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Research paper

Influence of lighting color temperature on effort-related cardiac response

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ABSTRACT

Higher color temperature refers to a higher proportion of blue spectral components of light, that are known to be associated with higher alertness state in humans. Based on motivational intensity theory (Brehm & Self, 1989), here we predicted that this lighting-induced alertness state should inform about the readiness to perform and this way influence subjective task demand and thus mental effort. To test this, study participants spent 15 min under one of four lighting color temperature conditions and then performed a cognitive task. As predicted, effort-related cardiac response, indexed by a shortened cardiac pre-ejection period, decreased with increasing color temperature of light, as indicated by a significant single planned linear contrast. These results demonstrate that spectral properties of light can influence mental effort mobilization.

1. Introduction

Light influences a number of non-visual processes such as the human circadian timing system, sleep, alertness, mood, concentration, and mental health (Cajochen, 2007; Münch & Kawasaki, 2013; Schmidt, Chen, & Hattar, 2011). It is the short wavelength (blue) light spectral components that play an essential role in the above mentioned non-image forming effects of light prominently, but not exclusively, mediated by intrinsically photosensitive retinal ganglion cells (ipRGCs) in the mammal retina (Berson, Dunn, & Takao, 2002; Hattar, Liao, Takao, Berson, & Yau, 2002; Thapan, Arendt, & Skene, 2001). The ipRGCs are highly sensitive to short wavelength light in the blue range with a peak at ~480 nm (Berson et al., 2002; Dacey et al., 2005; Tu et al., 2005). In fact, high correlated color temperature of white light that has more blue spectral components compared to light of low correlated color was associated with higher alertness state (Chellappa et al., 2011; Viola, James, Schlangen, & Dijk, 2008). We postulate that this light-induced alertness affects mental effort through its impact on experienced task demand.

Effort refers to intensity or energization aspects of behavior (Elliot, 2006) and describes a motivational process *during*, e.g., cognitive task, rather than a behavioral outcome, i.e. performance. Only a few studies investigating non-visual effects of light spectral properties included motivation or effort as one of dependent variables, although never as primary, and they did not find any significant results. Chellappa et al. (2011) found that 6500 K (blue-enriched) light induced greater melatonin suppression, enhanced subjective alertness, well-being, and visual comfort and also led to faster reaction times in tasks associated with sustained attention but not in tasks associated with executive function, compared to 2500 K and 3000 K light. There were no significant effects on mental effort ratings. Varkevisser, Raymann, Keyson, (2011) tested the effects of two illuminance levels (45 lx and 195 lx) and different combinations of colored lights (Red-Green, Red-Blue, Green-Blue, and Red-Green-Blue) in a mock-up office. The arousing effect of color combinations with blue components was only partially observed, and effects on motivation ratings, as part of well-being measures, were not significant. So far, light effects on motivation and invested effort have only been tested via self-reports and not via more reliable objective physiological measures.

Effort is defined as mobilization of resources to carry out instrumental behavior (Gendolla & Wright, 2009). According to the energy conservation principle (Gibson, 1900), we avoid wasting resources and employ only what is necessary. Following this principle, the motivational intensity theory (Brehm & Self, 1989) posits that effort should be proportional to perceived task demand as long as success is possible and justified. Wright (1996) integrated the motivational intensity theory with the active coping approach by Obrist (1981) and proposed that effort can be indexed by beta-adrenergic sympathetic nervous system impact on the heart. Non-invasively, this is best reflected as increased cardiac contractility and thus shortened cardiac pre-ejection period (PEP)—the time interval between the onset of left ventricular excitation and the opening of the aortic valve (Berntson, Lozano, Chen, & Cacioppo, 2004). In brief, shortened cardiac PEP indicates stronger effort mobilization.

