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Investigating daytime effects of correlated colour temperature on experiences, performance, and arousal

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ABSTRACT

Research in the late evening and at night has shown that acute activating effects of light are particularly sensitive to short-wavelength light. Yet, findings on such effects during daytime are still inconclusive. This study (N = 39) investigated effects of correlated colour temperature (CCT; 2700 K vs. 6000 K, 500 lx on the desk) on individuals' experiences, performance, and physiology during one hour of exposure in the morning versus afternoon. Except for a higher subjective vitality in the 6000 K condition in the morning, results showed no significant activating effects, and even subtle performance-undermining effects in the relatively high CCT condition. Moreover, participants rated both their mood and the light settings as less positive in the 6000 K vs. 2700 K condition. It is therefore questionable whether lighting solutions with commonly experienced intensity levels should provide a higher CCT during daytime office hours.

1. Introduction

Light enables vision, but also plays an important role in our physiological and psychological functioning. Since the discovery of a third class of photoreceptors (non-rod, non-cone) in the inner layer of the human retina (Berson, Dunn, & Takao, 2002; Foster et al., 1991; Freedman et al., 1999; Hattar, Liao, Takoa, Berson, & Yau, 2002), insights in the non-image forming effects of light have expanded rapidly. The newly discovered photoreceptors – technically speaking intrinsically photosensitive retinal ganglion cells (ipRGC) - are light sensitive ganglion cells projecting to various brain areas involved in the regulation of sleep and wakefulness, alertness, cognition, and mood (Gooley, Lu, Fischer, & Saper, 2003; Hattar et al., 2006, 2002; Lucas, 2013; Schmidt, Chen, & Hattar, 2011; Vandewalle, Maquet, & Dijk, 2009). The ipRGCs contain the photopigment melanopsin and are primarily responsible for the non-image forming effects of light (Hankins, Peirson, & Foster, 2008; Hattar et al., 2002; Provencio et al., 2000). However, the rods and cones in the outer layer of the retina also send signals to the ipRGCs, and input from these classical photoreceptors may contribute to the non-image forming effects (e.g., Dacey et al., 2005; Gooley et al., 2010; Güler et al., 2008; Lall et al., 2010; Lucas, Lall, Allen, & Brown, 2012).

The ipRGCs differ from the classical rods and cones in their sensitivity to light characteristics (Berson, 2003; Berson et al., 2002; Hattar et al., 2002). Higher light intensity levels, i.e., more photons, are necessary to induce melanopsin photoreception. Another important difference is that the spectral sensitivity of the ipRGCs is blue-shifted compared to the rods and three-cone (photopic) system (Brainard et al., 2001; Hankins et al., 2008; Thapan, Arendt, & Skene, 2001). The photopigment melanopsin is most sensitive to wavelengths around 460–480 nm, i.e., to light in the blue part of the spectrum (Berson et al., 2002; Brainard et al., 2001; Panda et al., 2005; Thapan et al., 2001). In addition to intensity, the effect of the spectral composition of light on human functioning has therefore also received a lot of attention in the current literature.

In the current study, we investigate the effect of correlated colour temperature (CCT) on alertness and vitality in the morning vs. afternoon using a multi-measure approach. Note that the CCT of a polychromatic light source increases when it contains relatively more power in the blue part of the spectrum, i.e., when the relative amount of short wavelengths light rises. Multiple studies have investigated the acute activating effect of light in the blue part of the spectrum in the evening or at night. These studies have tested either effects of monochromatic or narrowband blue light, or

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polychromatic white light with a relatively high CCT. Results of these studies revealed either positive effects or null effects of exposure to blue light or blue-enriched white light on alertness, cognitive performance, and physiological arousal during the subjective night (An, Huang, Shimomura, & Katsuura, 2009; Brainard et al., 2015; Cajochen et al., 2011, 2005; Chellappa et al., 2011; Ekström & Beaven, 2014; Figueiro, Bierman, Plitnick, & Rea, 2009; Figueiro, Rea, & Bullough, 2006; Heath et al., 2014; Kozaki, Koga, Toda, Noguchi, & Yasukouchi, 2008; Lockley et al., 2006; Morita & Tokura, 1996; Papamichael, Skene, & Revell, 2012; Plitnick, Figueiro, Wood, & Rea, 2010; Van de Werken, Giménez, De Vries, Beersma, & Gordijn, 2013; Van der Lely et al., 2015; Vandewalle et al., 2011). The most consistent results in the late evening and at night were shown for melatonin suppression, with lower levels of melatonin secretion under exposure to blue light, blue-enriched white light or unfiltered white light. Melatonin suppression is controlled by the suprachiasmatic nucleus (Benarroch, 2008) – our internal biological clock – one of the regions receiving direct input from ipRGCs (Hattar et al., 2002; Schmidt et al., 2011). These effects on melatonin were sometimes - although not always - accompanied with higher feelings of alertness, better ability to sustain attention, better performance on cognitive tasks, a more positive mood, stronger modulations in brain activity and/or higher physiological arousal. Thus, the current literature suggests that exposure to blue light or polychromatic white light with a high CCT may support persons to stay alert, concentrate on a task and engage in cognitive tasks at times when circadian and homeostatic sleep pressure are generally high and persons normally would experience relatively low light intensity levels.

