**Research Article**

Neuropsychobiology

Neuropsychobiology 2024;83:183–192
DOI: 10.1159/000541230

Received: November 14, 2023
Accepted: August 16, 2024

# Light Exposure on Alertness after Wake-Up in Healthy Men: Comparing Dim, Bright, Red, and Blue Light

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**Keywords**

Light irradiation · Subjective alertness · Objective alertness · Reaction time · Sleepiness

## Abstract

***Introduction:*** Light is a key factor in moderating human alertness, both subjective and objective. However, the methodology applies in research on the effects of exposure to light of different wavelengths and intensities on objective and subjective alertness varies greatly and evidence on objective alertness in particular is still inconclusive. Thus, the present, highly standardized within-subject laboratory study on $N = 44$ healthy males explored how LED light of different intensities (dim vs. bright light) and wavelengths (red vs. blue) affected objective (reaction time/RT) as well as subjective (sleepiness) alertness in the morning after wake-up. ***Methods:*** Participants spent two separate nights in the laboratory and were exposed to either one of the two light intensities or colors for 60 min after wake-up. Additionally, they indicated their sleepiness on the Karolinska Sleepiness Scale and participated in an auditory RT task before and after light intervention. It was hypothesized that both bright and blue light would lead to greater subjective and objective alertness when compared to dim and red light, respectively. ***Results:*** Results indicated that average RTs were longer for participants in the bright light condition ($p = 0.004$, $f^2 = 0.07$) and that RTs decreased post-light exposure irrespective of light being dim or bright ($p = 0.026$, $f^2 = 0.07$). However, dim versus bright light and RT did not interact ($p = 0.758$, $f^2 = 0.07$). Chronotype was a significant covariate in the interaction of dim versus bright light and subjective sleepiness ($p = 0.008$, $f^2 = 0.22$). There was no difference in RTs when comparing exposure to red or blue light ($p = 0.488$, $f^2 = 0.01$). Findings on subjective sleepiness and light of different wavelengths revealed that sleepiness was reduced after light exposure ($p = 0.007$, $f^2 = 0.06$), although the wavelength of light did not appear to play a role in this effect ($p = 0.817$, $f^2 = 0.06$). ***Conclusion:*** Hence, neither of the hypotheses could be confirmed. However, they indicated that evening types might benefit from exposure to bright light regarding sleepiness, but not morning types.

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## Introduction

One of the most fundamental acute effects of light on human functioning is its impact on alertness (e.g., [1–3]). Most commonly, the word "alertness" is used to denote the opposite of "sleep" [2, 4] sleepiness scales are widely used to determine subjectively perceived alertness [2, 3]. In psychological studies, the term is also applied to a state in which the person is not only awake but also sensitive to stimuli able to attend and respond to them [5–7] as well as able to concentrate on a given task [4]. It follows that situations requiring attention also require alertness and attention tasks present a viable option in the attempt to capture a person's objective state of alertness [3, 7].

Research on the alerting effects of light originates from work on sleep and wakefulness as well as circadian rhythms. The first empirical studies concerning the effects of light exposure on alertness mainly focused on the effects of light intensity in white light [8–11]. More recently, a specific subset of retinal ganglion cells, the so-called intrinsically photosensitive retinal ganglion cells (ipRGCs), were found to express the photopigment melanopsin, making them responsive to light even in the absence of input from rods and cones [12, 13], with a peak sensitivity for blue light, i.e., wavelengths around approximately 460–480 nm [12, 14–16]. As such, these cells constitute the main origin of non-image-forming signals of light information [17], in turn, named for their feature of not passing the visual cortex but is transmitted to the body's central clock in the suprachiasmatic nuclei (SCN), thus greatly influencing human beings' circadian rhythmicity and sleep-wake cycle [2, 3, 12, 17]. Additionally, non-image forming signals reach several subcortical structures and cortical areas known to be involved in different aspects of human alertness and cognitive performance, such as attention [18]. Consequently, the effects of different types of light on objectively measured and subjectively perceived alertness are of increased interest.