Previous research has shown that effort intensity can be influenced by different factors such as task difficulty (Richter, Friedrich, &

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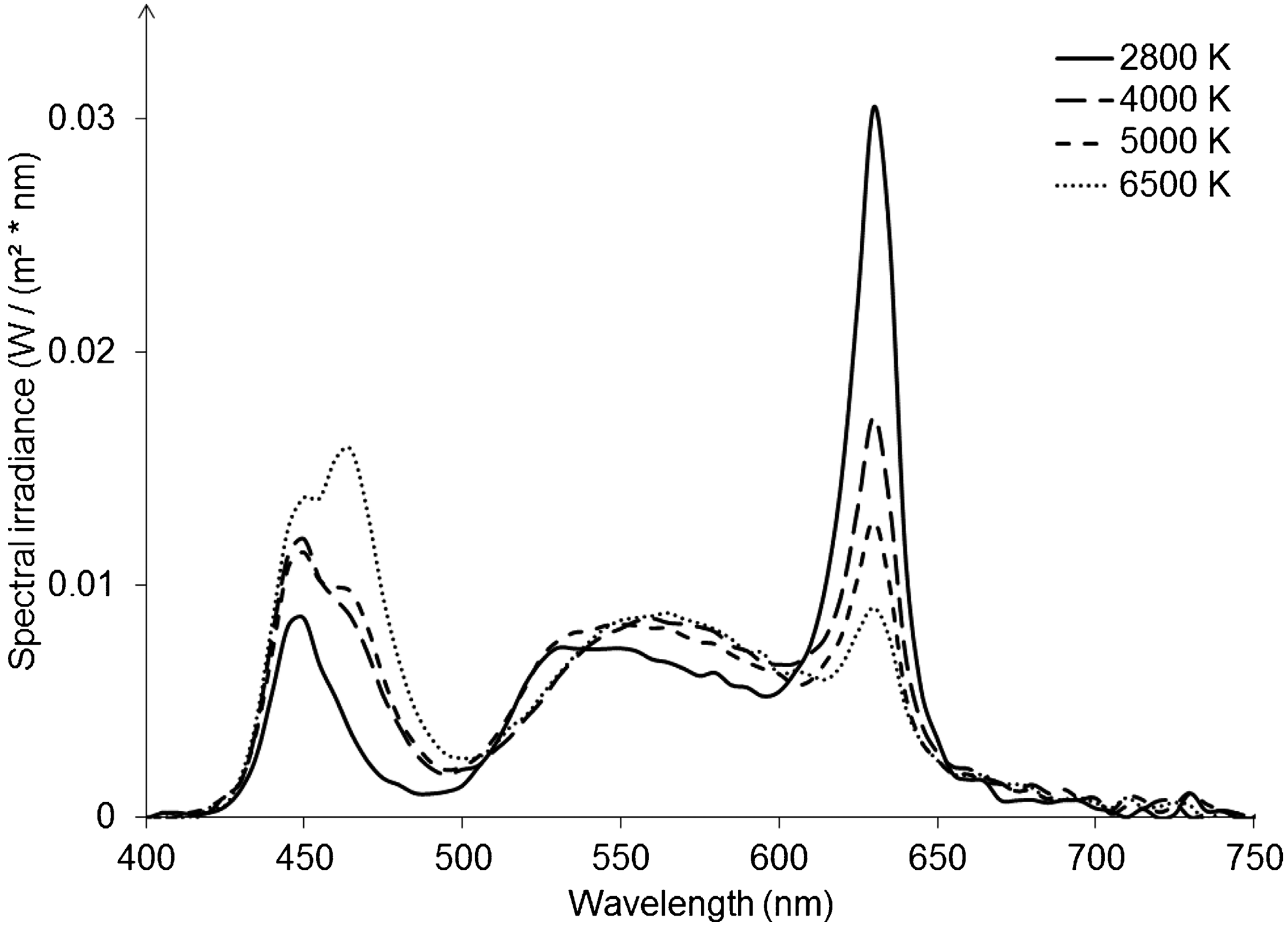

Fig. 1. Spectral power distributions of experimental lighting scenarios.

Gendolla, 2008), ability perceptions (Wright, 1998; Wright & Franklin, 2004), reward (Richter & Gendolla, 2009), mood (Gendolla, 2000), dysphoria (Brinkmann & Gendolla, 2007), implicit affect (Gendolla, 2012, 2015), or implicit pain (Silvestrini, 2015). However, whether one of the most important and daily recurrent environmental stimulus, light, impacts on effort intensity has not yet been tested according to our best knowledge. Thus, here we propose that also lighting can influence effort.

