

Investigating the Effects of Metameric Light on EEG Spectral Measures

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Abstract

Whether melanopic stimulation independently modulates daytime brain activity when other visual and photoreceptor related properties of light are closely controlled remains unclear. This within subjects, crossover study examined the acute effects of melanopic light exposure on electroencephalographic (EEG) activity in 22 healthy adults. Participants were exposed to dim light and two silent-substitution metameric light conditions that were closely matched in photopic illuminance (211.61 and 210.75 lux) and designed to minimize differences in rod- and cone-opic stimulation, while differing approximately threefold in melanopic EDI (55.35 and 174.88 lux). EEG was recorded during 15 minutes of uninterrupted exposure and spectral power was analysed using cluster-based permutation testing. Light condition significantly affected alpha-band power, with significant differences arising between dim light and the metameric conditions. In contrast, alpha band power did not differ significantly between the high- and low-melanopic metamers, and no robust theta or beta band effects were detected. These findings indicate that acute daytime light exposure was associated with changes in alpha band activity under the conditions tested, but provide no evidence that a threefold difference in melanopic stimulation, when other visual and photoreceptor related properties are closely controlled, produces a distinct short term EEG response.

Introduction

Light wields a profound yet often overlooked influence on human physiology and behaviour beyond image formation.¹ These non-image-forming (NIF) effects have become an important topic in lighting research and neuroscience, particularly as they relate to biological rhythms, level of alertness, and cognitive functioning. Electroencephalography (EEG) provides a valuable, objective method for quantifying how the brain responds to different light conditions and is therefore increasingly used to probe NIF pathways.

NIF effects are thought to be mediated by intrinsically photosensitive retinal ganglion cells (ipRGCs).^{2,3} IpRGCs exhibit intrinsic photosensitivity through the expression of melanopsin, a photopigment that is maximally sensitive to light at around 480 nm, within the blue region of the visible spectrum (Hankins et al., 2008). Thus, light that is relatively rich in this part of the spectrum (higher melanopic content) may more strongly activate neural pathways with which ipRGCs are connected. IpRGCs project not only to the lateral geniculate nucleus of the visual thalamus, thereby indirectly influencing the primary visual cortex, but also to other diencephalic structures, including the suprachiasmatic nucleus (SCN) of the hypothalamus, as well as to multiple brainstem nuclei.⁴⁻⁷ The SCN is the key structure that enables circadian effects, predominantly through its influence on melatonin release.⁸⁻¹⁰ Thus, by their connection to the SCN and other subcortical structures, ipRGCs can indirectly influence activity in cortical structures which may be measurable in the EEG and result in alertness-related, attentional and behavioural effects.^{7,11,12}

To quantify the impact of light on human functioning via ipRGCs activation, light is typically characterized by its melanopic Equivalent Daylight Illuminance (EDI),¹³ a metric that allows for a direct comparison of the melanopic content of different light conditions (in lux). It has been previously examined whether differences in melanopic activation are reflected in EEG markers of alertness, in which variations in melanopic EDI were achieved either through changes in illuminance or via tuning the spectral composition. The most consistent EEG finding across these manipulations was a reduction in alpha power (i.e., the EEG's periodic signal component in the 8–12 Hz range) under brighter light conditions, also occasionally accompanied by a suppression of theta power (between 4 and 8 Hz).^{3,14–16} Reductions in low-frequency power (theta and lower alpha) are commonly interpreted as objective neural markers of increased alertness, while task-related alpha desynchronization indexes cognitive engagement.^{17–19} Effects on EEG power in other classical frequency bands, such as beta (15–30 Hz) and delta (1–4 Hz) were reported less frequently and were not assessed as routinely.³ In studies employing spectral manipulations intended to increase melanopic activation (e.g., contrasting high versus low correlated color temperature (CCT)), some effects on alpha power were reported, although their direction was not consistent.^{20–24} Theta power changes also showed no systematic light-induced moderations across studies, overall pointing to mixed and sometimes contradictory findings.³ While, in comparison, the findings of illuminance seemed more consistent in terms of alpha power, there has been criticism that effects induced by contrasts in photopic illuminance are a byproduct of increased total retinal illumination due to the overall photopic input to the retina rather than isolated ipRGCs-mediated mechanisms.³ Studies comparing narrowband blue versus green or red light revealed no significant contrasts in EEG power density, except for differences between the dark/very dim condition and the narrowband lighting conditions, strengthening the claim that findings in these studies are also likely due to visual illumination differences and not isolated ipRGCs activations. Shown by a recent systematic review, overall, the current literature remains somewhat inconsistent regarding the effect of melanopic EDI on EEG power bands.³

