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Research report

Daytime light exposure: Effects on biomarkers, measures of alertness, and performance

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HIGHLIGHTS

- Light elicits an alerting response independent from melatonin suppression.
- Red light can increase alertness and performance during the day.
- This is the first study to show red light can increase daytime performance.

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ABSTRACT

Light can elicit an alerting response in humans, independent from acute melatonin suppression. Recent studies have shown that red light significantly increases daytime and nighttime alertness. The main goal of the present study was to further investigate the effects of daytime light exposure on performance, biomarkers and measures of alertness. It was hypothesized that, compared to remaining in dim light, daytime exposure to narrowband long-wavelength (red) light or polychromatic (2568 K) light would induce greater alertness and shorter response times. Thirteen subjects experienced three lighting conditions: dim light (<5 lux), red light (λ_{max} = 631 nm, 213 lux, 1.1 W/m^2), and white light (2568 K, 361 lux, 1.1 W/m^2). The presentation order of the lighting conditions was counterbalanced across the participants and each participant saw a different lighting condition each week. Our results demonstrate, for the first time, that red light can increase short-term performance as shown by the significant ($p < 0.05$) reduced response time and higher throughput in performance tests during the daytime. There was a significant decrease ($p < 0.05$) in alpha power and alpha–theta power after exposure to the white light, but this alerting effect did not translate to better performance. Alpha power was significantly reduced after red light exposure in the middle of the afternoon. There was no significant effect of light on cortisol and alpha amylase. The present results suggest that red light can be used to increase daytime performance.

1. Introduction

Humans are a diurnal species, programmed to be awake during the day and asleep at night. The endogenous circadian pacemaker, which is synchronized daily with the environment by 24-hour (h) light/dark patterns, sets the timing of circadian rhythms. In diurnal species, the circadian pacemaker promotes alertness during the day and sleep at night. Alertness and performance are influenced by the timing of the circadian system and by the duration of time awake, known as sleep homeostasis. The duration of time awake reflects a homeostatic process, resulting in an increase in sleep pressure as the number of waking hours increases [1–3]. Stable and high levels of alertness and consolidated sleep are then maintained when the phase relationship between the internal circadian timing system and the sleep/wake cycle is such that the circadian timing system opposes the homeostatic process to promote daytime alertness and nighttime sleepiness [4].

The effects of light on alertness at night are well documented [5–8]. Earlier studies showed that high levels of white light (>2500 lux at the cornea) were needed to affect objective and subjective measures of alertness [7,8]. The alerting effects of light at night have been associated with its ability to suppress the hormone melatonin [7,9]. The high levels of white light used in earlier studies will cease melatonin production [10] and since melatonin signals sleep in diurnal species [11], its suppression by light at night has been linked to alertness [12]. The effects of nighttime light exposure on performance are also well established [13–15], although

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negative results have been reported [16]. These earlier studies suggest that suppression of melatonin at night may be linked to increased subjective and objective alertness that may or may not translate into better performance at night.

Following studies performed in the 1990s [17,18] showing that genetically manipulated mice with no functional rods and cones would still phase shift the onset of wheel running activity following a light pulse, a new class of photoreceptor was discovered in the mammalian retina [19]. The intrinsically photosensitive retinal ganglion cells (ipRGCs) have a peak spectral sensitivity close to 482 nanometers (nm) and their axons form the retinohypothalamic tract that links the retina to the suprachiasmatic nuclei, where the mammalian pacemaker is located. It is well accepted that the ipRGCs interact with the classical photoreceptors (rods and cones) to transduce light signals into neural signals for the circadian pacemaker [20–24].

Since it has now been established that the spectral sensitivity of acute melatonin suppression [21,22], a marker of the circadian clock, peaks close to 460 nm, the impact of short-wavelength (blue) light on measures of alertness has been investigated [25]. It has been shown that light levels needed to affect measures of alertness can be greatly reduced when blue light is used, rather than polychromatic white light [9,25].

Studies looking at the effects of light on measures of alertness and performance were also conducted during the daytime, when melatonin levels are low [26–28]. Functional magnetic resonance (fMRI) studies show that bright white light (>7000 lux) as well as lower levels (7.5 lux) of short-wavelength (473 nm) light were more effective at activating brain regions associated with alertness than either remaining in dim light or exposing subjects to higher levels (24.5 lux) of 527 nm light [29,30]. These results suggest that melatonin suppression is not needed to affect measures of alertness and that the effects of light on measures of alertness were likely mediated by the responses of the ipRGCs.

