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Cold LED lighting affects visual but not acoustic vigilance

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Abstract

Previous studies demonstrated that both light intensity and spectral composition of light impact on brain functioning and regulate circadian rhythms. Further, several studies have shown that light exposure, especially blue light (about 460 nm), has positive effects on alertness, vigilance, mood, also increasing mental performance and work productivity. Unfortunately, results have not been always consistent. This study investigated the effect of different lighting conditions on attention with an experiment examining the impact of correlated colour temperature (CCT) on visual and acoustic vigilance. The performance of forty participants (20 men), aged from 20 to 35 years, was investigated under warm (3000 K) or cold (6800) white LED lighting conditions: under these conditions they executed a cross-modal vigilance task and filled in the Karolinska Sleepiness Scale (KSS) and the Global Vigor and Affect (GVA) scale. Results showed a positive effect of cold light on visual vigilance and absence of effects on acoustic vigilance. Specifically, a significant effect of the cold lighting condition was found in the visual response times (RT): participants in the experimental group when executing the task with 6800 K LED maintained the same visual vigilance level and did not experience the natural vigilance decrement, as occurred to the control group under 3000 K LED Furthermore, no effects were observed on sleepiness and vigour-mood self-assessments.

A hypothesis of the possible reason for this modality-specific effect could rely on different neural bases involved in visual versus auditory signals.

Keywords

LED lighting, correlated colour temperature (CCT), performance, sleepiness, attention.

Highlights

- Several previous findings demonstrated that lighting affects human performances on attentive tasks
- The effects of different lighting conditions on vigilance have been investigated
- Visual and acoustic vigilance tasks were tested under cold (6800 K) vs. warm (3000 K) LED lighting
- A significant effect of the cold lighting was found only on visual vigilance

1. Introduction

In industrialized countries people spend a lot of time inside buildings, receiving a little portion of natural light and a high amount of electric lighting: in fact, the interiors are often lit with artificial lighting even during daily hours. For this reason, the light source adopted is very important to guarantee human comfort and wellbeing. For long time the lighting design was based on the principle of visual comfort: the international Standards (UNI 10380; UNI 12464) [1], [2] indicated the illuminance level, illuminance uniformity, glare and color rendering index (CRI) as the quantities to control for achieving a comfortable visual task. The new regulations on energy efficiency in buildings (EN 15193) [3] influence the work of the lighting designer, imposing the selection of light sources with high luminous efficiency and other strategies to reduce energy consumption [4].

In the last decades researches demonstrated that light produce effects not only on the visual system, but also on human physiology and behaviour (see van Bommel 2004 for a review) [5]: these discoveries imposed to define new lighting criteria [6] and the principles of healthy lighting (CIE 158:2004; CIE 218:2016) [7], [8] were included in the concept of lighting quality. The luminous environment produces additional effect to vision, depending in particular on the light reaching the eyes: these non-visual effects are related mainly to the light features, such as spectral composition and intensity, and partially also to the environmental features that interact with the luminous beam incident on the eye, like colours and roughness of materials: even if these characteristics of materials are more relevant for the visual system, they can also partially impact on the non-visual process modifying through reflections the spectral composition of the light [9][10]. The recent diffusion of LED technology for office lighting imposes to investigate the impact of these new light sources on humans and their cognitive functioning.

The role of light in affecting humans differently from vision emerged in several psychological, physiological and photobiological studies. Light stimulus is the main responsible for the circadian entrainment of multiple physiological functions and its effect depends on timing, duration, previous exposure, intensity and spectral composition [11]; it has been demonstrated that the blue light (about 460 nm) [12], [13] is most effective in affecting melatonin suppression, heart rate, body temperature, alertness [14], [15] and sleep [16]-[18].

Behind the circadian rhythms, light produces direct effects on human brain, modulating several cerebral areas: 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 [19]-[26]. Nevertheless, Fisk and colleagues in their recent review (2018) concluded that studies about the influence of light on cognition should also consider implications on circadian system, sleep and arousal [27].