Observed inconsistencies in ipRGC-induced EEG effects might arise due to methodological limitations, including relatively small contrasts in melanopic EDI between experimental conditions, confounding effects of low-level visual properties (e.g., brightness, colour appearance) that are known to directly influence occipital alpha activity, and the general lack of experimental conditions that enable isolating melanopic stimulation from cone activation.³ In this context, the limited use of metameric lighting paradigms represents a critical gap.²⁵ Metameric light conditions, based on silent substitution, allow substantial differences in ipRGC activation while maintaining identical visual appearance, thereby helping to disentangle non-image-forming (NIF) effects of melanopic activation from purely visual effects on EEG measures^{26,27}. Previous studies using metameric light have shown that selectively manipulating melanopic levels while preserving visual appearance can influence alertness-related outcomes, including subjective sleepiness, reaction time, pupillary responses, and neural activity associated with attention and arousal^{7,27–31}. Wider adoption of metameric light interventions could

clarify whether and how melanopic stimulation per se contributes to EEG correlates of alertness during daytime exposure.

The study aimed at characterizing the spectral, temporal, and spatial EEG correlates of melanopic stimulation during daytime exposure. Our experimental design included a pair of metameric lights that, while being visually similar, differed substantially in melanopic activation (by a factor of three), alongside a dim light condition serving as the control condition. Key questions guiding our research included: Which brain regions are particularly sensitive to the targeted stimulation of ipRGCs, which EEG frequency bands exhibit discernible effects, and over what time course do these effects manifest? Given the inconclusive literature,³ analyses of the spatial, spectral, and temporal profile of these effects were conducted in an exploratory manner. At the same time, based on prior work and as specified in the preregistration, we expected the high-melanopic light condition to produce greater suppression of EEG alpha power than the low-melanopic and dim-light conditions. This hypothesis aligns with the general direction of the findings in several studies regarding the daytime effects of light on EEG markers.^{32–35} Due to the inconclusive nature of existing findings on the power density in the theta, beta, and gamma range, our hypotheses for other frequency bands were not established at the outset.

In this paper, we introduce two key methodological innovations that substantially advance the precision with which NIF effects of light can be studied. First, the study employs a novel metameric light pair calculated based on an optimized algorithm enabling the generation of metameric LED spectra, using a set of 11 primaries.²⁵ Whereas earlier silent-substitution studies have commonly used eight or fewer primaries^{36–42}, and systematic optimisation has shown that increasing the number of primaries enhances melanopic tuning flexibility, with 11-channel systems offering maximal control^{31,43}. Second, we apply Monte Carlo–based, cluster-level permutation analysis of EEG data to prevent biases due to multiple comparisons^{44,45}. By leveraging non-parametric, cluster-based permutation testing across spatial, temporal, and spectral dimensions, this analytical framework effectively addresses the multiple-comparisons problem inherent to high-dimensional EEG recordings. Together, these methodological advances enable us to systematically investigate light-induced moderations in EEG across cortical regions and frequency bands over time (0–15 minutes since experimental light onset), offering improved sensitivity and interpretability relative to conventional stimulus designs and analysis pipelines.

