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

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ABSTRACT

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

Table 1
Technical details of the light sources.

Type	Halogen lamp	LED Device
Power	53 W	36 × 1.2 W
Luminous Flux	850 lm	3492 lm
Colour Temperature	2800 K	4000 K
Colour Rendering Index	100	80

Table 2
Measure of illuminance and luminance at eye level.

Source	LED	Halogen
Irradiance [W/sqm](380–780 nm)	2,762E-01	6,559E-01
Luminance [cd/sqm]	9,589E-02	1,060E-01
Radiance [W/(sr*sqm)] (380–780 nm)	3,310E-04	8,754E-04

designed and built an experimental cabin. The building materials were aluminium and plasterboard cladding. The cabin was 3 m high and dimensions were 3.6 × 2.4 m. The ceiling was made of 0.6 × 0.6 m light grey removable plasterboard panels that could be easily replaced with the same type of ceiling fixtures. The floor was covered with opaque, dark green tiles. The cabin was furnished with an office desk (1.2 × 0.7 m) covered with an opaque grey material, a chair and a computer (the case was placed under the desk), a keyboard, a mouse placed at the centre of the desk and a 17-inch LCD monitor (luminance 250 cd/m^2; contrast ratio 400:1). For the present study, all the walls of the cabin, including the door, were opaque black. This reduced the effects of the reflected light component reaching the participants' eyes to a minimum. The only reflected light was that off the desk surface. The room in which the cabin was placed had no windows. During the experiments, all electric light in the room was turned off. Thus, no natural or electric light could affect the lighting conditions inside the cabin.

Fluorescent lamps used to be the traditional alternative to incandescent lamps. Since 1997, however, this new technology expanded with the creation of the first white LED. The high directionality of the light beam and its spectral power distribution recently raised some controversy about its effects on humans. Therefore, we used typical halogen lamp lighting in the control condition and a LED lighting system, with a relatively higher proportion of short-wavelength ("blue") radiation than halogen sources, in the experimental condition as a potential candidate for substitution in future applications. Technical details of the light sources are reported in Table 1.

All light sources were placed at ceiling level, roughly over the centre of the desk, to avoid generating glare or reflections on the monitor. As the LED fixture was the recessed type, it was the same size as the plasterboard panel. The six halogen sources were simply put into the lamp holders and placed in two equally spaced rows on the edges of the LED luminaire. Six halogen lamps were needed to produce the same illuminance level on the desk. The test environment and the position of the light sources are shown in Fig. 1.

Photometric measures were collected in both control and experimental conditions to characterize the luminous environment in terms of luminance, illuminance and spectrum emitted by the light sources on the workplane and at eye level (for measure at eye level see Table 2). Measures on the workplane were made 0.72 m from the floor and at eye level 1.15 m from the floor, with the sensor pointing towards the monitor above the desk. Spectroradiometric assessment was carried out with a portable spectroradiometer (JETI, Specbos 1211UV), luminance and 2D luminance measurements were made using Photometer Camera Techno Team LMK, based on the Canon EOS 550D digital reflex camera). All the equipment was calibrated.

The spectrum emitted by the light sources and the spectral power distribution at eye level are reported in Fig. 2a and b so that the quantity of blue light reaching the eye can be better appreciated. Illuminance measures were made with a luxmeter along a 0.2 m grid for both lighting conditions, showing an illuminance uniformity (E_{min}/E_{max}) of about $E_{min}/E_{max} = 0.8$ with LEDs, and $E_{min}/E_{max} = 0.7$ with halogen lamps, according to values suggested by

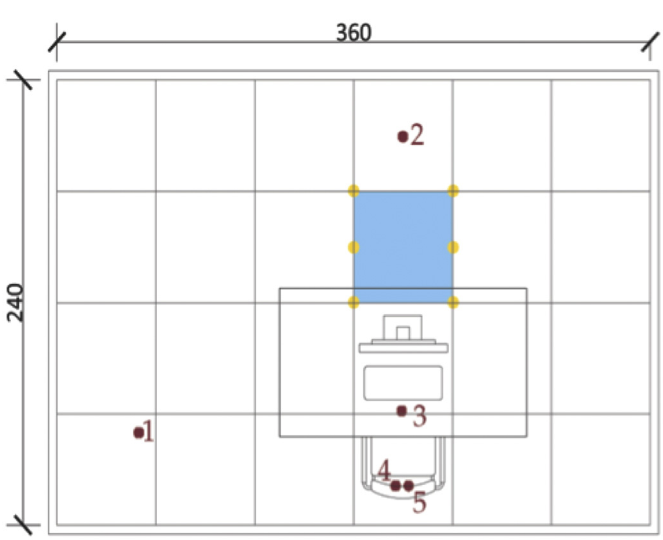

Fig. 1. Test environment and position of light sources.