In particular, positive effects of blue light exposure are reported for some components of attention such as enhancement of alertness and enhancement of vigilance' speed (see Vandewalle et al 2009 for a review) [19]. Blue light seems also to be effective in reducing sleepiness and enhancing cognitive performance in tasks requiring concentration and cognition [28]-[30]. Specifically, Deguchi and Sato (1992) [31] found that 7500 K light triggers orienting responses more than 3000 K light, but they did not reveal effect on simple reaction times. Self-reported judgements showed that the 17000 K light improves alertness, performance, and quality of nocturnal sleep more than 4000 K light [32]. Mills et al. (2007) [33] in a shift-working call centre, carried out a field experiment in which the effects of neutral CCT (4000 K) and high CCT (17000 K) sources were compared. They found improvements of work performance, alertness, fatigue and daytime sleepiness with 17000 K light in line with the results by Viola et al. (2008) [32]. Ferlazzo et al. (2014) [30] found positive effects with 4000 K LED light versus no effects with 2800 K halogen lamps on some components of visuo-spatial abilities and executive functions. These authors stressed the importance to investigate light exposure in a specifically-designed and fully-controlled luminous environment, since reliability and extent of the light effects are often critically discussed and it has been suggested that they could depend on specific experimental settings and protocols[34].

Regarding the impact of light on vigilance, the studies carried out in literature found mixed results: the review of Souman et al. [35] highlight that a large part of works investigating the increase of light intensity reported effects on subjective alertness, but few study demonstrated an improvement of objective performance; specifically, only the studies of Phipp-Nesson et al. [36] and Smolders et al. [37] reported a significant effect of light intensity using a Psychomotor Vigilance Task (PVT), while none of the

experiments adopting a reaction time task found effect on vigilance. Similar conclusions emerged in the few works comparing low vs. high CCT polychromatic white light [35]: some of them found effect on subjective alertness [38, [39] and only Chellappa et al. [29] reported an increase both in subjective and objective vigilance . Moreover, relevant seems to be whether the study was carried out during the day or in the evening and night, as an alerting effect of light was often reported in nocturnal studies. Smolders and de Kort (2017) [40] investigated the effect of white warm (2700 K) and cold lighting conditions (6000 K) on subjective alertness and objective vigilance performance in a morning vs. afternoon study, without finding significant effect of the CCT condition (except for vitality in the morning) and obtaining mixed results depending to time of the day.

Interestingly, whether light conditions affects vigilance decrement, rather than vigilance levels, has never been investigated so far. Vigilance decrement refers to the performance degradation over time while performing a monotonous task. It is usually investigated using tasks requiring participants to detect relatively rare target stimuli in a continuous stream of otherwise repetitive stimuli. The vigilance decrement is defined as the decreased probability of detecting the target stimuli and slowed response times in such tasks as the time on task increases [41]-[44].

This work is aimed at studying the impact that the new LED lighting can have on human performance, since in the recent years the use of new energy saving LED technology in many buildings is increasing. The following experiment investigated the effects of two LED lighting conditions on different aspects of vigilance: a warm LED has been compared with a cold LED for examining the effect of the different CCT on human attention. Two typical interior white LED with different CCT were used in this experiment: for the warm scenario a low CCT with large amount of yellow-orange light was selected (3000 K), while for the cold condition a LED with high quantity of blue component in the spectrum was used (6800 K).

To this extent, a cross-modal Visuo-acoustic Vigilance Test in which subjects have to perform at the same time a visual and an acoustic vigilance tasks was used under different lighting conditions. Along with vigilance performance and its decrement, also measures of self-assessment of sleepiness and mood (respectively, KSS and GVA scales) have been collected with the further aim to check also internal factors that may affect cognitive performance. All participants were also controlled for sleep quality and quantity

in order to identify possible sleep alterations that could act as confounding variables on cognitive functioning.

2. Materials and methods

An experimental study was conducted to investigate the effect of lighting on acoustic and visual vigilance, comparing warm and cold LED conditions.

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.

2.1 Participants

Forty healthy college students (20 women) took part at the experiment mean age of participants was 22.6 ±1.35 years for women and 22.8 ±1.36 years for men; all had at least 13 years of education. They were randomly assigned to two groups (namely, control and experimental; for more details see below in the Procedure section): the control group presented an age mean of 25.2 (±3.24) yrs. and an education mean of 16.3 (±2.41) yrs., while the experimental group had an age mean of 24.7 (±2.96) yrs. and an education mean of 16.9 (±1.87) yrs. It can be concluded that groups' sample did not differ significantly for both age and educational level (age: t=0.19, p=n.s.; education; t=0.13, p=n.s.).

All participants declared they had not recently (i.e., at least in the previous two weeks) travelled across time zones, had normal or corrected-to-normal vision, had not colour vision diseases, and had not drunk coffee or smoked cigarettes the two hours before testing. Moreover, participants filled in a questionnaire in which they indicated any previous or current diseases and any substances and alcohol consumption. The inclusion criteria were to have a good quality of sleep as measured by the Pittsburgh Sleep Quality Index (PSQI: cut-off score <5) [49], no history of neurological or psychiatric disorders and no substance abuse or dependence. All participants signed the informed consent before starting the experiment.