Most persons are, however, active during daytime and asleep at night. Investigation of acute effects of blue light or blue-enriched white light on alertness, performance, and arousal during daytime will provide insights into whether tuning the spectral composition of the lighting conditions may also enhance alertness and performance among day-active persons. Although melatonin levels and homeostatic sleep drive are generally already at their lowest during daytime, other ipRGC driven projections, for instance to the brainstem, may still induce arousing and/or alerting effects. To date, multiple studies have tested acute activating effects of exposure to blue light or white light with a high CCT during daytime. These diurnal studies have, however, rendered effects that are considerably less consistent than the nocturnal studies, as results showed both positive as well as negative effects of exposure to blue or blue-enriched light on alertness, cognitive performance, and arousal (e.g., An et al., 2009; Baek & Min, 2015; Boray, Gifford, & Rosenblood, 1989; Figueiro, Nonaka, & Rea, 2014; Gabel et al., 2013; Iskra-Golec, Wazna, & Smith, 2012; Knez, 1995, 2001; Knez & Enmarker, 1998; Mills, Tomkins, & Schlangen, 2007; Okamoto & Nakagawa, 2015; Okamoto, Rea, & Figueiro, 2014; Rahman et al., 2014; Rautkylä, Puolakka, Tetri, & Halonen, 2010; Revell, Arendt, Fogg, & Skene, 2006; Sahin & Figueiro, 2013; Stebelová et al., 2015; Vandewalle et al., 2007b, 2007a; Viola, James, Schlangen, & Dijk, 2008).

Together, these studies suggest that the spectrum of the lighting may influence individuals' feelings, behavior, and physiology during daytime. It is, however, questionable whether we should provide light with a relatively high power in the blue part of the spectrum during daytime, as adverse effects appear to emerge as frequently as do favorable ones. Differences between the studies may partly be explained by the diverse lighting manipulations in terms of wavelengths (e.g., blue vs. green or blue vs. red) or CCT levels (e.g., 17,000 K vs. 2900 K or 4000 K vs. 3000 K) used in studies. In addition, the lighting conditions in the various studies differed in intensity, duration and timing of the light exposure, whether there was daylight contribution, the type of indicators, and the statistical power.

In the current study, we investigate potential acute activating effects of CCT on individuals' psychological and physiological functioning during daytime working hours, and test whether the effects are moderated by time of day. Earlier studies showed that the diurnal acute activating effects of light intensity on subjective vitality, task performance, and EEG may depend on the timing of the light exposure (Huiberts, Smolders, & De Kort, 2015; Huiberts, Smolders, & De Kort, 2016; Smolders & De Kort, 2014; Smolders, De Kort, & Cluitmans, 2012, 2015; Smolders, De Kort, & Van den Berg, 2013). A few studies specifically investigated moderations in non-image forming effects of blue or blue-enriched light by time of day, revealing mixed results (Górnicka, 2008; Iskra-Golec et al., 2012; Rautkylä et al., 2010; Vandewalle et al., 2011). Vandewalle et al. (2011) reported significant effects of blue (473 nm) vs. green (527 nm) light on brain activity in the morning, but not in the late evening. Results by Rautkylä et al. (2010) revealed that students reported higher alertness while attending a lecture during autumn under exposure to blue-enriched light (17,000 K vs. 4000 K) in the afternoon, but not in the morning. In contrast, Iskra-Golec et al. (2012) reported more pronounced effects of blue-enriched light exposure (17,000 K vs. 4000 K) on subjective vitality among office employees in the morning, but not in the afternoon. A laboratory study by Górnicka (2008) reported no significant effect of exposure to a high CCT (17,000 K vs. 2700 K) in the morning and afternoon. It should be noted that in these latter two studies, participants were exposed to the lighting conditions for eight or nine hours during the day. It is therefore difficult to disentangle the effect of duration vs. timing of the light exposure. In the current study, participants were exposed to the lighting conditions for one hour in the morning vs. afternoon, allowing us to explore time of day as a potential moderator for the daytime effects of CCT on individuals' experiences, cognitive task performance, and physiological arousal.

As the effects of the spectral composition of light may depend on the type of measure (e.g., self-report, task performance, or physiological measure), we employed a multi-measure approach to investigate potential alerting and vitalizing effects of CCT (6000 K vs. 2700 K) on subjective experiences, task performance and physiological arousal. Moreover, repeated measures were employed to explore the occurrence and development of alerting and activating effects during an hour of exposure to polychromatic white light with a relatively high vs. low CCT. The present study thus complements earlier studies testing the effect of CCT on human functioning during daytime. More specifically, it provides additional insights in whether modulation of the spectral composition of white light may benefit individuals' level of alertness, mood, and task performance and influence their physiological arousal during daytime working hours, and whether these effects are dependent on the timing and duration of the light exposure. The current study also investigates the effect of CCT on subjective appraisals of the lighting condition, experience of the space, and beliefs concerning potential effects of the lighting condition on mood and performance, to explore whether these experiential aspects reflect the effects on alertness, mood, performance, and arousal.

2. Method

2.1. Design

A 2 × 2 mixed design was applied to investigate the effect of CCT (2700 K vs. 6000 K) for morning versus afternoon exposure. CCT was manipulated within subjects, while time of day was manipulated between subjects. Participants came to the laboratory on two separate days and were exposed to 2700 K in one session and to