We tested the hypothesis that higher color temperature of light, through its effects on alertness, should decrease mental effort intensity. In particular, we predicted that white light of higher color temperature (higher proportion of blue spectrum components) should induce a higher alertness state which should lead to lower perceived performance demand and thus to lower effort compared to white light of lower color temperature (lower proportion of blue spectrum components). This assumption is also based on findings that feeling alert is linked to higher attention and focus (Lindsley, 1988) and thus the readiness to perform a task. As a consequence of being focused and less distracted, perceived task demand should be lower and less effort should be invested for the task performance. Integrating this reasoning with motivational intensity theory (Brehm & Self, 1989), higher effort is expected under white light of lower color temperature than higher color temperature.

In the present study, after a 10 -min relaxation, participants were exposed to one of the four color temperature lighting conditions for 15 minutes, and thereafter they performed a 5 -min cognitive task. We expected that effort-related cardiac response (i.e. PEP reactivity) decreases with increasing color temperature of light.

2. Method

2.1. Participants and study design

Seventy-eight volunteers (53 women; average age 23.8 years) participated in the study for a monetary remuneration (CHF 20, equivalent to USD 20). We aimed at testing 20 participants per cell (Simmons, Nelson, & Simonsohn, 2011) but had several no-shows. People were recruited through messages on the online announcement board of the University of Basel. Only persons, who indicated having no cardiovascular diseases and who were not taking antidepressants were invited to participate. Participants were instructed to refrain from caffeine, nicotine, sports, and heavy meals for at least 2 h before the experimental session. None of the persons had color deficiency which was assessed with Ishihara's color deficiency test (Ishihara, 2016). Each participant was randomly assigned to one of four experimental lighting conditions: 2800 K, 4000 K, 5000 K, or 6500 K. We employed a between-persons design in order to minimize the salience of light manipulation. Also, this way we could avoid learning effects for the cognitive task, especially when considering working on the same task four times in a row. The experimenter was blinded and not aware of the experimental lighting conditions during the entire study. Women and men were equally distributed among experimental conditions. Exploratory one-way ANOVA did not reveal any differences between the experimental groups neither for age ($p = 0.85$) nor for body-mass-index ($p = 0.99$).

Data of several participants were discarded from the analysis: one participant did not refrain from physical activity prior the experimental session, one participant changed sitting position during the experiment

Table 1
Parameters for lighting conditions.

Lighting condition	Illuminance (lux)	CCT (K)	Chromaticity		CRI	Spectrally-weighted α-opic lux levels based on Lucas et al. (2014)				
			x	y		Melanopsin	S-cone	M-cone	L-cone	Rods
2800 K	504.49	2814	0.4283	0.3660	81.80	273	505	409	272	324
4000 K	506.71	4056	0.3665	0.3313	91.33	376	502	457	434	398
5000 K	502.70	5019	0.3434	0.3381	87.99	412	489	473	439	435
6500 K	503.11	6454	0.3171	0.3021	86.06	510	498	502	582	497