2.2 Experimental setting

The study took place in the morning (between 10 and 12 a.m.) within an experimental cabin of dimensions 3.6 m in length 2.4 m in width and 3 m in high; it was furnished with a desk of dimension 1.2 x 0.7 m with a chair and a computer provided with a mouse, a keyboard, a 17-inch LCD monitor and audio peripherals. The internal walls of the cabin were coated with opaque black cardboards to limit the light reflections and no window was present to completely exclude the entrance of natural light. The lamps were placed at the ceiling in front of the participants, at short distance from the table.

Two luminous conditions were tested: the warm scenario was realized with 3000 K white LED and the cold scenario with 6800 K white LED. In each condition the artificial lighting was provided with a LED device of dimensions 60x60 cm recessed in the ceiling, mounting a diffusive glass and composed of four luminous strips.

Photometric measurements were collected to estimate the luminous conditions in the two scenarios. The spectral composition of the LED lamps was recorded at the eye level by means of the spectroradiometer JETI Specbos 1211UV, to evaluate the different concentration of luminous emission, particularly in the blue wavelengths, of the adopted LEDs: the spectral curves of the lamps are showed in Figure 1.

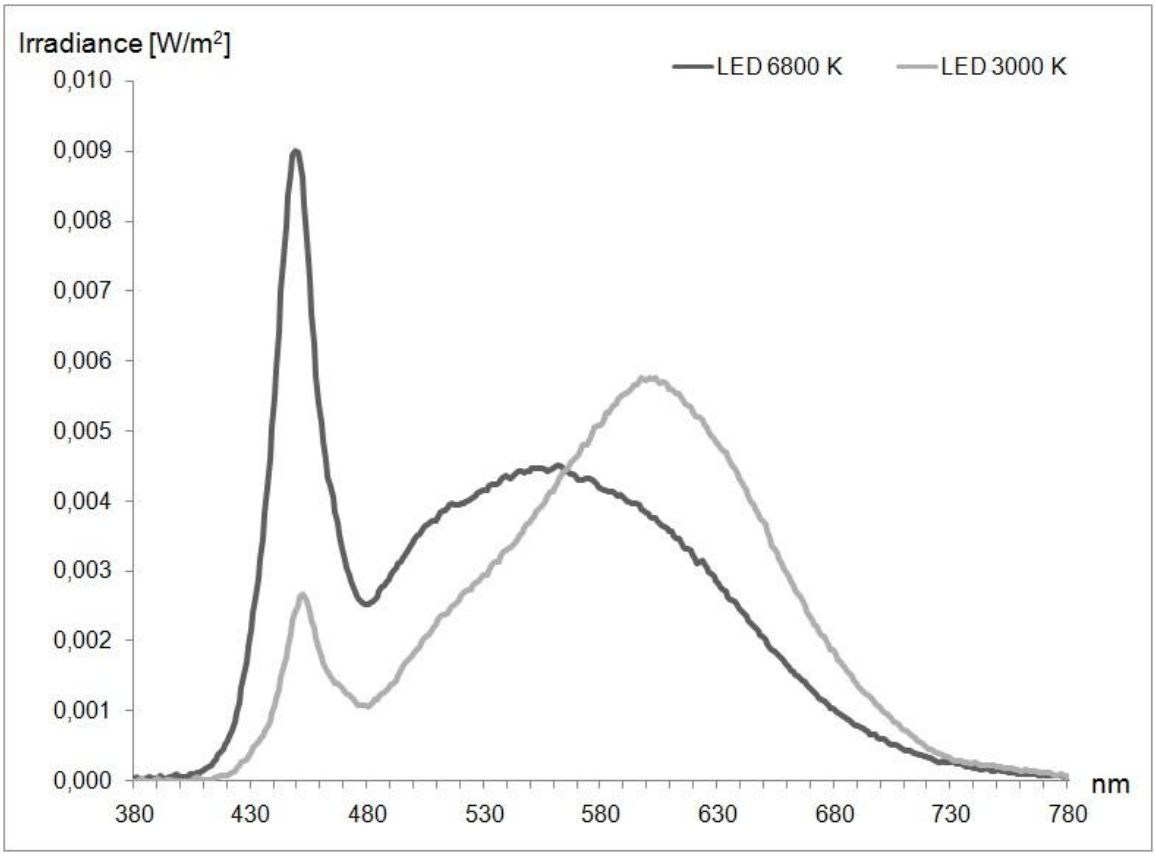

Figure 1. Lighting conditions. Spectral composition of the warm 3000 K LED and cold 6800 LED