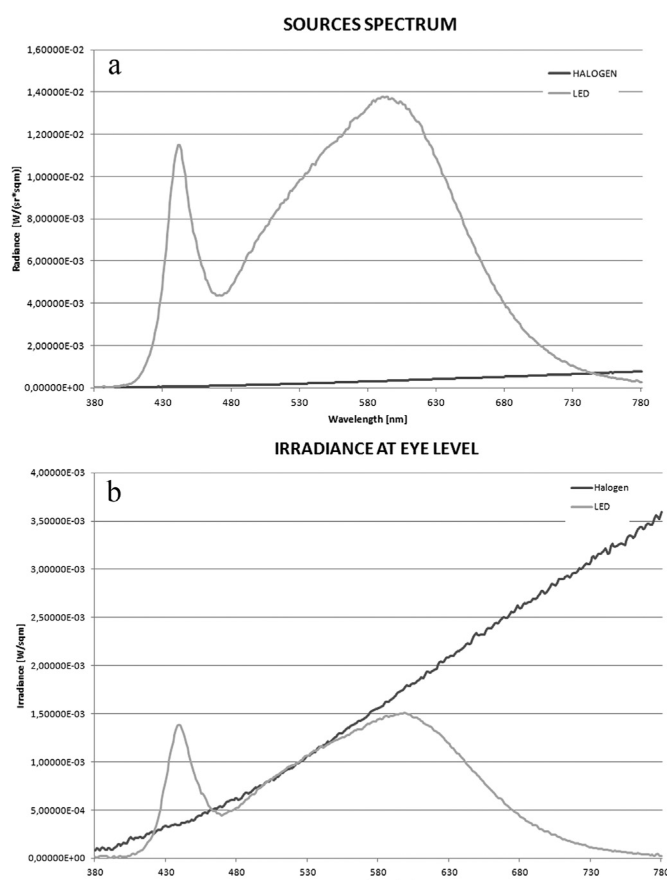

Fig. 2. a. Spectrum emitted by halogen lights and LEDs. b. Spectral power distribution of light sources at eye level.

Lighting Standards (ref. UNI EN 12464-1). Illuminance at eye level was also measured, with values of about 100 lux with halogen lamps and 90 lux with LED lighting systems. Finally, the luminance in the subject's field of view was also measured to obtain an image of the luminance distribution in the visual field (Fig. 3a and b).

The LED lighting fixture was equipped with a built-in driver which, according to manufacturer's specifications, should ensure both the appropriate optical performance of the diodes and the absence of flickering issues, as recommended by IEEE Standards (rif. PAR1789). In addition to manufacturer's care in fixture design, the experimental protocol did not involve dimming, further preventing experimental subjects from experiencing flicker during tests.

2.3. Cognitive tasks

Participants performed the following tasks.

2.3.1. Digit-Symbol Association Test

The Digit-Symbol Association Test is a subtest of the widely used WAIS-R (Wechsler, 1981; Italian Version: Orsini & Laicardi, 1997). It consists of nine digit-symbol pairs, reported at the top of the sheet of paper, followed by a list of digits. Participants have to write the corresponding symbol under each digit as fast as possible. The number of correctly associated symbols within the allowed time (120 s) is measured. We performed this test to ensure that control and experimental groups did not differ in terms of speed of processing.

2.3.2. Purdue Visualization Rotations (ROT) Test

The Purdue Visualization of Rotations Test (ROT) is a subtest of the Purdue Spatial Visualization Test Battery (Guay, 1977). In each trial, the pictures of two 3D objects are presented at the top (target object) and bottom (test object) positions of a 17'' computer monitor placed frontally at a distance of about 70 cm. The test object can be the same target object (in 18 trials) or its mirror version (in 72 trials), rotated along the natural axis. We used a modified version in which half of the test stimuli were presented during the first experimental session and the remaining stimuli were presented during the second experimental session. Participants were asked to compare and mentally rotate the two 3D object stimuli and decide whether or not they were the same object (see Fig. 4).