Methods

Study Design and Settings

A counterbalanced within-subjects design was used to compare three lighting conditions: dim (2.50 lx) versus low melanopic (55.35 lx) versus high melanopic (174.88 lx) lighting. The three lighting conditions were offered in three separate blocks on the same day, with exposure to dim light provided between the experimental conditions. EEG was recorded continuously from 64 channels during a 30-minute light exposure to capture modulations in brain activity with a high spatial and temporal resolution, the first 15

minutes of which were not interrupted by tasks. In the present study, we investigate EEG power densities in the delta, theta, alpha, and beta range assessed during these first 15 minutes of each lighting condition. All study procedures were conducted in accordance with the Declaration of Helsinki. The study was preregistered at the Open Science Framework (<https://osf.io/7hgcm>) and the protocol was approved by the Internal Ethical Review Board of Eindhoven University (ID: 1451).

Participants:

We included 22 healthy participants (recruited through the university participant database) in the age range of 18–35 years and classified as non-extreme chronotypes based on the morningness-eveningness questionnaire (MEQ; inclusion range of 31–69, with lower scores indicating extreme eveningness and higher scores indicating extreme morningness). Participants also demonstrated good general sleep quality across the past month, as assessed with the Pittsburgh Sleep Quality Index (i.e., overall score below 6 and no individual item scoring 3 or higher). Further requirements were good self-assessed health (defined as a SF-12 general health rating of ‘good’, ‘very good’, or ‘excellent’), normal vision without any deficiencies or pathologies, and no reported auditory deficiencies. Participants were excluded if they had engaged in shiftwork or travelled multiple time zones within the three months before the experiment. Participants were asked to not consume alcohol, drugs, caffeine or nicotine during the 24 hours before the start of the laboratory session and were instructed to adhere to their habitual sleep-wake schedule for the day prior to the experiment. Participants provided written informed consent prior to participating in the study and received a financial compensation for their participation.

Metameric Light Stimuli

The light conditions in this study were designed by solving an optimization problem to identify suitable silent substitution pairs called metamers. The metamers look virtually identical to the observer (i.e., similar luminous sensation and CCT) while differing in their activation of melanopic photoreception in ipRGCs. They have minimal differences in their activation of other photoreceptors (rods and cones).^{25,27}

The light conditions were designed to approximate a typical office lighting environment, using polychromatic spectra close to white light at an illuminance of 200 lux in the vertical plane at eye level.⁴⁶ Scenes were presented in the Boschman Colour Box (see Fig. 3; Boschman, 2021), a custom-made device in which 11 LED types with different spectra are mixed to produce a Ganzfeld-like light exposure for both metameric light conditions. The spectral power distribution and illuminance, melanopic EDI, and CCT for the metameric light pair, the dim light condition, and the ambient room lighting in the laboratory as used in the study can be found in Fig. 2 and Table 1, respectively. Additional details on the calculation and characterization of the light stimuli are provided in the Supplementary Information.

Table 1

Characteristics of the three light conditions (dim, low mel, high mel) and the ambient dim light between the conditions in the experimental room. All values were measured in the vertical plane at eye level.

	Illuminance [lux]	EDI [lux]					CCT [K]
		Melanopic	S-cone- opic	M-cone- opic	L-cone- opic	Rhodopic	
Low Mel	211.61	55.35	34.60	147.89	219.47	78.39	2097
High Mel	210.75	174.88	43.90	159.71	235.73	171.75	1773
Dim	9.14	2.50	1.47	6.46	9.46	3.52	2141
Ambient	4.46	1.80	0.19	3.06	4.73	2.27	1807

Procedure

The participants entered the laboratory at 10:00 AM. The experiment began with a preparatory phase of an hour to get the participant equipped with the electrodes for the EEG recording in ambient dim light. After the preparatory phase, the actual experiment began. There was a total of three experimental blocks during which the participant was consecutively exposed to each of the experimental lighting conditions, with a 30-min break in ambient dim light between the conditions. During the experimental condition, participants were asked to sit in front of the Boschman Colour Box while using a chin rest and fix their gaze to the mark at the back of the lightbox. Each experimental condition lasted 30 minutes: first 15 minutes of uninterrupted viewing, then 15 minutes of exposure with performance tasks and short questionnaires. This article reports on the findings on the EEG data collected during the first 15-minute uninterrupted exposure blocks. The data collected during the tasks in each experimental block will be reported in another paper as part of a different analysis.