Illuminance on the desk has been measured by means a luxmeter Delta OHM HD2302.0 using a grid of points distant 0.25 m; luminous information received by participants' eyes has been controlled measuring illuminance and luminance by means of a spectroradiometer JETI Specbos 1211UV placing the instrument in the position of the chair at 1.2 m from the floor, with the sensor facing monitor; values recorded are reported in Table 1. Both illuminance and luminance of the screen recorded at the eye's position were negligible since they contributed respectively less than 1 lx and than 0.15 cd/m^2 for all the visual stimuli presented.

Table 1. Photometric measures. Values of illuminance (E) and luminance (L) measured in the warm (3000 K LED) and cold (6800 K LED) lighting conditions

Lighting condition	**DESK**	**EYE**

	E min (lx)	E ave (lx)	E max (lx)	E ave (lx)	L ave (cd/m^2)
COLD LED (6800 K)	413	441	505	289	1.8
WARM LED (3000 K)	408	446	528	288	1.9

In accordance with the CIE Technical Note 003:2015 [45] recommendation, the circadian and neurophysiological effects elicited by the tested luminous conditions have been calculated using the toolbox provided by Lucas et al. (2014) [47]; it consents to calculate the five eye photoreceptors response starting from the spectral irradiance distribution (SID) of the light stimulus. The Table 2 shows the output, obtained selecting 1 nm input mode on the spreadsheet and inserting the SID values transformed in μW/cm². In addition, the circadian light (CL_A) and the circadian stimulus (CS) proposed in Rea et al. (2012) [48] have been calculated by means of the tool provided by the same authors [http://www.lrc.rpi.edu/programs/lightHealth/index.asp].

Table 2. Non-visual effects calculations. Eye photoreceptor response and circadian effect of the warm (3000 K LED) and cold (6800 K LED) lighting conditions

Lighting condition	S cone (μW/cm²)	Melanopsin (μW/cm²)	Rod (μW/cm²)	M cone (μW/cm²)	L cone (μW/cm²)	CL_A (circ. lux)	CS (unitless)
COLD LED (6800 K)	23.01	34.45	41.12	47.01	48.55	405	0.375
WARM LED (3000 K)	6.56	16.89	24.57	38.82	49.15	257	0.288

The values presented in Table 2 were calculated on the basis of the spectrum measured in vertical at eye level, not considering the impact of eyeglasses or contact lenses, which filtering the radiation could produce a little different stimulus on the retina.

2.3 Tasks

A cross-modal task has been administered to participants: it was preferred to two unimodal tasks since it can have a short duration time without diminishing its experimental validity. Participants sat inside the cabin in front of a 17" LCD computer monitor distant about 50 cm and performed the cross-modal Visuo-Acoustic Vigilance Task wherein they had to respond as fast as possible to visual and acoustic target stimuli.

- Acoustic Vigilance: Participants were presented with a series of regularly alternated high (2000 Hz) and low (1000 Hz) tones (e.g., 1000 - 2000 -1000 - 2000 Hz, etc.) at 60 dB. Tones were sampled at 48000 Hz, were100 msec. in duration, and were presented binaurally. A tapered cosine window (Tukey window) was applied to the initial and final 20% to prevent clicks to be heard. A total of 903 tones were presented, in 7 blocks of 129 tones each. Within each block, on 9 pseudo-random occasions the same tone was presented twice, violating the alternation rule. The second occurrence of the same tone was the target stimulus participants has to respond to as fast as possible (within a 1 sec window) by pressing the left button of the mouse using the index finger of their dominant hand. The mean interval between two successive target tones was about 14 sec.

- Visual Vigilance: Participants were presented with a series of regularly alternated red (RGB: 255,0,0) and green (RGB: 0,192,0) squares (e.g., red - green -red - green, etc.) on black background, appearing at the centre of a 17" LCD computer monitor for 500 msec. each. All the visual stimuli subtended about 1.15° of visual angle. A total of 903 stimuli were presented, in 7 blocks of 129 stimuli each. Within each block, on 9 pseudo-random occasions a square of the same colour was presented twice, violating the alternation rule. The second occurrence of a square with the same colour was the target stimulus participants has to respond to as fast as possible (within a 1 sec window) by pressing the left button of the mouse using the index finger of their dominant hand. The mean interval between two successive target squares was about 14 sec.