Participants placed their index finger between the two response keys (labelled YES or NO) of a horizontally oriented mouse that was placed so as to correspond with their body midline. The other hand rested on the desktop.

Participants were instructed to limit their movements to key pressing during the testing session. In each trial, participants were asked to determine whether or not two pictures represented the same object and to respond by pressing one of two keys as quickly and accurately as possible. The next trial was presented after a 500 ms interval. This version of the ROT was computer controlled (SuperLab Pro version 4.0, Cedrus Corporation, San Pedro, CA) using a PC. The software allowed recording response times (1 ms time resolution) and accuracy.

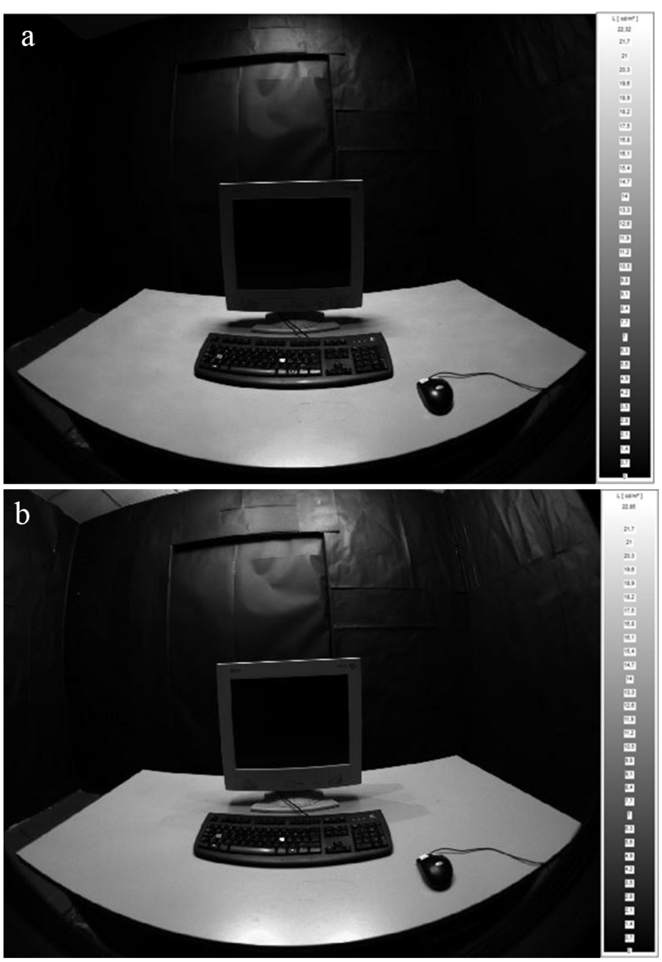

Fig. 3. a. Luminance distribution in the visual field with halogen source. b. Luminance distribution in the visual field with LED.

