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Alerting effects of short-wavelength (blue) and long-wavelength (red) lights in the afternoon

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HIGHLIGHTS

- Light can be used to increase alertness in the afternoon, close to the post-lunch dip hours.
- Red light is a stronger alerting stimulus in the afternoon than blue light.
- Long-wavelength cones mediate the alerting effects of red light during the daytime.

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ABSTRACT

Light has an acute effect on neuroendocrine responses, performance, and alertness. Most studies to date have linked the alerting effects of light to its ability to suppress melatonin, which is maximally sensitive to short-wavelength light. Recent studies, however, have shown alerting effects of white or narrowband short-wavelength lights during daytime, when melatonin levels are low. While the use of light at night to promote alertness is well understood, it is important to develop an understanding of how light impacts alertness during the daytime, especially during the post-lunch hours. The aim of the current study was to investigate how 48-minute exposures to short-wavelength (blue) light (40 lux, 18.9 microWatts/cm^2 λ_{max} = 470 nanometers [nm]) or long-wavelength (red) light (40 lux, 18.9 microWatts/cm^2 λ_{max} = 630 nm) close to the post-lunch dip hours affect electroencephalogram measures in participants with regular sleep schedules. Power in the alpha, alpha theta, and theta ranges was significantly lower ($p < 0.05$) after participants were exposed to red light than after they remained in darkness. Exposure to blue light reduced alpha and alpha theta power compared to darkness, but these differences did not reach statistical significance ($p > 0.05$). The present results extend those performed during the nighttime, and demonstrate that light can be used to increase alertness in the afternoon, close to the post-lunch dip hours. These results also suggest that acute melatonin suppression is not needed to elicit an alerting effect in humans.

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1. Introduction

The endogenous circadian pacemaker, which is synchronized daily with the environment by the 24-hour light/dark patterns incident on the retina, sets the timing of circadian rhythms. In diurnal species, the circadian pacemaker promotes alertness during the day and sleepiness at night. The timing of the circadian system and the duration of time awake (sleep homeostasis) influence alertness and performance [1].

The duration of time awake reflects a homeostatic process, resulting in an increase in sleep pressure as the number of waking hours increases. Therefore, stable and high levels of alertness and consolidated sleep can be maintained when the phase relationship between the internal circadian timing system opposes the homeostatic process to promote daytime alertness and nighttime sleepiness. The circadian drive for daytime alertness, however, is not sufficiently strong to oppose the increased homeostatic sleep pressure during one specific time of day, which is referred to as post-lunch dip [2,3]. In fact, it has been shown that the timing of this dip in alertness varies between 14:00 and 16:00 (for a review, see [4]).

Human error is estimated to be a causal or contributing factor in 45–90% of accidents [5]. Acute or chronic sleep deprivation resulting in increased feelings of fatigue is one of the leading causes of human error and accidents in the workplace [6]. The daytime distribution of incidents and performance failures throughout the 24-hour day suggests a time of day effect with two peaks that can be seen in the early morning and mid-afternoon (post-lunch dip) hours [7].

Previous studies have shown that in addition to resetting the timing of the circadian pacemaker, light can have an acute effect on neuroendocrine responses, performance, and subjective and objective alertness. Most studies examined the effects of light on alertness at

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night, when the detrimental effects of fatigue can be easily observed. Compared to dim light or darkness, light at night (>2500 lx of white light) increased task performance, elevated core body temperature, and increased heart rate [8,9]. Light at night has also been shown to increase high frequency (beta range) and reduce low frequency (theta and alpha ranges) electroencephalographic (EEG) activity, as well as reduce slow-eye movements and subjective sleepiness, all measures that have been associated with decreasing sleepiness and increasing alertness at night [8–10].

The impact of nocturnal exposure to low levels (>5 lx) of short-wavelength (blue) light on subjective and objective alertness, performance, and biomarkers (melatonin and cortisol) has also been investigated [11–13]. Melatonin is a hormone produced at night and under conditions of darkness, and is used as a marker of the circadian system. It is now well accepted that the circadian system, as measured by acute melatonin suppression, is maximally sensitive to short-wavelength (blue) light; therefore, lower levels of short-wavelength (as low as 5 lx) light have been shown to have a similar impact on melatonin levels, objective and subjective alertness, and performance to higher levels (>2500 lx) of white light.

In most studies to date, the alerting effects of light have been linked to its ability to suppress melatonin [13]. In a recent study, however, Figueiro et al. [14] demonstrated that exposures to both short-wavelength (blue) and long-wavelength (red) lights in the middle of the night increased beta and reduced alpha power relative to preceding dark conditions, although only blue light significantly suppressed melatonin levels relative to darkness. Exposures to high (i.e., 40 lx at the cornea), but not low (i.e., 10 lx at the cornea), levels of red and of blue light significantly increased heart rate relative to darkness. Their findings suggest that the acute melatonin suppression is not needed for light to have an affect on measures of alertness at night. These results are consistent with studies showing alerting effects of light during the daytime, when melatonin levels are low [15,16].