To this day, several studies have compared the effects of short wavelengths (around 460 nm, appearing bluish to the human eye) versus longer wavelengths (around 635 nm, appearing reddish to the human eye) or of higher versus lower light intensities on subjectively perceived alertness. Here, acute effects are stronger for higher light intensities in polychromatic white light [1, 19–23]. Moreover, some studies found higher subjective alertness for exposure to blue light when compared to longer wavelengths [1, 21, 24–27]. However, other studies did not find a positive effect of intense light exposure (blue-enhanced bright white light) in the morning or afternoon on subjective alertness [28, 29] and similar effects have been obtained with monochromatic blue light [30, 31].

Regarding objective alertness, a few works have presented significant effects of higher light intensities on RT and other measurements of cognitive performance [29, 32, 33], although others did not find an effect of white light of varying intensities on RT after exposure or even adverse effects [9, 20, 22, 28, 34–36]. When measuring objective alertness as RTs, some studies found improved RT performance with blue or blue-enriched light compared to longer wavelengths [25, 26]; others, however, did not observe any effect at all [30, 37].

All in all, a closer look at the literature reveals that the effects of exposure to light of different wavelengths and intensities on objective alertness in particular are still inconclusive [34, 38, 39]. It should be noted, however, that the literature on the acute effects of light on subjective alertness as well as on objective performance varies in light manipulation (polychromatic light intensity or light spectrum, monochromatic/narrowband light intensity or dominant wavelength, constant light exposure or intermittent exposure), in exposure duration (10 min–24 h), time of day of exposure onset, sleep duration before light exposure (4–10 h), adaptation phase duration (0–24 h), adaptation light level (0–400 lx), standardization of sleep (e.g., sleeping at home or in the laboratory), choice of dependent outcome variables, as well as sample size (*N* = 6–39).

Therefore, the aim of the present exploratory study was to investigate the effect of light exposure at different intensities and wavelengths after wake-up on sleepiness as a partial measure of subjective alertness as well as RT as a measure of objective alertness. Participants slept at the laboratory, thus assuring that pre-testing light exposure and wake-up times were standardized and controlled. In turn, the high level of standardization in the present study allows for greater comparison of possible findings to come. For this purpose, two experiments were conducted, with the first utilizing different light intensities (bright white vs. dim) and the second polychromatic light of different wavelengths (red vs. blue). Based on the literature introduced above, the hypotheses were formulated as follows:

H1: Exposure to bright light after wake-up leads to both greater subjective alertness (lower subjective sleepiness) and objective alertness (faster reaction times) when compared to dim light.

H2: Exposure to blue light after wake-up leads to both greater subjective alertness (lower subjective sleepiness) and objective alertness (faster reaction times) when compared to red light.

## Methods

### *Participants*

A power analysis was calculated with the package "Superpower" in R Studio Version 5 based on the findings of Smolders and de Kort [20] on the effects of bright light on subjective alertness as these most closely aligned with the study protocol. The power analysis revealed that, in order to observe a potential interaction between brighter versus dimmer light and subjective alertness in a 2 × 2 within-subject design with power = 0.90 and $\alpha = 0.05$, at least $N = 20$ participants would have to be analyzed per condition.

Early-morning light exposure has been observed to influence the hormone cortisol and the cortisol awakening response (CAR), a typical rise in cortisol levels upon awakening [40–42]. Cortisol in turn, the CAR in particular, is believed to play a role in regaining alertness in the morning [43]. However, sex differences in cortisol reactivity have been observed, likely influenced by sex hormones such as estradiol [44]. Hence, to gain better understanding on how light exposure affects subjective and objective alertness independent of a potentially moderating influence of sexual hormones, only participants who identified as male were included in this particular study. Adult men were recruited through an online advert published on the university's website and tested between June and October 2017 and April and May 2018. Participants were compensated for taking part in the experiment with a 1-time payment of 50 EUR. Volunteers' individual state of health was pre-assessed via telephone screening with respect to defined inclusion and exclusion criteria. These included any ophthalmologic or hearing diseases as well as sleep disorders, the latter of which were excluded based on volunteers' replies to the Pittsburgh Sleep Quality Index (PSQI; [45]). The study protocol was approved by the Local Ethics Committee of the Medical Faculty of the Technical University of Dresden, Germany (No #EK353092014), and was conducted in accordance with the principles outlined in the Declaration of Helsinki (2013). All participants provided written informed consent and received a written information sheet prior to the day of testing.