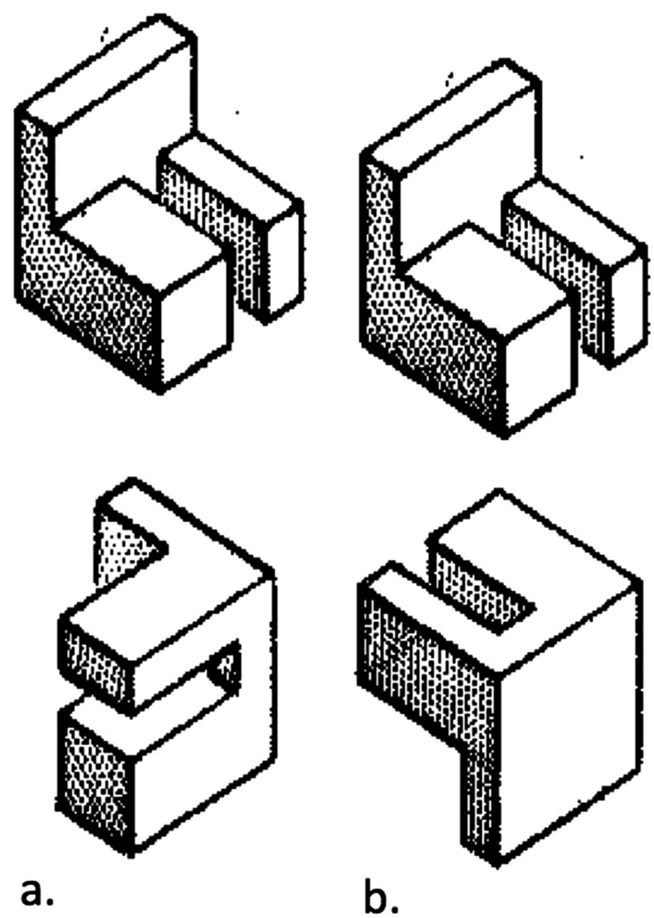

Fig. 4. a. Correct example in which a correspondence between the target 3-D object stimulus (up) and the rotated 3-D object stimulus (down) is shown. b. Uncorrected example in which no correspondence between the target 3-D object stimulus (up) and the rotated 3-D object stimulus (down) is shown. Participants in a. had to press the Yes key of the mouse and in b. the No key of the mouse.

2.3.3. Task switching paradigm

In the Task switching paradigm (Sdoia & Ferlazzo, 2008) participants underwent a session consisting of 340 trials, presented on a 17'' computer monitor, placed frontally at a distance of about 70 cm. In each trial, participants had to perform one of three tasks: i) judge the parity of a digit stimulus (even/odd); ii) judge the numerical magnitude of a digit stimulus (greater/smaller than 5); and iii) compare the colours of two digit stimuli (b and b', same/different colour) separated by a trial in which one of the other two tasks had to be executed (see Fig. 5).

The b- and b'- stimuli were chosen independently of each other. Only one trial could be included between the b- and b'- stimuli of the colour comparison task. In each trial, the upcoming task was precued by a square to indicate a subsequent parity task, a diamond to indicate a subsequent magnitude task and a circle to indicate a subsequent colour comparison task. All cues were grey and were centrally displayed on a black background, subtending a visual angle approximately 7° wide°×°7° high. Target stimuli were digits from 1 to 9, excluding 5 (subtending a visual angle 3° wide × 5° high). They were displayed in red or green (with equal probability).

In each trial, a cue was presented for 1000 ms, followed by a target stimulus that appeared inside the cue. On the parity and magnitude tasks, both the cue and the target stimuli remained on the screen until the response was made or 3000 ms had elapsed. On the colour comparison task, the first stimulus of the pair (b-stimulus) remained on the screen for 1000 ms. The second stimulus of the pair (b'-stimulus) remained on the screen until the subject responded or 3000 ms had elapsed. The response and the first stimulus of the comparison task were always followed by a black screen, which lasted 700 ms, followed by the next cue. The second stimulus (b') of the colour comparison task was not precued because cuing for comparison was presented before the b-stimulus onset, indicating the need for comparison after execution of an interposed task.

Participants had to press one of two response buttons on the computer keyboard (the “A” or “L” keys) with the left or right index finger. They used the left hand for odd digits, digits smaller than 5 and different–colour pairs of stimuli and the right hand for even digits, digits greater than 5 and same–colour pairs of stimuli. Trials were presented in a series of alternating, non-alternating and repeated sequences of four trials in random order. In the non-alternating sequence, three different tasks were executed (CBAb', i.e., parity-colour-magnitude, or magnitude-colour-parity); in the alternating sequence, the same task was performed in the first and third trials (ABAb', i.e., parity-colour-parity, or magnitude-colour-magnitude); and in the repetition trials, the same task was performed in three successive trials (AAA, e.g., parity–parity–parity). We presented 34 alternating and non-alternating sequences and 17 repeated sequences in random order. Because of the random presentation, participants were not aware that different sequences were presented.

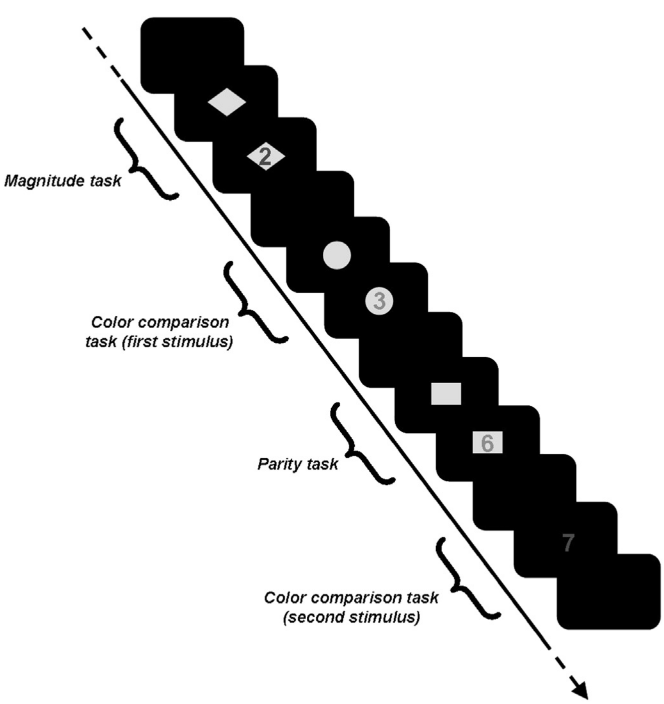

Fig. 5. Task-switching paradigm. Schematic representation of task cues and stimuli.