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

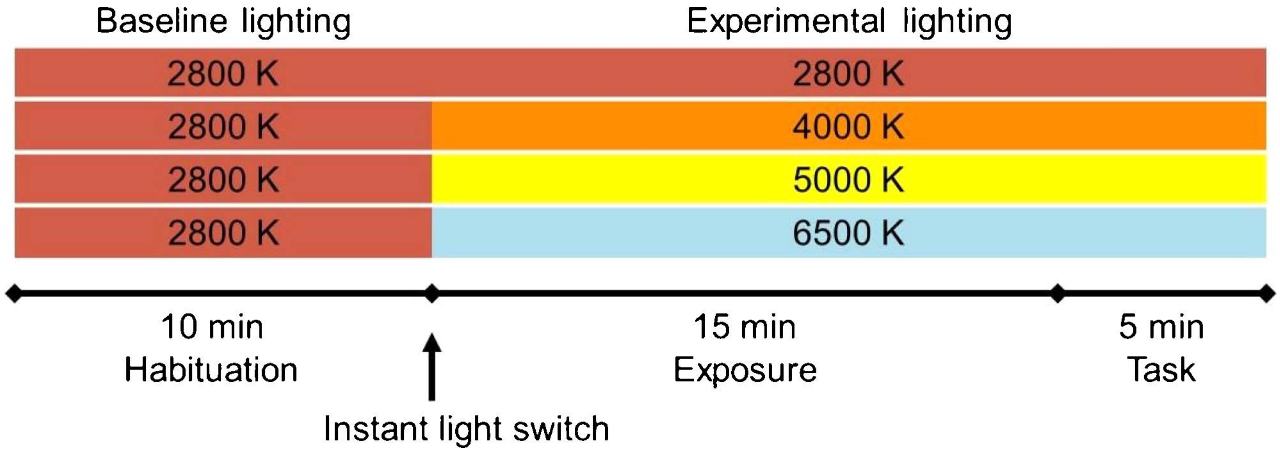

Fig. 2. Schematic representation of the procedure depicting the timescale of experimental episodes and experimental lighting conditions.

although was instructed otherwise, ICG data of two participants and blood pressure/heart rate data for further two participants was not recorded properly due to technical problems, resulting in a final sample of 74 participants for PEP and 72 for HR, SBP, and DBP.

2.2. Lighting conditions

Vertical front lighting panel (width 220 cm, height 140 cm) consisted of 24 LED panels (RGB + White) each containing 144 LEDs (i.e. total of 3456 LEDs) and was covered by a diffuser. Four lighting scenarios were prepared as experimental lighting conditions: 2800 K, 4000 K, 5000 K, and 6500 K. The spectral power distributions for each lighting scenario are presented in Fig. 1. It is noticeable from this figure that different color temperature conditions were mainly achieved by adjusting the proportion of blue and white LEDs (peaks at 450 nm and 470 nm, accordingly) and red LED (peak at 640 nm). The parameters of lighting conditions are presented in Table 1. Measurements were taken vertically, at 120 cm height from floor and 100 cm distance from panel corresponding to the eye level of a person sitting in a position during the experimental session. During the study, the lighting scenarios were manipulated from the experimenter's room using DMXControl (Version 2.12.2) software.

2.3. Measurements and apparatus

For measuring cardiac PEP, impedance cardiogram (ICG) and electrocardiogram (ECG) were simultaneously recorded non-invasively with Cardioscreen apparatus (medis Medizinische Messtechnik GmbH, Ilmenau, Germany). The sampling rate was 200 Hz for 60 participants and was upgraded to 1000 Hz for the remaining participants. For this device, four disposable electrodes and an ear clip were used. The electrodes were attached to the base of left side of the neck and on the left middle axillary line at the height of xiphoid.

We also assessed systolic blood pressure (SBP), diastolic blood pressure (DBP), and heart rate (HR) along with PEP in order to control for potential preload (ventricular filling) or afterload (arterial pressure) effects on PEP (Sherwood et al., 1990). Blood pressure was measured continuously and non-invasively with SOMNOtouch (SOMNOmedics GmbH, Randersacker, Germany) using pulse transit time (see Bilo et al., 2015 for validation). A set of four disposable electrodes were attached to the torso and soft silicone finger sensor was mounted on a finger. All obtained cardiovascular measures were stored on an internal drive and transferred to a personal computer.