While the use of light at night to promote alertness in the graveyard shift is well understood, it would be important to also develop lighting schemes that will promote alertness during the daytime, especially during the post-lunch hours. The aim of the current study was to extend the findings from Figueiro et al. [14] and investigate how exposure to short-wavelength blue light (λ_{max} = 470 nanometers [nm]) and long-wavelength red light (λ_{max} = 630 nm) during the middle of the afternoon, close to the post-lunch dip hours, affects objective measures of alertness and subjective measures of sleepiness in participants with regular sleep schedules. It was hypothesized that, if light can impact alertness via pathways other than melatonin suppression, as suggested by Figueiro et al. [14], both blue and red lights would decrease alpha, theta, and alpha theta power as well as decrease self reports of sleepiness relative to dim light.

2. Materials and methods

2.1. Participants

Thirteen healthy, paid volunteers, eight males (19–28 years, median = 20.5) and five females (18–25 years, median = 21), who met the following criteria were accepted and completed the study: (1) neither extreme late nor early type according to their responses on the Munich ChronoType Questionnaire [17], (2) no report of any physical or mental health problems (neither diagnosed with bipolar disorder nor depression) (3), no experience of shift work or travel to a different time zone within the 3 months prior to the experiment, and (4) no color blindness, as measured by the Ishihara for color blindness test. Participants were asked to refrain from alcohol and caffeine intake 12 h before the experimental session. Participants were also asked go to bed between 22:00 and 23:00 the night before the experiment and wake up no later than 7:30, and refrain from napping on the day of the experiment. Compliance was verified with sleep logs that participants were asked to keep during the experiment weeks. Participants were required to keep this sleep schedule during the entire experimental period to assure that measurements were performed close to the timing of their post-lunch dip, which typically occurs 16 to 18 h after bedtime, from 14:00 to 16:00 [4]. Upon arrival to the laboratory, participants signed an informed consent form approved by the Institutional Review Board at Rensselaer Polytechnic Institute.

2.2. Lighting conditions

In addition to dark (<0.01 at cornea), two experimental lighting conditions: long-wavelength "red" (λ_{max} = 630 nm) and short-wavelength "blue" (λ_{max} = 470 nm) were delivered to the corneas of each participant by arrays of light emitting diodes (LEDs) with a full width at half maximum of 25 nm placed in 60 × 60 × 60 cm light boxes. The LEDs (Lumileds, Luxeon I) were hidden from the direct view of the participants, and light boxes were painted white, so that a uniform and non-glaring distribution of light was achieved. Temperature inside the light boxes was constant throughout the experiment (range was between 68 and 70 °F). Before the experiment, each of the light boxes was calibrated using a Gigahertz-Optik X91 illuminance photometer to provide 40 lx of blue (40.2 μW/cm^2) and red (18.9 μW/cm^2) lights at the plane of the participant's cornea. It has already been established that the acute alerting effect of light has a broader spectral sensitivity than acute melatonin suppression, which is maximally sensitive to light peaking at 460 nm and insensitive to light peaking at 630 nm. Therefore, we equated the stimuli according to the orthodox photopic luminous efficiency function (lux), which has sensitivity at long-wavelengths. This does not imply, however, that the spectral sensitivity of the acute alerting effect of light is accurately characterized by this spectral weighting function.

2.3. Electroencephalogram (EEG)

The BioSemi ActiveTwo system (BioSemi, Amsterdam, Netherlands) with active electrodes was used for EEG recordings. Electrodes were placed on participant's scalps according to the International 10–20 system at Fz, Cz, Pz, and Oz. Two additional electrodes were attached to the right and left earlobes to serve as reference electrodes for those attached to the scalp. The BioSemi system replaces the ground electrodes, which are used in conventional systems, with the Common Mode Sense (CMS) active electrode and the Driven Right Leg (DRL) passive electrode, both of which are placed on the forehead of the participant. These two electrodes form a feedback loop, which drives the average potential of the subject (the Common Mode voltage) as close as possible to the analog-to-digital reference voltage in the analog-digital box. In order to monitor eye blinks, one electrode was placed directly below the right eye.

2.4. Subjective sleepiness (KSS)

To obtain information on subjective sleepiness, the Karolinska Sleepiness Scale (KSS) was rated four times (at the beginning, 12 min, 36 min, and at the end of the session). The KSS scale ranged from 1 to 9, where 1 = "very alert," 3 = "rather alert," 5 = "neither alert nor sleepy," 7 = "sleepy, but no difficulty remaining awake," and 9 = "very sleepy, fighting sleep, an effort to remain awake."

2.5. Procedure

Participants experienced three experimental sessions, separated by one week. Participants were asked to come to the Lighting Research Center laboratory at 14:00 to get instructions and be fitted with scalp electrodes for EEG recordings. All participants reported having eaten between 60 and 90 min prior to arriving at the lab.

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