During the vigilance task, acoustic and visual stimuli were presented simultaneously, with a 500 msec. interstimulus interval. The visual and acoustic target stimuli were never presented simultaneously and at least three standard stimuli had to be presented between two successive target stimuli. Overall, the vigilance task lasted about 15 minutes (included the written instructions displayed on the screen before starting) and participants were unaware of the organization in blocks of the series of stimuli. Reaction times to the target stimuli (time interval between the appearance of the target stimulus and the mouse button press, 1 msec. resolution), false alarms, and missing responses were recorded during the task.

2.4. Scales and questionnaires

Sleepiness and vigor-mood were assessed by using, respectively, Karolinska Sleepiness Scale (KSS) [49] and Global Vigor and Affect scale (GVA) [50]. The KSS is a 9-point Likert scale based on a self-reported, subjective assessment of the subject's level of drowsiness at the time, varying from 1= "extremely alert" to 9= "very sleepy, fighting sleep". Participants are asked to self-assess their status by marking the number/definition that best describe their current condition and the number corresponding to the definition was the dependent variable. The GVA is a visual analogue scale in which participants are asked to answer to some questions about their current status (e.g. "How alert do you feel?"; "How happy do you feel?"): for each question, subjects answered by making a stroke with a pen on a 100 mm long line, the stroke corresponding to the point indicating the intensity of the self-evaluation. Each line was anchored at one end with "not at all" and at the other end with "very much": the distance of the mark from the left end of the line (i.e., "not at all") was considered as a dependent variable. Such a scale allows to obtain two indices: the first of general vigor and the latter of affect.

Finally, sleep quantity and quality was assessed by means of a sleep log (previously used and validated in several other sleep studies, as for example Curcio et al., 2004) [51], to be filled in immediately at awakening for the two days before and the morning of the experimental session. Sleep log was aimed at evaluating potential conditions of sleep deprivation and/or decrease in sleep quality in the night before the experimental sessions and was thus used as inclusion/exclusion criterion: to this extent total sleep time, sleep latency, sleep efficiency, number and duration of nocturnal awakenings, and several other sleep-related information have been assessed. Only people with a good self-reported quality of sleep (higher than

80 on a visual analogue scale ranging from 0 to 100), an acceptable sleep efficiency (higher than 85 on a visual analogue scale ranging from 0 to 100) and with a sufficient amount of sleep (at least 7.5 hours per night) in the nights before the experimental sessions were included in the investigated sample.

2.4 Procedure

Participants were randomly assigned to the two groups, namely the control (CG) or the experimental group (EG). Both groups executed the Visuo-acoustic Vigilance Test and filled in the KSS and GVA scales twice: in the first phase, i.e. baseline session (BS) and in the second one, i.e. test session (TS). These two sessions were separated by a 20 min pause and followed by a fourth phase indicated as ending. The four phases lasted about 15, 20, 15 and 5 minutes, respectively. Some delayed assessments limitedly to KSS and GVA have been repeated at fixed hours (POST1 at 3 p.m.; POST2 at 6 p.m.; POST3 at 9 p.m.).

Participants in CG performed all the four phases of the experiment under warm light (LED 3000 K), whereas participants in EG executed the BS under the warm scenarios and the pause, the TS and the ending part under cold light (LED 6800 K). Table 3 explains the luminous scenarios during the four phases of the experiments.

Table 3. Luminous scenarios. The control group executed the whole experimental procedure with warm LED lighting, while the experimental group executed only the baseline session under warm LED and the other sessions with cold LED.

GROUP	**Baseline Session**	**Pause**	**Test Session**	**Ending**
Control	warm LED (3000 K)	warm LED (3000 K)	warm LED (3000 K)	warm LED (3000 K)
Experimental	warm LED (3000 K)	cold LED (6800 K)	cold LED (6800 K)	cold LED (6800 K)

The warm LED was used as baseline in both groups for its low blue light content that assure a very limited stimulation on the non-visual system, as indicated in Table 2. Conversely, the 6800 K LED was selected just for its high blue light content as test scenario for the EG. To this extent, the study will directly compare the performance of the EG in the TS respect to BS, hypothesizing an increase of vigilance with the cold LED light; the same comparison between BS and TS should not evidence a different performance in the CG that executed the whole test under the cold LED lighting.