2.4. Procedure

The procedure was adapted from previous research on effort and related cardiovascular response (see, for instance, Gendolla, 2000). It was approved by the Ethics Committee northwest/central Switzerland (EKNZ). Upon arrival to the lab, participants were welcomed and seated in a comfortable chair. They read and signed an informed consent form, and then the experimenter applied electrodes and went to the control room. All experimental procedures were fully computerized (PEBL; Mueller, 2014; Mueller & Piper, 2014). During habituation, which was announced as "relaxation episode", participants could read popular magazines for 10 min during which physiological baseline measures were taken. Lighting was set to the 2800 K scenario for all participants during habituation. After habituation, participants learned that lighting will be now adjusted and they will continue the "relaxation episode" for 15 more minutes (exposure episode). At this point, lighting was instantly set to one of the experimental lighting condition: 2800 K, 4000 K, 5000 K, or 6500 K. This lighting setting remained the same until the end of the session (see Fig. 2 for procedure and lighting settings). After this "relaxation episode", participants performed a modified 5-min Sternberg cognitive task (Sternberg, 1966) under the corresponding lighting condition. Their task was to indicate if a letter presented on the screen was also presented in a letter series displayed prior to the target letter. Each task trial started with a fixation cross (1000 ms) followed by four-letter series (750 ms) which was backward masked and a target letter appeared for max 2500 ms. Inter-trial-interval lasted between 2500 and 5000 ms. In total, 36 task trials were presented. Before the task, participants had the possibility to practice by performing 6 task trials with correctness feedback. This feedback was absent during the task. Participants filled in the Karolinska Sleepiness Scale (KSS; Åkerstedt & Gillberg, 1990; Kaida et al., 2006) before the baseline, after the light exposure, and after the cognitive task, which is considered to be a reliable measure to assess alertness for healthy people (Cajochen, 2007; Kaida et al., 2006). At the end of the session, participants also rated task difficulty level, their capability to perform the task, and invested effort on the scale from 1 (not at all) to 7 (very much). They also evaluated glare of the lighting source from 1 (not at all) to 5 (very much). At the end of the experiment, participants were thanked, debriefed, and received their monetary remuneration. The experimental session lasted in total about 60 min. Half the participants participated in the experiment in the morning (9 am to 12 am), and the other half in the afternoon (1:30 pm to 4:30 pm). The assignment to experimental conditions was counterbalanced in terms of time of the day and gender.

2.5. Data analysis

ICG signals were processed offline with software developed by Richter (2010). PEP (in ms) was determined as the interval between R-onset of the ECG and B-point of the ICG (Berntson et al., 2004). Shorter PEP indicated stronger cardiac contractility. The dZ/dt signal was ensemble-averaged over periods of 1 min and PEP values (in milliseconds, computed as the interval between R-onset and B-point) were scored for each average. Cardiac PEP, blood pressure, and HR values were calculated for 1-min intervals. Physiological reactivity scores were calculated for each participant by subtracting the baseline scores from the scores obtained respectively during the light exposure and during the task. Negative PEP reactivity values signify stronger contractility during the episode of interest in reference to the baseline.

To test our specific prediction about decreasing PEP reactivity with increasing color temperature of light we tested singled planned linear contrast (see Richter, 2016) with contrast weights −3, −1, +1, and +3 for lighting conditions 2800 K, 4000 K, 5000 K, and 6500 K, accordingly.

The KSS measures were not recorded for the beginning of the experimental session due to technical reasons. Therefore, we could not estimate the change of subjective alertness resulting from experimental lighting manipulations.

3. Results

3.1. Cardiovascular baselines

Cardiovascular baseline scores for PEP, SBP, DBP, and HR were calculated as the averages of the last 5 min of the habituation episode, which provided stable values (Crombach's αs > 0.99, calculated through all measure points for each minute; the same applies for further reliability calculations). Cell means and standard deviations appear in Table 2. Exploratory single linear planned contrasts on these baseline scores did not yield any significant effects (*ps* > 0.44).

Table 2
Cell means and standard errors (in parentheses) for cardiovascular baseline values.

	2800 K	4000 K	5000 K	6500 K
PEP	106.51 (2.36)	104.13 (2.10)	106.33 (2.18)	107.27 (2.11)
SBP	114.33 (2.82)	117.39 (2.92)	113.58 (3.21)	114.84 (2.63)
DBP	68.50 (1.71)	67.74 (2.05)	66.24 (1.87)	67.20 (1.56)
HR	71.55 (3.05)	72.35 (2.69)	68.26 (2.34)	69.98 (2.07)

Note. Cell *Ns* were 17 for 5000 K and 19 for all other conditions. *PEP* pre-ejection period, *SBP* systolic blood pressure, *DBP* diastolic blood pressure, *HR* heart rate. Units of measures are milliseconds for PEP, millimeters of mercury for SBP and DBP, and beats per minute for HR.