### *Procedure*

Testing took place at the university's laboratory. Prior to participation, participants were randomly assigned to either the bright and dim light or red- and blue-light condition set. Whether or not participants were exposed to light of one or the other wavelength within their assigned condition set first was randomly assigned as well. For each of the two testing days, participants arrived at 10 p.m. and were thereupon informed about the testing procedure. During this time, they were also tested for their color vision. Participants went to bed at 11 p.m., their sleep quality recorded with actigraphy via the Motionlogger activity watch [46]. When using the restrooms at night, they were instructed to wear dark sunglasses, which reduced the incident light to less than 1 lx. After being woken up at 6:30 a.m., participants were lying down on their beds, still in dimly lit conditions and having a relaxed chat with the person conducting the experiment. They did not consume any drinks or food during this time frame. They were also allowed to visit the bathroom, again wearing sunglasses and filled in the Karolinska Sleepiness Scale (KSS; [47]) shortly before light exposure commenced at 7:30 a.m. During light irradiation, the AuReTim audio psychomotor vigilance test [48] was performed two times: For the first time at baseline within the first minute, for the second time 45 min into light exposure. Following light exposure, at 8:45 a.m., participants filled in the KSS once again. Participants were sent home at 9:15 a.m. The study protocol is illustrated in Figure 1.

### *Apparatus and Materials*

The instruments used for light exposure were two half Ulbricht spheres indirectly illuminated by LEDs equally positioned around the inside of the opening. The LEDs were covered with a spectral selective diffusor to ensure a homogeneous illumination of participants' retinas. The LEDs were regulated via computer (USB to DMX Controller) and powered by electrical DC-dimming. Four light exposure settings were used (see Table 1): Bright white light (414 lx; mix of blue, green and red), dim white light (<2 lx), blue light (201 lx; peak wavelength 470–480 nm), and red light (235 lx; peak wavelength 635 nm). These light settings take findings reported by Cajochen et al. [2] into account, which state that with no prior light exposure, light of lux as low as 40 lx can induce changes in alertness and cognitive performance. Using a luxmeter, illuminance (lx) was measured on eye level before and after exposure to each light spectrum. Light conditions were adjusted to the same number of photons, resulting in the illuminance levels depicted in Table 1. For bright light, 1/3 of the intensity of each color was used. Light exposure took place in a second darkened room with stray light levels below 1 lx. Here, participants were positioned in a chair in front of the light sources with their chins resting on a chinrest so that their faces reached into a half-sphere (2PI-Geometry) at eye level.