The Backward Inhibition effect was computed as the difference between average reaction times on the third trials in the alternating (ABA) and non-alternating sequences (CBA); the switch cost was computed as the difference between average reaction times in the third trials of the repetition (AAA) and non-alternating sequences (CBA). The task was computer controlled using software specifically written by one of the Authors. The time resolution was 1 ms.

2.3.4. NASA-Task Load Index (TLX)

The NASA-TLX is a multidimensional rating scale with six bipolar dimensions: mental demand (MD), physical demand (PD), temporal demand (TD), performance (P), effort (E), and frustration (F). A description of the dimensions of these six bipolar dimensions can be found in Hart and Staveland (1988). At the beginning and the end of each experimental session, participants had to fill in the paper version of the NASA-TLX, which reports each dimension and the six bipolar scales on a continuous 12 cm line. In the present study, we analysed the rates on each scale as well as the average rate (Raw TLX).

2.4. Procedure

When they arrived, participants were instructed about the general study procedures. Then they read and signed the informed consent and were randomly assigned to the experimental or the control group. Participants in both groups underwent a baseline and a test session. At each session, they performed the ROT and the Task Switching paradigm in counterbalanced order. Both tasks were computer controlled; stimuli were presented on a computer monitor placed at about 70 cm from the participant. In the baseline session, all participants performed the tasks with halogen lamps (see Table 1 for details). Then, they were allowed to rest for a few minutes.

During the pause, the lighting condition was changed to LED for the experimental group, while the previous lighting condition was maintained for participants in the control group. After the rest break, a 20-min adaptation phase began. During this time, participants 1) filled in the NASA-TLX and a questionnaire in which they were asked to report any previous or current neurological or psychiatric diseases, alcohol and drug consumption habits, and to provide biographical information; and 2) performed the Digit-Symbol Association Test. Then, the test session resumed and participants performed the ROT and the Task Switching paradigm again in counterbalanced order. Participants in the experimental group performed the tasks while the LED lamp was on and participants in the control group performed the task with halogen lamps.

3. Results

Six participants (all males) were excluded from the sample for neurological diseases (head trauma) or regular drug consumption (cannabis). Thus, 20 participants remained in the experimental group and 18 in the control group.

3.1. Digit-Symbol Association Test

Scores on the Digit-Symbol Association Test were submitted to one-way analysis of variance to ensure that the two groups of participants did not differ in terms of speed of processing. No significant difference emerged between the number of hits of participants in the experimental and control groups ($F_{1,36} = 0.01$, $p = .91$).

3.2. ROT Test

For each participant, the average Response Time (RT) in each condition was computed considering only trials in which the correct response (hit and correct rejection) was given, with a response time within the mean $\pm$ 2 standard deviations range.

Both RTs and accuracy (hits and correct rejection) were analysed in a Group (experimental, control) by Phase (baseline, test) mixed ANOVA design. In both cases, Levene's test showed no significant violation of the homogeneity of variances assumption.

RT results showed a marginally significant effect of Phase ($F_{1,36} = 3.95$, $p = .05$) because participants were faster in the test phase compared with the baseline; no effect of Group and no Group-by-Phase interaction was significant ($F_{1,36} = 0.15$, $p = .70$, and $F_{1,36} = 0.23$, $p = .64$, respectively). Although the expected Group-by-Phase interaction was not significant, it should be noted that on average the RTs of participants in the Experimental group improved more in the Test phase compared with the Baseline than the RTs of participants in the Control group. The lack of a significant effect was likely due to the large variability in response times.

Results of the analysis on accuracy showed no significant effect of Group ($F_{1,36} = 0.21$, $p = .65$), but showed a significant effect of Phase ($F_{1,36} = 11.14$, $p < .01$) and a significant Group-by-Phase interaction ($F_{1,36} = 5.21$, $p = .03$). The effect of Phase was due to participants being on average more accurate during the Test phase compared with the Baseline.