3.2. Cardiovascular reactivity

We averaged 1-min scores of PEP, SBP, DBP, and HR assessed during the 15-min light exposure (Crombach's αs > 0.99) and during the 5-min task performance episode (Crombach's αs > 0.99).

We additionally tested for time effects during the exposure (15 min) and during the task episode (5 min) by analysing the 1-min reactivity scores with an explorative 4 (light) × 15 (time) mixed-model ANOVA (with Greenhouse-Geisser corrections) for the exposure episode and a 4 (light) × 5 (time) mixed-model ANOVA (with Greenhouse-Geisser corrections) for task performance. The analysis for the exposure episode did not reveal significant time effects for PEP ($p = 0.088$), SBP ($p = 0.397$), nor DBP ($p = 0.305$), but a significant time effect for HR ($p = 0.049$) scores that decreased during the episode. Other effects were not significant (*ps* > 0.09). During the task episode, we found significant main effects for the factor "time" in all PEP, SBP, DBP, and HR measures (*ps* < 0.001) due to a stronger general reactivity at the beginning of the task while other effects were not significant (*ps* > 0.23).

3.3. Cardiac PEP reactivity

Most relevant, a single planned linear contrast was significant for PEP reactivity scores during task performance, $t[73] = 2.17$, $p = 0.034$, Cohen's $d = 0.51$. Cell means and standard errors are depicted in Fig. 3 (right panel). Reactivity decreased from 2800 K ($M = -2.82$, $SD = 4.89$) and 4000 K ($M = -3.15$, $SD = 3.79$) through 5000 K ($M = -1.27$, $SD = 5.69$) to 6500 K ($M = 0.20$, $SD = 5.33$) lighting condition. These results show that increasing lighting color temperature (in Kelvin) leads to decrease of PEP reactivity.

Although we did not have a specific *a priori* hypothesis, we tested the same linear single contrast for average PEP reactivity scores during the light exposure episode prior task performance. Cell means and standard errors are depicted in Fig. 3 (left panel). The linear contrast was significant, $t[73] = 2.36$, $p = 0.021$, Cohen's $d = 0.55$. Reactivity scores decreased from 2800 K ($M = -0.48$, $SD = 1.80$), through 4000 K ($M = 0.16$, $SD = 1.87$) and 5000 K ($M = 0.07$, $SD = 1.92$) to 6500 K ($M = 1.24$, $SD = 2.71$) lighting conditions. These results reflect the pure effect of lighting conditions as participants were engaged in the same activity during the baseline and light exposure episodes.

To test for probable carry-over effects of light from exposure to task performance, we repeated the analysis for reactivity scores during the task by including reactivity scores during exposure as a covariate. The analysis revealed a significant relationship between reactivity scores during both episodes, $F[1, 73] = 20.99$, $p < 0.001$, $\eta_p^2 = 0.23$. Consequently, after including the covariate, the single planned linear contrast was not significant ($p > 0.26$).

To further decompose the analysis between the conditions, we performed cell comparisons for both task and exposure episodes. The comparisons revealed that during the light exposure, PEP reactivity significantly differed between 2800 K and 6500 K cells, $t[73] = 2.53$, $p = 0.014$, Cohen's $d = 0.59$, whereas other comparisons did not reveal any significant differences (*ps* > 0.09). For the task performance, PEP reactivity significantly differed between 4000 K and 6500 K conditions, $t[73] = 2.10$, $p = 0.040$, Cohen's $d = 0.49$, whereas all other differences were not significant (*ps* > 0.06).