The tests were executed in the morning, starting about at 10:00 am. Before the participants' arrivals the warm lighting was lit on; they seated within the cabin and get acclimatized with the environmental conditions for 5 minutes, during which they were instructed about the general study procedures. After the beginning of the experimental procedure participants were not allowed to exit the cabin or to live the seat till the end; during the pause, after having filled in the questionnaires, participants relaxed themselves seated with open eyes and the screen turned off. The complete duration of the procedure was about 1 hour. The questionnaire delayed assessments were executed outside the experimental cabin in the afternoon and evening at fixed hours.

2.5 Statistical analyses

Sleep variables as assessed by sleep log (time of sleep onset, total sleep time, sleep efficiency, number and duration of awakenings, sleep onset latency, time of final awakening, sleepiness and tiredness at awakening) were compared between the two groups of participants (CG vs. EG) by means of a Student' t test.

Performance data at the vigilance task were analysed separately for the visual and acoustic target stimuli. Only reaction times slower than 100 msec. and faster than 1000 msec. were retained and analysed. The proportions of missing responses (the participant fails to respond to a target stimulus) and false alarms (the participant responds to a non-target stimulus) were arcsin transformed prior the analysis.

The Box's M test was carried out in order to assess the possible presence of violation of the equality in within group covariance matrices assumption. The mean reaction times (RTs), the proportion of missing responses, and the proportion of false alarms (both arcsin transformed) to visual and auditory target

stimuli presented during the first and the second half of the experimental session (lasting about-6-6.5 minutes each) were analysed in the same Group (EG vs. CG) by Time (first vs second half) with an Ancova design, in which the data collected during the baseline session were used as covariate. This statistical design allowed us to control for the large performance variability among the participants.

Finally, scores of KSS and GVA scales (both vigor and affect) were compared by means of an ANOVA 2x5, Group (CG Vs. EG) x Time (BS; TS; POST1; POST2; POST3).

3. Results

Statistical analyses carried out on all sleep diary variables showed no differences between groups (t_{38}<1; p=n.s.). On the basis of these results no participants showed a significant impairment of previous sleep and thus all those recruited were included in the study.

One participant in the CG was excluded from all the analyses, as his reaction times to both visual and acoustic target stimuli were more than 2 standard deviations slower than the group mean. Furthermore, the percentage of false alarms was less than 5%, thus they have not been further analysed.

With regards to the vigilance task baseline behavioural data, no difference was found between the CG and EG groups for the arcsin transformed proportion of missing responses to visual and auditory target stimuli (t_{37}=.46, p=.65 and t_{37}=1.07, p=.29, respectively) and for the reaction times to visual and auditory target stimuli (t_{37}=-1.5, p=.14 and t_{37}=-.15, p=.88, respectively).

With regards to the arcsin transformed proportion of missing responses to visual targets, the Box's M test showed no violation of the equality of within group covariance matrices assumption (Box's M=5.00; Chi-square(6)=4.56; p=0.60). Ancova results did not show any significant main effects of Group ($F_{1,36}$<1) and Time ($F_{1,36}$=2.02, p=.16), nor a significant Group by Time interaction ($F_{1,36}$=1.03, p=.32; see Table 4).

With regards to the arcsin transformed proportion of missing responses to auditory targets, the Box's M test showed a significant violation of the equality of within group covariance matrices assumption (Box's M=50.40; Chi-square(6)=45.97; p<.01). Since the approximately equal sample size across the cells, however, the same Ancova design was run, and the results did not show any significant effects of Group, Time, or Group by Time interaction ($F_{1,36}$<1 in all the cases; see Table 4).

Table 4. Statistical results. Mean percentage of missing responses and mean RTs to target visual and auditory stimuli presented during the baseline phase and during the first and second half of the test phase to participants in the control and experimental groups. Standard errors are reported in parentheses

	GROUP	VISUAL VIGILANCE			ACOUSTIC VIGILANCE		
		Baseline	Test (First half)	Test (Second half)	Baseline	Test (First half)	Test (Second half)
MISSING RESPONESE	Control	41.67 (3.36)	36.26 (3.20)	40.64 (3.82)	24.63 (3.66)	18.42 (2.75)	25.44 (3.83)
	Experimental	43.89 (3.27)	33.89 (3.12)	43.33 (3.72)	32.22 (3.57)	19.72 (2.68)	23.06 (3.73)
REACTIONTIMES (msec.)	Control	478.10 (10.81)	470.20 (7.85)	494.76 (8.98)	450.36 (11.08)	426.22 (6.95)	438.87 (8.99)
	Experimental	500.75 (10.54)	491.14 (7.85)	491.44 (8.98)	452.62 (10.80)	437.08 (6.95)	451.92 (8.99)

With regards to the reaction times to visual targets, the Box's M test showed no violation of the equality of within group covariance matrices assumption (Box's M=4.83; Chi-square(6)=4.41; p=0.62). Ancova results did not show any significant main effect of Group or Time ($F_{1,36}$<1 in both cases). However, a significant Group by Time interaction ($F_{1,36}$=5.38; p=0.03) was observed. Results of the Newman-Keuls test showed that participants in the control group were significantly slower to respond to visual targets

during the last 6 minutes of the task compared to the first 6 minutes (p=.009), while participants of the experimental group (LED 6800 K) did not show the same increase in RTs (Table 4).