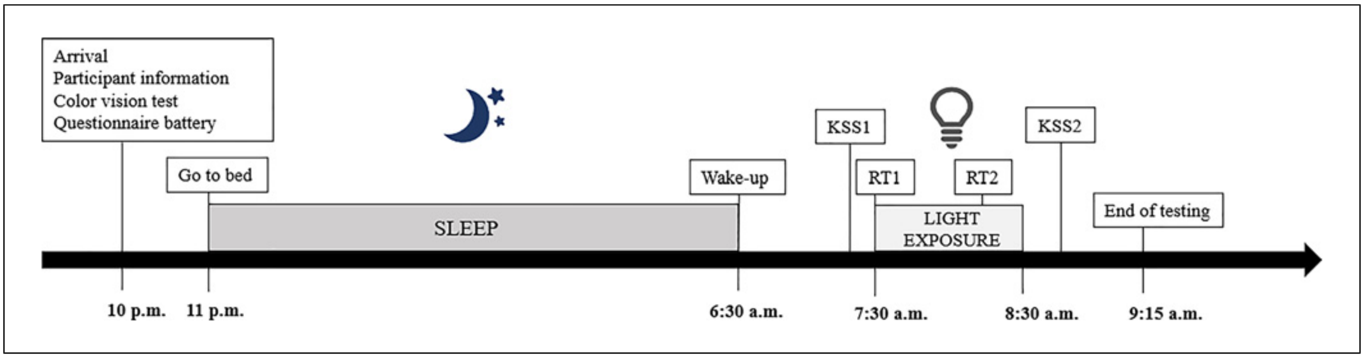

**Fig. 1.** Testing procedure from arrival of participants to end of testing.

**Table 1.** Characteristics of different types of light

| | Red | Blue | Bright white, 1/3 R + G + B |
|---|---|---|---|
| Number of photons | 4.26E+14 | 4.26E+14 | 4.26E+14 |
| Spectral irradiance, W/m$^2$ | 1.341 | 1.760 | 1.566 |
| Illumination at the eye, lux | 235 | 201 | 414 |
| (Narrowband) spectra with different peak wavelengths, nm | 635 | 475 | Combination RGB |
| Luminance, cd/m$^2$ | 74.8 | 64.0 | 131.8 |

W/m$^2$, watt per square meter; nm, nanometers; cd/m$^2$, candela per square meter; R, red; G, green; B, blue.

To test participants' alertness, the auditory psychomotor vigilance test AuReTim [48] was conducted during light exposure. AuReTim measures auditive attentiveness and was set to produce 30 stimuli spaced over approximately 4 min. The participants hear a stimulus, a short beeping sound, via earbuds and have to respond as quickly as possible by pressing a finger/hand button. Two distinct tones are applied, a deep tone requiring no response as well as a high tone that participants were instructed to respond to. The AuReTim is a reaction time task requiring both sustained attention as well as response inhibition (paradigm based on [34]).

### *Instruments*

Participants' sleepiness pre- and post-intervention was assessed with the KSS by Åkerstedt and Gillberg [47] on each testing day. The KSS is a one-dimensional nine-point scale validated with electroencephalographic activity and correlates highly with another subjective sleepiness scale, the Visual Analog Sleep Scale [49]. The higher the score, the higher sleepiness is subjectively perceived. Chronotype was assessed with a validated German Version of the Morningness-Eveningness Questionnaire [D-MEQ; [50]. Here, a higher score of 59 and above indicate morning types, whereas a lower score of 41 and below indicate evening types. Scores in-between indicate neutral types.

### *Statistical Analysis*

Statistical analyses were performed using SPSS Statistics Version 27 and jamovi Version 2.2.5.0 [51]. AuReTim and KSS data were checked for outliers, i.e., values three standard deviations below or above the mean; however, this criterium did not apply to any of these data. On account of being unequally distributed, AuReTim RTs were adjusted using the natural logarithm prior to analysis. In total, $N = 44$ male participants were included in the study. $N = 9$ participants partook in all four conditions. Because of the partly unbalanced design, mean baseline values for RTs and KSS scores between the $N = 35$ participants who partook in two and

**Table 2.** Pre- and post-intervention means (M) and standard deviations (SD) for AuReTim RTs and KSS scores for the dim- and bright-light condition

| | Dim | | | | Bright | | | |
|---|---|---|---|---|---|---|---|---|
| | pre | | post | | pre | | post | |
| | M | SD | M | SD | M | SD | M | SD |
| RT | 367 | 96 | 328 | 67.2 | 398 | 158 | 389 | 201 |
| KSS | 4.92 | 1.98 | 5.00 | 2.55 | 5.58 | 1.88 | 4.19 | 1.77 |

RT values reported in milliseconds as originally obtained to facilitate easier understanding. RT, reaction time; KSS, Karolinska sleepiness scale.