However, the planned comparisons of the Group-by-Phase interaction showed that only participants in the Experimental group improved their accuracy during the Test phase ($F_{1,36} = 16.67$, $p < .01$, partial Eta$^2 = 0.32$); the accuracy of participants in the Control group did not change from the Baseline to the Test phase ($p = .46$).

3.3. Task Switching

Participants performed the Task Switching paradigm quite well; indeed, errors in the third trials of each kind of sequence were less than 5%. Thus, errors will not be further analysed.

For each participant, the Backward Inhibition (difference between reaction times on alternating and non alternating sequences) and the Switch Cost (difference between reaction times on the repetition and non-alternating sequences) effects were computed. Only trials in which participants responded correctly with a reaction time that did not exceed their mean reaction time +2 standard deviations were included.

Both the Backward Inhibition and the Switch Cost effects were analysed in a Group-by-Phase mixed factorial ANOVA design. In both cases, Levene's test yielded no significant violation of the homogeneity of variances assumption.

Results of the Backward Inhibition showed a significant Group-by-Phase interaction ($F_{1,36} = 6.36$, $p = .016$) but no significant main effects of Phase ($F_{1,36} = 2.9$, $p = .09$) or Group ($F_{1,36} = 3.4$, $p = .07$) (Fig. 6). Planned comparison showed that for participants in the control group the Backward Inhibition effects measured during the baseline and the test sessions were not significantly different ($F < 1$). By contrast, for participants in the experimental group the Backward Inhibition effect was significantly smaller (actually absent) during the test session compared with the baseline session ($F_{1,36} = 9.42$, $p < .01$, partial Eta$^2 = 0.21$).

The analysis on the Switch Costs showed no significant main effect of Group or Phase ($F < 1$ in both cases) and no significant Group-by-Phase interaction ($F_{1,36} = 1.45$, $p = .24$).

3.4. NASA-Task Load Index (TLX)

Both the average rate (Raw TLX) and the rates on the single dimensions of the NASA TLX were analysed in a Group (experimental, control) by Phase (baseline, test) mixed ANOVA design. Levene's test showed no significant violation of the homogeneity of variances assumption.

Results of the Raw TLX analysis showed only a marginally significant effect of Phase ($F_{1,36} = 4.10$, $p = .05$) and the effect of Group and the Group-by-Phase interaction did not reach statistical significance ($F_{1,36} = 0.03$, $p = .85$, and $F_{1,36} = 1.96$, $p = .17$, respectively). The main effect of Phase was due to participants rating a lower overall workload during the Test phase than the baseline. It should be noted that although not significantly, participants in the Experimental group rated their workload as lower in the Test phase compared with the Baseline than participants in the Control group.

Results of analyses on the ratings of the single dimensions of the NASA TLX showed a significant Phase main effect (Bonferroni corrected to control for the alpha inflation) only for Mental Demand, Physical Demand, and Temporal Demand ($F_{1,36} = 8.68$, $p < .01$, partial Eta$^2 = 0.19$, $F_{1,36} = 15.48$, $p < .01$, partial Eta$^2 = 0.30$, and $F_{1,36} = 8.20$, $p < .01$, partial Eta$^2 = 0.18$, respectively). All participants rated the Mental and the Temporal demands lower in the Test Phase than the Baseline, whereas Physical demands were rated higher during the Test Phase than the Baseline. The ratings of Performance, Effort, and Frustration did not vary between the Baseline and the Test Phase ($p > .05$ in all the cases). The Group effect and the Group-by-Phase interaction did not reach statistical significance for any dimension of the NASA TLX ($p > .05$ in all cases) (Table 3).

4. General discussion

Previous studies analysing the effects of different fluorescent lights on human perception, cognition, physiology and psychology