With regards to the reaction times to auditory targets, the Box's M test showed no violation of the equality of within group covariance matrices assumption (Box's M=5.25; Chi-square(6)=4.79; p=0.57). Though RTs of participants in both the groups increased in the last compared to the first 6 minutes (Table 4), Ancova results did not show any main effect of the Group and Time factors, nor a Group by Time interaction ($F_{1,36}$<1 in all the cases).

No significant differences emerged between CG and EG on self-assessments of sleepiness (KSS), affect and vigor (GVA). More specifically, for KSS no significant main effects (Group $F_{1,190}$=1.96, p=n.s.; Time $F_{4,190}$=0.87, p=n.s.) or interaction (Group x Time $F_{4,190}$=0.98, p=n.s.) were observed. Similarly no significant main effects or interaction were observed for both Vigor (Group $F_{1,190}$=0.23, p=n.s.; Time $F_{4,190}$=2.56, p=n.s.; Group x Time $F_{4,190}$=1.76, p=n.s.) and Affect subscale (Group $F_{1,190}$=1.77, p=n.s.; Time $F_{4,190}$=0.87, p=n.s.; Group x Time $F_{4,190}$=0.99, p=n.s.) of GVA.

4. Discussion

Basing on existing literature, several results show differences in cognitive performance due to different lighting spectra [52], [31]-[33], but other works, including some on vigilance, found mixed results ; for this reason this study examined the influence of lighting having different percentage of blue radiation on different aspects of human vigilance in healthy young individuals. In particular, the experiment was aimed at investigating the effects LED lighting with different CCT (3000 K and 6800 K) on cross-modal vigilance performance and self assessments of sleepiness, vigour-mood and effort.

Results obtained evidenced that the impact of light on vigilance basically depends on the sense involved: for this reason, the effects on visual and acoustic vigilance will be separately discussed.

A statistically significant effect of the lighting condition on visual vigilance was observed: the control group performing the task under warm LED light (3000 K) showed a natural increase of reaction time (i.e. reduction in vigilance level), while the experimental group under cold LED light (6800 K) offered a very similar performance in first and last minutes of the cognitive task, indicating a stable performance

independently by the time elapsed. Differently, no effect of light emerged with respect to the acoustic vigilance: a natural decrement of vigilance was observed under both lighting conditions, but these effects did not reach the statistical significance. Participants were faster and more accurate on acoustic vigilance in spite of lighting condition. This observation is in line with other studies [53],[54] that found that response times to auditory stimuli are reported to be faster than response times to tactile and visual stimuli. Furthermore, it is known that performance on acoustic vigilance is less variable than visual vigilance and it seems to be less sensitive to experimental manipulation such as sleep deprivation[54] .

Taken together these results seem to suggest that the cool LED light interacts in a more relevant way with the visual component of the vigilance than with the acoustic components. A possible reason for this modality-specific effect could rely on different neural bases involved in visual versus auditory signals. Nonetheless the existence of a well known crossmodal interaction during cognitive processing has also been reported [52]-[57], hypothesizing the key role of supramodal regions [58], it should be borne in mind that visual and acoustic signals are basically processed in different and anatomically separated sensory specific areas. Regarding the present results, it might be hypothesized that lighting could influence only those areas involved in modality specific processing for visual stimuli and not those specialized for acoustic ones and for supramodal activity.

Another possible explanation for this effect, could be based on the evidence that the acoustic modality is probably modulated by other environmental factors not based on lighting. Future studies should further investigate what kind of environmental factors may affect acoustic vigilance. Moreover, we could not exclude an effect due to the sample size, considering that response times in acoustic vigilance are faster and less variable than those in visual vigilance it is possible that some effects could be noted only in larger sample. However, in our sample is not present a large variability in response times either in visual or in acoustic tasks, but participants differed only in the speediness in which they performed the two tasks.