**Table 3.** Pre- and post-intervention means (M) and standard deviations (SD) for AuReTim RTs and KSS scores for the red- and blue-light condition

| | Red | | | | Blue | | | |
|---|---|---|---|---|---|---|---|---|
| | pre | | post | | pre | | post | |
| | M | SD | M | SD | M | SD | M | SD |
| RT | 391 | 172 | 379 | 206 | 328 | 121 | 322 | 104 |
| KSS | 5.22 | 1.88 | 4.41 | 1.55 | 5.07 | 1.94 | 4.11 | 1.95 |

RT values reported in milliseconds as originally obtained to facilitate easier understanding. RT, reaction time; KSS, Karolinska Sleepiness Scale.

the $N = 9$ participants who partook in all four light conditions were compared for each light condition with independent samples *t* tests. None of these comparisons turned up significant (see online suppl. Table 1; for all online suppl. material, see https://doi.org/10.1159/000541230 in the online suppl. materials). To check whether or not sleepiness differed significantly between groups prior to light exposure, paired *t* tests were conducted comparing KSS scores pre-intervention for each group. Additionally, paired *t* tests on total wake minutes (WMs) during the nights slept in the laboratory were performed, to gain insight into whether or not groups differed in how well they had slept according to actigraphy readings. WMs were defined as the sum of sleep onset latency in minutes and minutes awake after sleep onset. As the study design was within-subject and some of the data were incomplete, mixed linear models were then calculated (see e.g., [52]), using the jamovi module GAMLj. Chronotype, as assessed with the D-MEQ, was thought to be a covariate in the relationship between light exposure and RTs as well as sleepiness after wake-up and, hence, was statistically factored in as such. In the same vein WMs during the night as recorded by actigraphy were factored in as a covariate for all mixed models. Additionally, pre-intervention sleepiness scores were introduced as an additional covariate for the mixed models on light exposure and RTs. Where covariates proved statistically insignificant, they were subsequently removed from calculations (see online suppl. Tables 2, 3 in the online suppl. materials). Results are reported for mixed models without insignificant covariates. All multiple analyses were corrected applying Bonferroni-correction. Effect sizes for mixed models were calculated using Cohen's proposed function for $f^2$ [53].

## Results

Of these, 26 participants in total, aged M = 27.07, SD = 7.14, were exposed to dim and bright light and 27 participants in total, aged M = 25.7, SD = 6.88, received red- and blue-light irradiation. Pre- and post-intervention means and standard deviations for RTs and KSS scores can be found in Table 2 (dim vs. bright light) and Table 3 (red vs. blue light). Means and standard deviations for WMs and D-MEQ scores are listed in Table 4, as well as ranges for D-MEQ scores.

### *Dim- and Bright-Light Exposure*

There was no statistically significant difference between the two conditions regarding subjective sleepiness scores pre-intervention, $t(25) = -1.43$, $p = 0.165$, $d = -0.28$ [−0.67, 0.11]. There was no statistically significant difference between both light conditions in WMs, $t(95) = -0.78$, $p = 0.440$, $d = -0.08$ [−0.28, 0.12] either.

In the mixed model for bright versus dim light and RTs, a significant main effect of RTs, $F(1, 21.4) = 5.70$, $p = 0.026$, $f^2 = 0.07$, and light condition, $F(1, 23.1) = 10.38$, $p = 0.004$, $f^2 = 0.07$, emerged; however, the interaction between light condition and RTs did not turn up significant, $F(1, 21.4) = 0.10$, $p = 0.758$, $f^2 = 0.07$.

The mixed model for dim-versus bright-light conditions and KSS scores including only chronotype as a covariate did not reveal a significant main effect of either sleepiness, $F(1, 72) = 3.68$, $p = 0.059$, $f^2 = 0.22$, or light condition, $F(1, 72) = 0.00$, $p = 1.000$, $f^2 = 0.22$, and no significant interaction of light condition and sleepiness, $F(1, 72) = 3.68$, $p = 0.059$, $f^2 = 0.22$. Chronotype was a significant covariate at $F(1, 23) = 10.13$, $p = 0.004$, $f^2 = 0.22$. A subsequent Pearson correlation revealed that chronotype was significantly and negatively correlated with sleepiness in the bright light

