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Effects of new light sources on task switching and mental rotation performance

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A B S T R A C T

Recent studies investigated the non-visual effects of light on cognitive processes and mood regulation and showed that light exposure has positive effects on circadian rhythms and alertness, vigilance and mood states and also increases work productivity. However, the effects of light exposure on visuo-spatial abilities and executive functions have only been partially explored. In this study, we aimed to investigate the effects of new LED light sources on healthy participants' performance on some components of visuo-spatial abilities and executive functions in a specifically-designed and fully-controlled luminous environment. Participants had to mentally rotate 3-D objects and perform a switching task in which inhibitory processes and switch cost were measured. Results suggest that cooler light exposure improves the cognitive system's capacity to deal with multiple task representations, which might remain active simultaneously without interfering with each other, and visuo-spatial ability, producing fewer errors in the mental rotation of 3-D objects.

1. Introduction

Since the 1990s, good lighting conditions have been defined as those that balance the needs of humans with regard to energetic, economic, and environmental issues and architectural design requirements. Thus, they improve human performance, energy efficiency, spatial appearance, safety, health and well-being. But the general picture became more complicated when Brainard et al. (2001) and Thapan, Arendt, and Skene (2001) independently provided unexpected insights into the fundamental processes of a class of ganglion cells in the human retina (i.e., the intrinsically photosensitive retinal ganglion cells, ipRGCs). They are light sensitive like conventional cones and rods, and have a specific opsin (melanopsin) as photopigment, with a peak sensitivity at approximately 480 nm, whereas S cones have the cyanolabe, sensitive to short wavelengths ($\lambda_{max} \approx 420$ nm), M cones contain the chlorolabe, maximally sensitive to wavelengths around 535 nm, L cones have the erythrolabe, sensitive to long wavelengths ($\lambda_{max} \approx 565$ nm), and rod opsin has a maximum sensitivity around to 500 nm (e.g., Lucas et al., 2014). Differently from cones and rods that belong to the conventional image-forming visual system, ipRGCs project to subcortical structures within the circadian system, such as the suprachiasmatic nucleus of the hypothalamus. Thus, they have a major role in synchronizing circadian rhythms to the 24-h light/dark cycle. In particular, due to the spectral sensitivity of melanopsin, physiological rhythms are more sensitive to light sources emitting relatively more energy in the short-wavelength region of the spectrum, thus having a "cooler" Correlated Colour Temperature (CCT) than lamps emitting high quantity of energy in the red wavelength region of the spectrum.

The identification of ipRGCs generated great excitement, and provided new impetus for the lighting research field (Commission Internationale de l'Eclairage, 2004; Veitch, 2006). Indeed, many international research groups with experts in very different fields have started to explore the role of the spectrum of light sources, the ratio of light to dark periods, the relative sensitivity of the different parts of the visual field and, more generally, the effects of light exposure on health and behaviour (Bellia & Bisegna, 2013; Bellia,

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Spada & Bisegna, 2011; van Bommel, 2006; Boyce, 2010; Pechacek, Andersen, & Lockley, 2008; Rea, Figueiro, & Bullough, 2002).

Whereas a number of studies investigating the non-visual effects of light have shown that light exposure, especially to blue light (about 480 nm), has positive effects on circadian rhythms, alertness and vigilance, mood, and also increases work productivity (see Vandewalle, Maquet, & Dijk, 2009 for a recent review), results have not been always consistent.

For instance, Deguchi and Sato (1992) investigated the effects of three different CCT conditions (3000 K, 5000 K, and 7500 K) on mental activity: though no effect on simple reaction times was found, it was observed that 7500 K light triggers orienting responses more than 3000 K light. Noguchi and Sakaguchi (1999) reported that CCT influenced physiological activity more than illuminance levels: lower values of EEG alpha attenuation coefficient and lower mean EEG frequency of the theta-beta bandwidth EEG, as well as higher subjective drowsiness, were obtained with 3000 K compared to 5000 K light, whereas no significant effect of illuminance was observed.

Instead, empirical evidence failed to confirm the long-term effects of different types of classroom illumination on attention and memory (Ferguson & Munson, 1987). Furthermore, Boray, Gifford, and Rosenblood (1989), comparing three fluorescent lamps conditions with different CCT (3000 K, 4150 K, 5000 K), found no effect of lamp type on performance. Boyce and Rea (1994) reported similar results in an office simulation experiment in which no effects of lighting were found on the ratings of a fictitious job candidate, or on the performance at memory and comprehension tasks.