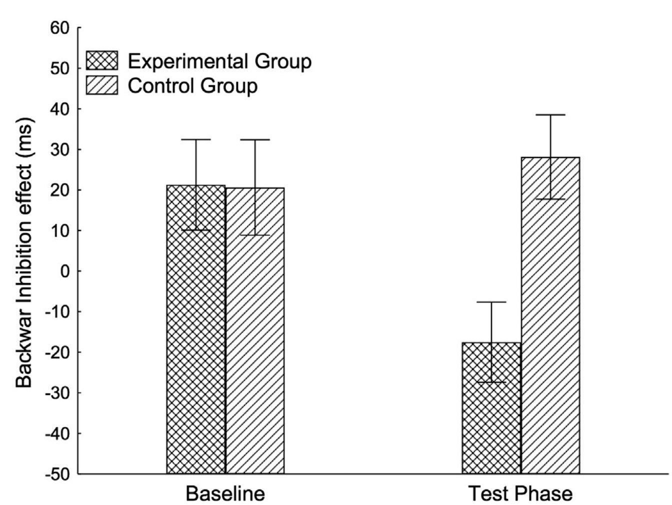

Fig. 6. Average Backward Inhibition effect (ms) as a function of Group (Experimental, Control) and Phase (Baseline, Test Phase). Bars represent the standard error of the mean.

arrived to different and often contrasting results, as discussed in Veitch and McColl (2001). The aim of the present study was to investigate whether new LED light sources with a 4000 K CCT affect some components of executive functions and visual-spatial abilities in healthy individuals compared to halogen lamps, using a different lab setting respect to the previous literature.

Similarly to a recent study wherein three LED lighting and fluorescent settings were studied (Hawes et al. 2012), we compared the effects on human performance of two light sources with very different spectra, new LED and traditional halogen lamps. In particular those authors recorded faster response time with 4175 K LED light than with 3345 K fluorescent lamps. With similar CCT conditions, we also observed different responses to different spectra.

The study was carried out in a specifically-designed, fully-controlled luminous environment, and was performed using a strictly controlled experimental design, which could explain the presence of effects not previously reported in literature. Furthermore, we investigated inhibitory processes and mental rotation abilities that have not been studied so far when investigating the effects of different light sources. Results show that performance on complex tasks tapping executive functions and visual-spatial abilities are modulated by exposure to a cooler light. Indeed, when participants had to decide whether two pictures represented the same object seen from two different perspectives (rotated along the natural axis; ROT test), they were significantly more accurate (higher number of hits and correct rejections) after 20 min of exposure to LED lights than with halogen lamps. Control participants who performed the same task twice with halogen lamps did not show the same pattern of results. Therefore, the effect was not due to learning or habituation. Instead, participants in both groups were significantly faster during the test phase than the baseline, which is a clear effect of learning. Nevertheless, participants in the experimental group improved their response times slightly, although not significantly, more than participants in the control group. Likely, the lack of a significant effect of response times is due to their large variability.

Performance on the Task-Switching paradigm was also clearly modulated by exposure to a cooler light. Indeed, participants in the experimental group showed a significantly reduced Backward Inhibition (BI) effect during the test phase than the baseline, whereas participants in the control group showed no difference between the baseline and the test phase. The BI effect is an inhibitory process of executive functions and is considered one of the mechanisms that reduce the interference between multiple representations of tasks, thus facilitating the execution of a new task. It is interesting that in the present study reduced Backward Inhibition efficiency was not associated with increased switch cost.

Previous studies (e.g., van Baarsen, Ferlazzo, Ferravante, Smit, Van Duijn, & Van Der Pligt, 2011) on the effect of chronic stress on executive functions reported that BI decreased and the switch cost increased during 520 days of isolation and confinement, confirming the negative relationship between the two mechanisms. Results of the present study suggest that exposure to a cooler light improves the capacity of the cognitive system to deal with multiple task representations that might remain active (i.e., not inhibited) simultaneously without interfering with one another. It should be noted that the effect is moderate in size, which suggests that it might have relevant practical implications.

In the present study, the effects of LED light exposure on visual-spatial abilities and executive functions cannot be explained by between group differences in processing speed or general reduction of the mental workload associated with the cognitive tasks.

Table 3
Average scores for each task as a function of Group (Experimental, Control) and Phase (Baseline, Test Phase). Standard errors of the mean are reported in parentheses.