**Table 4.** Means (M) and standard deviations (SD) for WMs and D-MEQ scores

| | Dim | | Bright | | Red | | Blue | |
|---|---|---|---|---|---|---|---|---|
| | M | SD | M | SD | M | SD | M | SD |
| WMs | 30.4 | 18.5 | 32.0 | 22.4 | 25.5 | 23.5 | 26.6 | 13.7 |
| D-MEQ | 51.8 | 10 | 51.8 | 10 | 48 | 6.9 | 48 | 6.9 |
| D-MEQ | 32–68$^a$ | | | | 38.5–62$^a$ | | | |

Wake minutes (WMs) per test night are calculated as the sum of minutes awake after sleep onset and sleep onset latency as per actigraphy readings. Means and standard deviations of D-MEQ (German version of the Morningness-Eveningness Questionnaire) scores were reported across all light conditions. As participants were tested within-subject, means and standard deviations of D-MEQ repeated within a light condition set. $^a$Range.

condition, $r = -0.451$, $p = 0.024$, 95% CI ($-0.718$, $-0.061$), i.e., a greater tendency to morningness was accompanied by less sleepiness. Chronotype was not associated with sleepiness in the dim light condition, $r = -0.288$, $p = 0.163$, 95% CI ($-0.613$, $0.121$).

### *Red- and Blue-Light Exposure*

There was no significant difference between the two conditions regarding KSS scores pre-intervention, $t(26) = 0.34$, $p = 0.739$, $d = 0.07$ ($-0.31$, $0.44$). Additionally, both groups did not differ in WMs during the night, $t(107) = -0.63$, $p = 0.531$, $d = -0.06$ ($-0.25$, $0.13$). The mixed model for red versus blue light and RTs did not reveal a significant main effect of RTs, $F(1, 47.6) = 1.58$, $p = 0.214$, $f^2 = 0.01$, or of light condition, $F(1, 49.9) = 1.56$, $p = 0.218$, $f^2 = 0.01$, and no significant interaction between RT and light condition either, $F(1, 47.6) = 0.85$, $p = 0.360$, $f^2 = 0.01$.

In the mixed model for red versus blue light and KSS scores, a significant main effect of sleepiness emerged, $F(1, 78) = 7.75$, $p = 0.007$, $f^2 = 0.06$. However, there was neither a significant main effect of light condition, $F(1, 78) = 0.48$, $p = 0.488$, $f^2 = 0.06$, nor a significant interaction between RTs and light condition, $F(1, 78) = 0.05$, $p = 0.817$, $f^2 = 0.06$.

## Discussion

Whether it be in our natural or artificial environments, light fundamentally influences how alert we feel and are (e.g., [1–3]). The aim of the present study was thus to investigate, in the context of a highly standardized study on adult men, effects of exposure to light of different wavelengths in the morning on objective alertness, as measured by RT, as well as subjective sleepiness, as measured by KSS scores. In order to standardize influencing factors, including light exposure prior to testing and wake-up time, study participants slept in the laboratory.

The present results show a statistically significant difference in the influence of light of different intensities on objective alertness as measured by RT and a statistically significant reduction in RTs after light exposure. However, the interaction did not turn up significant. In essence, post-exposure RTs were reduced irrespective of the type of light exposure employed and male participants in the bright light condition took longer to react to the AuReTim stimuli on average. Therefore, the different effects of light intensity (dim vs. bright light) on RT as brought to the attention by some of the literature presented earlier could not be replicated [29, 32, 33]. This is, however, in line with the large body of literature unable to find an effect of light intensity in the morning on RTs [9, 20, 22, 28, 34–36].

There might still be statistical reasons underlying the findings presented here: As the power analysis was conducted on the basis of findings on subjective alertness, the sample size might not have been powered sufficiently to detect effects on objective alertness. RTs might also simply reduce over time as a result of the male participants gradually becoming more alert, although it has to be stated that neither subjective sleepiness, wake minutes during the night as per actigraphy or chronotype proved significant covariates when factored into the mixed model. Light exposure duration in this study lasted for 60 min and, as noted by Cajochen et al. [2], effects on human behavior can already be observed in exposure lasting up to 30 min. Hence, insufficient length of light irradiation is unlikely to be a factor in different types of light exerting influence on objective alertness. It might also be that, as ipRGCs show peak sensitivity for light in the blue spectrum, whereas the bright light employed in this study was a mix of red, blue and green light, blue light is needed to induce sufficient changes of activity in relevant cortical areas. As for the consistently higher RTs found in the bright light condition, subjective sleepiness and WMs did not differ significantly between both light conditions before experimental light irradiation and any prior light exposure was carefully controlled for. Another factor might be at play explaining why male participants in this condition consistently took longer to react, besides statistical shortcomings. Additionally, while previous findings have demonstrated the importance of chronotype for vigilance and cognitive performance requiring response inhibition [][][54, 55], chronotype did not play a significant role for performance in the AuReTim cognitive task in particular, which calls for response inhibition as well.