3.4. SBP, DBP, and HR reactivity

Planned single linear contrast tests for reactivity scores during the task performance for SBP, DBP, and HR were not significant (*ps* > 0.33). During light exposure, the linear contrasts did not yield significance for SBP, DBP, nor HR (*ps* > 0.49). Mean reactivity scores

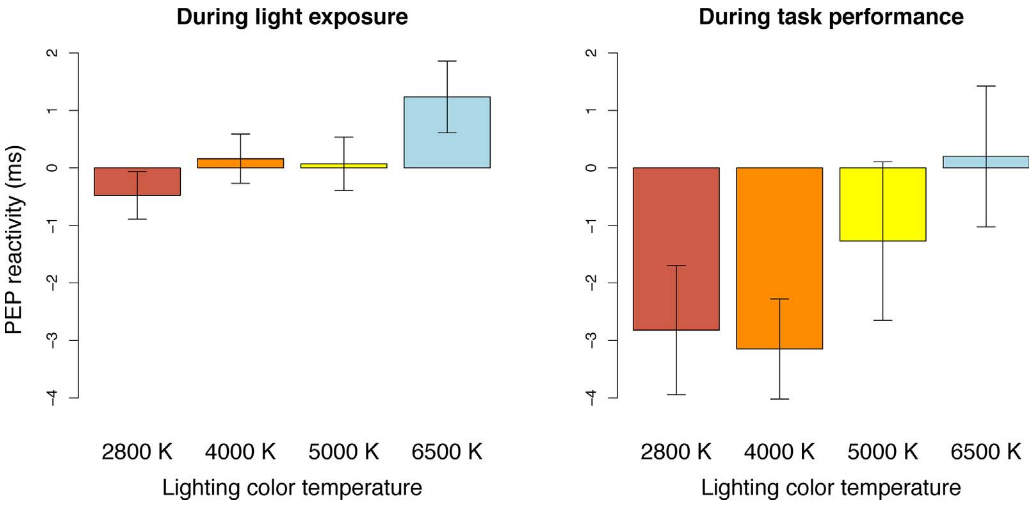

Fig. 3. PEP reactivity mean scores (± SEM) during task performance under experimental lighting color temperature conditions.

Table 3
Cell means and standard errors (in parentheses) of blood pressure and heart rate reactivity scores during light exposure and during task performance.

	2800 K	4000 K	5000 K	6500 K
Exposure				
SBP	−0.89 (0.60)	−1.00 (0.83)	−0.06 (0.40)	−0.98 (0.39)
DBP	−0.02 (0.29)	−0.51 (0.44)	0.16 (0.28)	−0.54 (0.21)
HR	−0.50 (0.51)	−1.19 (0.97)	−0.74 (0.53)	−0.32 (0.60)
Task				
SBP	2.75 (1.77)	2.40 (1.48)	1.52 (0.81)	2.11 (1.27)
DBP	2.31 (0.91)	1.20 (0.83)	1.29 (0.52)	1.21 (0.67)
HR	1.23 (0.86)	0.25 (1.35)	−0.14 (0.81)	1.80 (1.06)

Notes. Cell *N*s were 17 for 5000 K, 18 for 2800 K and 4000 K, and 19 for 6500 K conditions. *SBP* systolic blood pressure, *DBP* diastolic blood pressure, *HR* heart rate. Units of measures are millimeters of mercury for SBP and DBP and beats per minute for HR.

and standard deviation for exposure and task performance episodes for SBP, DBP, and HR are presented in Table 3.

3.5. *Task performance and self-report measures*

3.5.1. *Performance*

Two single planned linear contrasts did not yield any significant effects of light neither on response times for correct responses in square-root transformation (Sheskin, 2003) (uncorrected grand $M = 860.61$, $SD = 198.79$), nor on accuracy (grand $M = 94.67\%$, $SD = 0.05$) scores ($ps > 0.44$).

3.5.2. *Alertness*

KSS scores after lighting exposure (grand $M = 4.93$, $SD = 1.76$) and after the task performance (grand $M = 4.27$, $SD = 1.79$) did not show significant linear patterns ($ps > 0.56$).

3.5.3. *Task ratings*

A single planned linear contrast for task difficulty ratings (grand $M = 2.54$, $SD = 1.10$) did not reveal significant lighting effect ($p = 0.96$). The same test did not show any significant effect ($ps > 0.88$) for invested effort (grand $M = 3.28$, $SD = 1.31$) nor for perceived capability (grand $M = 5.03$, $SD = 1.37$) ratings.