In a systematic review, Veitch and McColl (2001) reported that even if "the evolutionary hypothesis holds that general cognitive performance should be best under light that is similar to daylight", this hypothesis does not have support in the literature of the period 1941–1999 due to the lack of sound theoretical models and weak methodology (see also McColl & Veitch, 2001). Interestingly, the fluorescent lamp conditions compared in several studies they cited could have delivered radiation close to what we believe now are the important wavelengths for ipRGCs, because of mercury peaks at 404 and 435 nm. This might have reduced the differences between experimental conditions.

In the years after 1999 other experiments were designed to take advantage of the ipRGCs by deliberately adding more short-wavelength radiation to a white spectrum, suggesting that an addition in that range might be beneficial. For instance, Viola, James, Schlangen, and Dijk (2008) tested the response of 94 white-collar workers to two different lighting conditions, white light (4000 K) and blue enriched white light (17,000 K), each lasting 4 weeks. Self-reported judgements showed that the 17,000 K light improves alertness, performance, and quality of nocturnal sleep more than 4000 K light. A similar study (Mills, Tomkins, & Schlangen, 2007), conducted in a shift-working call centre and comparing neutral CCT (4000 K) and high CCT (17,000 K) sources, showed improvements of work performance, alertness, fatigue and daytime sleepiness with 17,000 K light.

Results from neuroimaging studies support the hypothesis of non-visual effects of light on performance by showing that different wavelengths, time and intensity of light exposure can modulate the neural activity in cortical areas (e.g., limbic, dorsolateral prefrontal cortex, intraparietal sulcus and superior parietal lobule) as well as in subcortical structures (e.g., locus coeruleus, hippocampus, amygdala) during cognitive tasks (Vandewalle et al., 2009). The non-visual effect of light on mood regulation and long-term memory has been also confirmed by amygdala and hippocampal activation during tasks assessing these functions (Vandewalle et al., 2006, 2007).

Although neuroimaging studies have shown light-induced activity in both the prefrontal cortices and parietal lobes (Vandewalle et al., 2009), which are known to be involved in visuo-spatial abilities and executive functions, the effects of blue-enriched light exposure on these processes have only been partially explored.

The recent development and consequent availability of different classes of lighting systems has created the need for more accurate and stringent analyses of their effects on human performance and health. Note that until recently this issue was largely ignored in the technical literature. The above-mentioned studies were performed principally investigating the effects of fluorescent sources on human physiology, behaviour and performance, but only few studies have been carried out to inquire the effects produced by new LED sources on the same fields. A recent work (Hawes, Brunyé, Mahoney, Sullivan, & Aall, 2012) compared visual perceptual, affective and cognitive implications of four different luminous scenarios: one fluorescent lighting (3345 K) and three LED lighting (4175 K, 4448 K, 6029 K). They reported a better performance of 24 volunteers on cognitive tasks with LED sources because their reaction times resulted faster with the increase of CCT, and that significant improvements were recorded with 4175 K in respect to 3345 K.

In the present study, we aimed to investigate the effects of new LED light sources on healthy participants' performance in two different cognitive tasks, namely, Task-Switching (e.g., Rogers & Monsell, 1995) and Mental Rotation Task (Guay, 1977). Both tap specific aspects of the executive functions (i.e., inhibitory processes; Mayr & Keele, 2000; Sdoia & Ferlazzo, 2008) and visuo-spatial abilities (i.e., generation, inspection and manipulation of mental images) that have been scarcely explored until now despite their importance in daily life.

For this purpose, we compared participants' performance and self-reported mental workload under halogen lamp lighting and the new LED lighting, characterized by different spectra, the latter presenting two spikes in the blue and yellow regions, the former presenting a curve with a minimum in the blue region and a maximum in red wavelengths.

2. Materials

2.1. Participants

Forty-four healthy college students (22 men) took part in the experiment after signing the informed consent sheet and receiving information about participation. The study was designed in accordance with the ethical principles of the Declaration of Helsinki and was approved by the local ethics committee of the Psychology Department, University Sapienza of Rome. Mean age of participants was 25.6 years (S.D. = 3.87) for women and 25.31 years (S.D. = 4.85) for men; all had at least 13 years of education. The inclusion criterion was no history of neurological or psychiatric diseases (including substance abuse or dependence). This was determined by participant' responses to a questionnaire in which they were asked to indicate any previous or current diseases. Testing always took place at the same time of the day. All participants declared they had had adequate sleep and had not recently travelled across time zones, had normal or corrected-to-normal vision and had not drunk coffee or smoked cigarettes before testing.

2.2. Experimental setting

To investigate human circadian and cognitive responses under different lighting and environmental conditions, researchers in the lighting laboratory of the Department of Astronautical Electrical and Energetic Engineering of the University Sapienza of Rome