On the other hand, the present study did observe that chronotype played a significant role for the men participating in the relationship between light of different intensities and subjective alertness, as measured by reported sleepiness. A closer look at Pearson correlations revealed a significant negative association between sleepiness and chronotype, i.e., greater sleepiness was related to a lower score on the D-MEQ, indicative of evening types. This seems intuitive as participants were sent to bed at 11:00 p.m. and woken up at 6:30 a.m., comparatively early for those inclined toward later times of going to bed at night and rising in the morning. It is important to note here that this significant correlation could only be obtained in the bright-light condition. While the main effect of sleepiness pre- and post-intervention as well as the interaction between sleepiness and light condition did not turn up significant, this finding, viewed in context of the mean KSS scores reported in Table 3, suggests that it might be male evening types, in particular who could benefit from exposure to bright light when woken up prior to their preferred time. A direct effect of exposure to bright light on subjective alertness, as reported in multiple studies [1, 19–21, 23], could thus not be observed for this sample.

At this point it should briefly be discussed that seasonal effects of bright light exposure on sleepiness have been observed in the past [56], in which such exposure only led to significantly reduced reported sleepiness on autumn and winter mornings. The authors concluded that the reduced amount of daylight during these months might explain such effects. It follows that in the case of this study, in which all male participants of the bright and dim light conditions came to the laboratory during the months of July and August, a greater natural exposure to bright light might have reduced the probability of replicating findings. However, lighting prior to experimental light exposure was highly standardized and minimized across all participants and such a preceding history of light exposure – or lack thereof – has been termed a mediating factor in the relationship between light and the effects it exerts [3, 57]. Hence, it does not seem likely that seasonal effects played a determining role in the reported results on light and alertness.

Exposure with light of different wavelengths (red, blue) did not have an effect on objective alertness as measured by RT. Findings demonstrating an effect of blue light on RT [25, 26] could not be replicated. As mentioned above, ipRGCs are particularly sensitive to blue light and provide input for non-image forming signals to also be transmitted to and influence activity in cortical areas involved in attention processes. Still, statistically significant changes of RTs induced by either red- or blue-light exposure could not be observed in the men participating here. It should be noted once again that results could have been underpowered.

Regarding the effect of red and blue light on sleepiness post-awakening as a partial measure of subjective alertness, a main effect of sleepiness pre- and post-exposure was observed. The main effect for light condition and the interaction turned up non-significant; however, the conclusion one would arrive at based on this study population would be that light exposure, regardless of wavelength, reduces subjective feelings of sleepiness in adult men. The findings on blue-light exposure exerting influence on subjective alertness replicated in a variety of previous studies [1, 21, 24–27] and of non-image forming signals induced by ipRGC input reaching subcortical structures related to alertness [2, 18] could thus not be inferred and replicated in this study. All in all, neither hypothesis could be confirmed in this sample.

The strength of this study lies in the high standardization of its design and in the care taken to control influencing variables, such as light exposure prior to wake-up, duration and intensity of light exposure [3, 57], as well as wake-up time, chronotype, sleep quality, and pre-intervention sleepiness. However, the study only included male participants, limiting the generalizability and comparability of its findings to the general public. Subsequent research efforts building on the one here presented should include female participants and apply the proper means to ensure that a potentially moderating effect of sexual hormones is controlled and comparability between female participants as regards their menstrual cycles is existent.

