposed model. They do not allow assessing states *during* task performance and only give a retrospective assessment by the person themselves. Retrospective reports can be influenced by memory and various biases such as social desirability. For instance, it is likely that participants perceive the task as more difficult and effortful during performance (which would go in line with task performance scores), but it is possible that they cannot reflect on it retrospectively, therefore the difference is not observed in self-reported measures.

Another possibility is that a different mechanism than lights' alerting property leads to light effects on effort. An alternative mechanism could be that instead of inducing a lower or higher alertness state (biological, nonvisual hypothesis), CCT affects effort by activating cognitive associations with warm-appearing light vs. cool/cold-appearing light (psychological, visual hypothesis). Warm-appearing light is potentially associated with relaxation, evening, fatigue concepts and therefore lower alertness, leading to higher task demand appraisal and thus higher effort for easy and moderate tasks, or to disengagement for difficult tasks. In contrast, cool-appearing light might be associated with higher alertness, daytime, readiness, performance, and energy concepts and thus might lead to lower task demand appraisal and therefore lower effort. Our current study design was not suitable to test this idea. A way to test these contrasting hypotheses – biological and psychological – would be by using metameric lighting conditions. Metameric light stimuli have different spectral power distributions but the same color and illuminance. If the biological hypothesis is true, cardiovascular outcomes would respond to changes in spectrum and not in color. If the psychological hypothesis is true, cardiovascular outcomes would respond to color changes but not spectrum changes.

Lighting color in the 2800 K condition did not change throughout the entire experimental session, while in the 6500 K condition, it changed from 2800 to 6500 K starting at the light exposure phase. This might also be another explanation for the observed lighting effects besides the aforementioned biological/nonvisual hypothesis. A change in lighting conditions might have an alerting effect *per se* due to attention, without necessarily having a physiological effect. If this hypothesis was true, then in the previous study employing four lighting conditions (Lasauskaite & Cajochen, 2018), one of which corresponded to baseline light, should have led to a weaker effort in conditions of 4000 K, 5000 K, and 6500 K and a stronger effort in 2800 K condition. However, the effort increased with decreasing color temperature of light. Therefore, the idea that merely changing light appearance might reduce effort mobilization seems not plausible.

3.5. *Relevance*

Findings of this current study indicate that higher color temperature of light (higher short-wavelength light proportion within the light spectrum) could be beneficial for designing places for learning and work contexts, like schools or offices. Our results show that higher CCT leads to investing fewer resources for the same performance results. Lower CCT (lower short-wavelength light proportion within the light spectrum) might even contribute to the development of essential hypertension (abnormally high blood pressure without a medical cause) and subsequently lead to cardiovascular diseases. It is important to pay attention to conditions that affect effort levels and resource investment at the workplace, as they may systematically affect cardiovascular responses (Gendolla et al., 2009; Gendolla & Richter, 2005). This would be especially applicable for places without or with limited daylight and dominant artificial ambient lighting. This study was conducted in controlled laboratory conditions with healthy young participants. Thus, we are prudent to generalize the results to real-life applications. Yet, optimal daytime lighting (higher rather than lower CCT of white light) in the contexts of learning and work may even lead to health benefits and increase well-being of indoor space occupants.

3.6. *Limitations*

The current study employed a short light exposure duration (15 min). However, in a review on acute light effects on alertness, Souman et al. (2017) considered that a few minutes up to 24h of light exposure lead to acute impacts. It is thus unclear how the longer duration of light exposure, e.g., hours, and prolonged/chronic exposure to different color temperatures of light, for instance, in office or school settings, would affect effort-related cardiac response. In addition to the study showing that short-term changes in lighting conditions *during* task performance does not affect effort-related cardiac response (Lasauskaite et al., 2019), exposure duration might be one of the parameters to be investigated in future studies to better understand the relationship between light and motivation. Furthermore, future studies should employ more conventional ceiling lighting since our results are based on a setting with a frontal lighting source along with more a prolonged light exposure especially when considering the indications that the direction of light impacts intrinsically photosensitive ganglion cells differently (Glickman et al., 2003; Rea et al., 2021; Rüger et al., 2005).

3.7. Summary

This work replicates the previously shown effect of CCT on effort-related cardiovascular response. Lower color temperature of light leads to higher effort during a mental challenge than higher color temperature also for an auditory task involving working memory performance (n-back). Together with our previous studies on lighting color temperature impact on effort, these results contribute further build the picture of light's impact on motivation. This present research is critical because it demonstrates that light affects mental effort not only for cognitive challenges solved through vision but also during an auditory short-memory task. This means that the effects of light can be attributed to motivation and effort directly and not through light's visual properties regarding the task stimuli or material.

Author statement

Ruta Lasauskaite: Conceptualization, Methodology, Formal analysis, Data Curation, Writing – Original Draft, Project Administration, Funding acquisition. **Michael Richter**: Conceptualization, Methodology, Writing – Review & Editing. **Christian Cajochen**: Resources, Writing – Review & Editing.

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Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.jenvp.2023.101976.

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