4. Discussion

The present study tested the hypothesis that lighting color temperature influences mental effort. The results supported our hypothesis by demonstrating that increasing lighting color temperature can decrease mental effort, measured as task performance-related responses of cardiac PEP, an index of beta-adrenergic impact on the heart (Berntson et al., 2004). Furthermore, the lack of effects on blood pressure and heart rate effects makes (particularly the lack of decreases) makes it implausible that PEP effects occurred due to preload or afterload effects. To our best knowledge, this is the first evidence for lighting color temperature effects on mental effort as main dependent variable using objective effort-related cardiac measures.

Since feeling alert is linked to higher attention and focus (Lindsley, 1988), we hypothesized that light influences motivation through its impact on alertness and consequently the readiness to perform the task. Based on the collected data, we could not test this element of the predicted theoretical mechanism. Lacking the alertness ratings at the beginning of the experimental session due to a technical failure represents a limitation of this study. Thus, we cannot conclusively argue whether light affected effort through changes in subjective alertness. Yet, other studies from our laboratory have demonstrated that different color temperature of light leads to differences in subjective alertness after 30 min of light exposure (e.g., Chellappa et al., 2011).

The results also indicate that the cardiac contractility (measured as PEP) was stronger for exposure episode compared to the baseline in the 2800 K condition, for which lighting did not actually change during the entire experimental session One possible explanation is that people might get sleepier and therefore less alert with time under 2800 K which leads to stronger effort. However, we cannot prove this hypothesis due to the missing alertness measures during baseline.

Our proposed model predicts that light impacts on effort-related cardiovascular response through experienced task difficulty. The present results did not provide evidence that lighting conditions affected subjective task difficulty and subjective invested effort ratings. As evident by a significant main effect of time for the physiological measures, the lighting effect diminished with time during task performance. Thus, even if some participants found the task more difficult especially at the beginning of the performance episode, after the task, however, when asked to evaluate experienced difficulty and effort at the end of the experiment, they might have only relied on current experience and therefore no difference in ratings were observed. Also, in our experiment we were initially interested in effort intensity *during* task performance and therefore ratings given *retrospectively* must not reflect the demand perception during task performance (see Robinson & Clore, 2002).

We found no effects of lighting conditions on task performance neither in terms of reaction time nor in accuracy within the modified Sternberg task. Even if some of previous studies found performance effects that corresponded to effort-related cardiovascular response (e.g., Silvestrini, 2010, 2011; ; Lasauskaite, Gendolla, & Silvestrini, 2013), we did not predict lighting effects on response accuracy or reaction speed because the concepts of effort and of performance are not equivalent. Some researchers consider speed and accuracy as indicators of effort (e.g., Bijleveld, Custers, & Aarts, 2010), but performance and effort can dissociate. Performance depends not only on effort, but also on other factors such as ability and strategy (see Locke & Latham, 1990). Therefore, the lack of lighting effects on task performance are not surprising.

Influence of lighting color temperature on effort was apparent not only during the cognitive task performance, which was predicted, but also during the lighting exposure episode for which we did not have specific *a priori* expectations. This is also apparent within additional statistical analysis, suggesting that the observed light effects during task performance may reflect carry-over effects of the prior exposure episode. Thus, changing light color temperature by itself can influence effort intensity during cognitive task activity of even low demand. This effect is already apparent during only 15 min light exposure, which can be referred as to an immediate effect by light on mental effort. On the other hand, comparisons of single experimental design cells suggest that effects might have appeared mainly due to the blue-enriched light condition of 6500 K. Future studies on dose-response relationships should clarify this uncertainty.

The current results are important in the context of studying environmental influences in cognitive performance contexts, like office work and schools. Until now, research investigating effects of color temperature in achievement settings focused on alertness, mental concentration, and/or performance (Hygge & Knez, 2001; Knez, 2001; Mills, Tomkins, & Schlangen, 2007; Viola et al., 2008). Our present research extends this research showing that working in different lighting conditions can require different amount of effort (i.e. higher under warmer light and lower under cooler light) and nevertheless lead to the same performance results. We further show that using cardiovascular measures for estimating mental effort, we can capture subtle alterations even under low cognitive demand and short-term light exposures (15 min). Thus, simply changing the lighting conditions at the work place may significantly impact on the employee's invested mental effort under conditions of low and higher cognitive demand.

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