Additionally, future research should extend the findings on hand by looking at light effects, on objective alertness in particular, in bigger data sets with a greater chance of statistical detection of underlying differences, especially taking into account that post hoc comparisons applying corrections such as Bonferroni's, aiming to counter the multiple comparisons problem, increase the likelihood of producing false negatives and decrease statistical power. Additionally, the presented results may also indicate that regardless of the type or length of light exposure at this time of day, cognitive performance on measures of objective alertness is simply more dependent on other factors apart from light and circadian rhythmicity. However, as the results presented here contradict existing evidence on the importance of chronotype for vigilance and response inhibition (see e.g., [54, 55]), additional measures of cognitive performance and therefore objective alertness should be considered for future research. This would allow for greater insight into which aspects of human cognition in particular are affected by chronotype in which way, especially given that differences in brain activity of inhibition-related brain areas dependent on chronotype have been observed [55]. Regarding subjective alertness, Shapiro et al. [4] proposed that sleepiness and alertness are not simply opposing ends of the same spectrum, but might be, albeit interrelated, distinct measures. As such, asking participants about their acute sleepiness as a sole measure of subjective alertness would not thoroughly detect the differences and variance potentially present in the sample. Future research should consider implementing additional measures of subjective alertness which do not rely on accounts of sleepiness, such as the Toronto Hospital Alertness Test (THAT) or ZOGIM-A introduced by Shapiro et al. [4]. It should be noted, however, that neither of these two questionnaires are meant to capture acute subjective alertness and would thus have to be adapted accordingly.

On another note, our conclusions are limited by the circumstance that effects of light intensity versus colored light could not be compared within-subject for the present study. Future studies might consider it advantageous to combine the different light exposure conditions of the present two experiments in a within-subject design, allowing for an individual comparison of the potential effects of dim light, bright light, and colored light. Furthermore, while brightness was not a factor varied within blue- and red-light exposure for this study, an experimental design examining if and how brightness interacts with the wavelength of light used for irradiation could be of interest. Additionally, future research should consider comparing different levels of exposure to light prior to the actual experimental irradiation with light, especially when effects of bright light are to be studied: It might be that effects of chronotype on sleepiness in the bright-light condition observed in this study were enhanced by the fact that participants' environment was kept very dark prior to experimental light irradiation (see e.g., [3]). Similarly, time of day of light exposure is of interested to compare (see e.g., [57]). Biological measures known to correlate with or influence alertness, such as caffeine intake, cortisol, or melatonin (see e.g., [19, 43, 58, 59]), might also provide further insight into potential mediating or modulating factors in the relationship between light exposure and alertness.

Nevertheless, due to the highly standardized methodology of this study, the results here further underline the complexity of determining light effects on human alertness and suggest that chronotype might determine how much a person's feelings of sleepiness are alleviated by bright-light exposure in the morning.

## Statement of Ethics

The study protocol was approved by the Local Ethics Committee of the Medical Faculty of the Technical University of Dresden, Germany (No. #EK353092014), and was conducted in accordance with the principles outlined in the Declaration of Helsinki (2013). All participants provided written informed consent to participate in the study and received a written information sheet prior to the day of testing.

## Conflict of Interest Statement

One of the authors (T.S.) is with the STZ eye-trial at the Center for Ophthalmology, a company which provides an out-of-the-box version of the AuReTim test.

## Funding Sources

This work was supported by the Federal Ministry of Education and Research (BMBF), Germany (award number: 13N13397). This study was conducted in the subproject: "Einfluss von Licht auf die hormonelle Stressverarbeitung" (influence of light on the hormonal stress management) as part of the joint project: "Nicht-visuelle Lichtwirkungen" (non-visual effects of light).

## Author Contributions

Liza Mekschrat: formal analysis and writing – review and editing. Torsten Straßer: supervision and resources. Shiwa Gassabei: investigation. Bjarne Schmalbach: formal analysis and supervision. Mathias Niedling: review. Katja Petrowski: supervision and writing – initial draft.

## Data Availability Statement

All data generated or analyzed during this study are included in this article. Further inquiries can be directed to the corresponding author.

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