The absence of a statistical effect on the self-assessed sleepiness and vigour could be due to the very short exposure to the cold lighting (about 35 minutes), so that its effect could has not perceived by participants. This is in contrast with some previous studies which reported earlier onset of light-induced moderations in subjective sleepiness than vigilance performance or also reporting mainly an effect on self-

report measures and not on performance tasks: in our opinion, this difference could arise from different source light' characteristics, that could differently influence behavior, performance and self-perception. For this reason, a potential limitation of the present study is the lack of physiological measures for detecting the level of body activation. Another potential limitation of the study is related to the relatively small sample size, especially given the fact that the study was a between-subjects design: a possible future study would we planned as a whithin-subjects design in order to avoid possible effects due to interindividual differences.

Furthermore, results of this experiment seem to confirm that the effect of light on vigilance is related to the light CCT: the positive effect on visual vigilance should be due to the percentage of blue light contained in the spectrum. With the cold lighting, participants did not experience the vigilance decrement that normally happens with time during the task execution, but registered constant RTs; similar performance was not observed under the warm control luminous condition (LED 3000 K), under which participants registered in the last minutes slower RTs compared to the first minutes.

The effect of lighting on visual vigilance seems due to the luminous spectral emission of the lamps used in the experiments and, in particular, it could be caused by the blue radiation content and by the emission intensity in the blue wavelengths. This is confirmed by the calculations reported in Table 1, where the 6800 K LED resulted to have higher values of melanopsin stimulation, circadian light and circadian stimulus than the 3000 K LED: these quantities assess the effect elicited by light on the circadian system, so that higher values indicate higher capability of light in suppressing the blood melatonin and consequently in activating the "diurnal" human body functions. Even if the melanopsin stimulation, CL_A and CS quantify the effect of light on the circadian system and that their validity for the direct effects on brain has not already demonstrated, also an increase of arousal, brain functioning and attention level correspond to the activation of the physiological functions.

Results obtained seem to indicate that higher content of blue radiation in the cold LED affected the visual vigilance performance: it is possible that the high percentage of blue light in the cold LED have produced a stimulation that significantly affected the performance of participants in the experimental group, not producing the natural decrement of vigilance level, which instead occurred to participants under the warm LED light.

5. Conclusion

This study confirmed how the choice of the artificial lighting scenario inside the environment is important not only for the visual comfort but also for cognitive performance. In accordance with the international literature [such as [28], [29] [28], [29] indicating that the non-visual effects are produced as consequence of a blue light stimulation, the experimental results of this work found a positive influence of cold LED (6800 K) on visual vigilance, while no effects have been observed with the warm (3000K) LED condition. This positive effect obtained by participants under cold LED light consisted in the capability of maintaining at the end of the task the same vigilance level they had at the beginning, while participants under the warm lighting condition did not experienced the same significant effect. This could be due to the higher amount of blue light contained in the spectrum of cold LED respect to that in the warm LED, as showed in Figure 1.

It is important to notice that these results are strictly confined to the visual vigilance function; in fact, in the same experiment carried out in this study, no significant effect of light was found respect to the acoustic vigilance and on self-assessed sleepiness and vigour. Moreover, in a previous study [30], the same Authors found that a significant effect on the executive functions was produced under neutral LED light (4000 K); we could speculate that the amount of blue light required for the mental activation can depend on the function involved. Further investigations are required for explaining this point.

Also, actually it is not already clear the duration of the stimulating effect of the blue light on the attentive functions: future developments will investigate for how long the light stimulation affects the human performance and for how much time the effects persist after the end of the exposition.

Results obtained in this, as well as in previous studies, suggest that the use of blue enriched light in working places like offices or factories and in schools could stimulate the cognitive performance; in particular, seems important to adopt cold light where is needed to maintain high vigilance levels, for instance in aircraft cabins, control rooms and operating room. Undoubtedly, visual vigilance is critical also in everyday tasks, such as driving, participating in business meetings and concentrating in reading.

Anyway, results obtained in this work are related to a very controlled experimental setting, in which natural light was excluded and light reflections were reduced to a minimum: in this way it is possible to refer the effect on vigilance to the artificial lighting condition. Further studies in real settings should be performed to confirm the ability of the artificial light to affect visual vigilance where other environmental luminous stimuli are present: generally, interiors are provided of multiple sources of light like windows, white walls and ceiling, reflective and coloured surfaces that can change the light stimulus reaching the human eye.

Moreover, future studies should investigate more in deep how a prolonged exposition to LED lighting at evening and night impacts on the circadian system and, in particular, on nocturnal sleep before the use of LED inside house will widespread.

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