However, recent studies have demonstrated that long-wavelength (red) light can increase objective and subjective measures of alertness at night [31] and during the day [32]. These results suggest that long-wavelength cones mediate these effects because the ipRGCs are not sensitive to low levels of long-wavelength light [19].

Consistently, studies using transgenic animals showed that rods and cones participate together with ipRGCs in the direct (normally referred to as acute) effects of light on the sleep/wake system [33–35]. More importantly, the role that the ipRGCs play in these direct effects of light on the sleep/wake system varies over the course of 24 h. Previous studies showed that ipRGCs play a major role in these direct effects during the early part of the dark phase. Measurements of the melanopsin photopigments show a gene expression variation across the day, with the highest expression at the transition between light and dark [36].

In addition to the well-known effects of spectral irradiance incident on the retina on physiological and endocrine processes, studies claim that color in itself can affect a range of physiological, psychological, and behavioral responses in humans [37]. The exact effect elicited by colors on humans is, however, still under debate. For example, while a few studies claim that the color red is more arousing and alerting than the color blue, other studies did not show any significant difference in terms of the physiological arousal between red and blue colors [38]. Nevertheless, when studying the effects of saturated colored lights on humans, it is important to take into account these possible psychological effects.

Sahin and Figueiro [32] recently reported a study comparing the effectiveness of afternoon exposures to red (640 nm peaking light) and blue (470 nm peaking light) lights on measures of alertness. It was hypothesized that if the alerting effects of light were mediated by the response of the ipRGCs only, the blue light would have an effect on measures of alertness. Their results showed, however, that red light significantly increased alertness compared to dim light, and that although blue light exposures also increased alertness compared to dim light, this difference did not reach significance. The authors suggested that afternoon exposure to red light may elicit a stronger alerting effect on people than blue light and that response from photoreceptors other than the ipRGCs may be contributing to these effects.

The main goal of the present study was to further investigate the effects of two types of light, a narrowband long-wavelength (red) and a warm correlated color temperature (CCT) polychromatic (white) light on performance, biomarkers and measures of alertness during the daytime. Polychromatic white light was used instead of narrowband, short-wavelength light so that we could indirectly investigate the impact of saturated colored light (red) on measures of alertness. The two light sources (red and white) were matched in terms of spectral irradiances. Calculations showed that the white light would be stimulating photoreceptors involved in circadian phototransduction, but not the red light. Based on the findings by Sahin and Figueiro [32] it was hypothesized that red light would not only increase measures of alertness, but would also increase performance in short-term and long-term tasks. It was also hypothesized that, compared to remaining in dim light (control), exposure to red light or white light would induce greater alertness and shorter response times. These results would also give us some clue as to whether the saturated color red could elicit a stronger alerting response in subjects at different points throughout the day.

2. Materials and methods

2.1. Participant selection

Sixteen participants were recruited through email notices, electronic postings, and word-of-mouth. Data are reported here from 13 subjects (7 female), mean ± standard deviation (SD) aged 23 years ± 5.5, who completed the study and followed the experimental protocol. All participants were non-smokers and free from any major health problems. Participants were excluded from the experiment if they were taking any prescription medication or if they had traveled across more than two time zones during the month prior to starting the study. All participants passed the Ishihara test for color blindness (Kanehara Shupman Co., Tokyo, Japan). All participants completed a consent form approved by the Institutional Review Board at Rensselaer Polytechnic Institute and were paid for their participation. The study was conducted in accordance with the Declaration of Helsinki [39] and conformed to international ethical standards.

Every participant completed a Munich Chronotype Questionnaire (MCTQ) [40] prior to the study. The mean ± SD of reported chronotype was 3.5 ± 1.9. Participants kept a sleep/wake diary during all weeks of the experiment, starting one week prior to starting the study. These diaries documented bedtimes, rising times, caffeine consumption, and quality of sleep. Participants were asked to maintain a regular sleep/wake schedule during the three weeks of the experiment, with bedtimes no later than 23:00 and wakeup times no later than 08:00. Compliance was monitored by use of a continuously-worn wrist Daysimeter [41,42] which measured light/dark as well as activity/rest patterns. Sleep schedule was verified prior to each experimental day to ensure compliance.

2.2. Lighting conditions

The three lighting conditions participants were exposed to were dim light (<5 lux), red light (λ_{max} = 631 nm, 213 lux, 1.1 W/m^2), and white light (2568 K, 361 lux, 1.1 W/m^2). Clear safety glasses were