Tasks	Baseline		Test phase	
	Exp. group	Control group	Exp. group	Control group
Digit Symbol Association Test	65.15 (2.27)	65.50 (2.39)	–	–
ROT Test Response times (ms)	9175.01 (943.05)	9266.77 (994.07)	7572.03 (738.60)	8283.40 (778.55)
ROT Test Accuracy	33.20 (1.44)	35.72 (1.52)	37.35 (1.27)	36.50 (1.34)
Task Switching Switch Cost (ms)	4.93 (14.69)	3.68 (15.48)	19.14 (13.40)	20.92 (14.12)
Task Switching Backward Inhibition (ms)	21.28 (11.16)	20.62 (11.77)	−17.53 (9.87)	28.14 (10.40)
Task Switching Repetition sequence	690.49 (25.42)	786.84 (26.79)	671.09 (24.82)	707.73 (26.16)
Task Switching Non alternating sequence	695.42 (25.04)	790.53 (26.40)	690.23 (27.72)	728.65 (29.22)
Task Switching Alternating sequence	716.70 (28.71)	811.14 (30.27)	672.69 (26.17)	756.79 (27.59)
NASA Raw TLX	51.71 (3.38)	49.68 (3.57)	44.58 (3.81)	48.38 (4.01)
NASA TLX Mental Demands	65.75 (4.97)	60.56 (5.24)	52.25 (5.29)	56.11 (5.58)
NASA TLX Physical Demands	31.00 (4.48)	33.06 (4.72)	40.75 (5.85)	51.11 (6.17)
NASA TLX Temporal Demands	58.00 (5.21)	51.67 (5.49)	46.50 (5.02)	44.17 (5.29)
NASA TLX Performance	57.00 (4.47)	50.56 (4.71)	44.75 (4.91)	42.78 (5.17)
NASA TLX Effort	56.00 (4.44)	58.89 (4.68)	51.75 (4.71)	51.94 (4.96)
NASA TLX Frustration	42.50 (6.03)	43.33 (6.36)	31.50 (5.59)	44.17 (5.89)

Indeed, participants in the experimental and the control group did not perform differently on the Digit–Symbol Association Test. Also, the overall mental workload (Raw TLX), measured by the NASA TL, as well as its single dimensions, was reduced during the test phase compared with the baseline. Nevertheless, the amount of improvement was the same for participants in both the experimental and the control group.

Although the literature on the so-called non-visual effects of light is increasing, there is still no broad consensus about the nature, reliability and extent of these effects (see Vandewalle et al., 2009 for a review). Indeed, a number of methodological issues are still open, including the parameters of light stimulation (wavelengths, time of exposure, etc.). There are also theoretical issues. For example, it is still unclear whether the described effects on cognitive processes, such as long-term memory, should be considered as direct or indirect effects due to more general improvement of arousal, mental workload, mood, etc.

To disentangle the direct and indirect non-visual effects of light on cognition, we focused on executive functions and visual spatial abilities. Indeed, neuroimaging studies (Vandewalle et al., 2009) have reported that exposure to blue light affects the activities of a number of brain areas linked to these cognitive functions (e.g., prefrontal cortex, parietal cortex and subcortical brain structures such as the locus coeruleus).

Furthermore, it is important to investigate these processes thoroughly because they are crucial in several professional fields in which high-level spatial abilities are required as well as good ability to inhibit behaviour. Examples of this include pilots engaged in flight, surgeons performing an operation and, in general, workers confronting an emergency situation. Our results suggest that a cooler light exposure improves performance by reducing errors and maintaining multiple mental representations.

A characteristic of this study is to have carried on the experiments (visual tests) in a fully controlled environment with a strictly controlled experimental design. The setting has been designed to maximize light effect in each test session, avoiding interferences of external light or unwanted reflections, and assuring the same illuminance levels on the desk with different light sources. More, both experimental and control groups performed a baseline and a test session, but only for the control group the lamp switch was operated from first to second session. This procedure allowed to exclude the task learning effect in results and to obtain a truthful measure of the different spectra effect. While other works have one time used less-controlled experimental settings, which gave a measure that could not separate the experience at the task from the lamp type effect. This could be a reason for finding effects that others have not in that range of CCTs (Veitch & McColl, 2001).

Differently from previous experiences (Deguchi & Sato, 1992; Hawes et al., 2012; Noguchi et al., 1999) in which similar CCTs were studied using similar light sources, in our experiment very different light spectra (as shown in Fig. 2) were used: the experimental group was exposed to a typically radiative light source (halogen lamps), characterized by a minimum of emissions in the short wavelengths first, and then to a LED emission characterized by a continuous trend with two spikes, in the blue and in the yellow regions, probably emphasizing the effect of increasing performance. Specifically, under a cooler light people seem to make fewer errors and to perform multiple tasks simultaneously. In any case, at present the nature of these improvements is still unclear as is the duration of these positive effects. Future studies should determine how long the effects last. Indeed, new light sources could be adopted in work contexts and during critical phases of decision-making.

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