During the breaks, participants were free to move their heads and gaze in the dimly lit room. Bathroom visits, when necessary, were allowed during the breaks, and during such visits participants were asked to wear light-blocking goggles (Move Eyewear brand, UV400, orange) to minimize their exposure to uncontrolled light. After completing all three experimental conditions, all electrodes were removed, and participants were debriefed about the experiment and compensated for their participation.

EEG Acquisition

EEG data were collected from 64 channels using the SAGA 64 + system (TMSi 2019b, BrainWave, EEG cap). The electrodes were placed according to the international 10–20 system, and electrode impedance was ensured to be below 5 k Ω for all 64 EEG channels. The ground electrode was placed at location AFz, and signals were recorded using an average reference. The data were digitized at a rate of 4000 Hz. Due

to technical problems with the trigger synchronization during the data collection, the EEG data of two participants were not included in further analyses.

Data Analysis

Data analysis was performed using the FieldTrip toolbox (Oostenveld et al., 2011) and custom-written scripts in MATLAB R2020b (The MathWorks, Natick, MA, USA).

Data preprocessing

Prior to analysis, the EEG data were re-referenced to the average of the two mastoid channels and filtered in the range of [0.5–40] Hz, using a windowed sinc finite impulse response (*firws*) filter, with a filter order of 930. Subsequently, the data were down sampled to 400 Hz for ease of computation. For each participant and condition, the standard deviation of the signal was calculated separately for each channel. Channels with a standard deviation greater than twice the mean standard deviation across all channels were classified as bad and excluded from subsequent preprocessing steps. Five frontal electrodes (Fp1, Fp2, Fpz, AF7, and AF8) were classified as bad in the majority of participants. All channels classified as bad were subsequently reconstructed by spatial interpolation from the remaining valid channels before the group-level analyses.

The EEG data of the three light conditions were combined into a single data structure, and the initial cleaning steps were performed on this aggregated dataset. This was to ensure that no selection bias was introduced by separately treating the experimental conditions for the identification of artifacts. As a cleaning procedure we applied independent component analysis (ICA), combined with visual inspection, to reject 1) spatial components from the data that reflect eye blink artifacts, and 2) isolated sections of the data that contained generic artifacts, based on a variance criterion. To this end, data were cut into 1-second epochs, and epochs for which the maximum Z-scored variance in any of the channels exceeded the value of 10 were replaced with NaNs (to preserve the temporal structure in the data).

Spectral analysis

After preprocessing, the data were transformed into the spectral domain, using a Hanning-windowed Fast Fourier Transform (FFT) on 2-second data windows (50% overlapping moving window).

Subsequently, the data were reorganized into channel-by-frequency-by-time matrices for each lighting condition, where the time axis reflected the latency after the onset of each 15-minute period. To stabilize the spectral power estimates, the data were smoothed with a smoothing window of 60 seconds and subsequently log-transformed (base 10) to improve Gaussianity.

Statistical analysis

Statistical comparisons of EEG power in prespecified frequency bands were performed using cluster-based permutation tests⁴⁷. This approach controls the family-wise error rate associated with multiple comparisons arising from the high spatial (64-channel EEG), temporal (15 minutes of continuous data, approximately 900 time points), and spectral resolution of the data (1–40 Hz in 0.5-Hz steps; 81 frequency bins). Permutation testing is a non-parametric method that does not assume normality and is therefore well suited for EEG data. Under the null hypothesis of exchangeability across conditions, condition labels were randomly permuted within participants and test statistics recomputed to generate a null distribution. Spatio-temporo-spectral clusters were formed by thresholding mass-univariate test statistics at a nominal $p < 0.05$ and grouping adjacent data points across channels, time, and frequency. Cluster-level statistics were computed by summing test statistics within each cluster and evaluated against the permutation distribution. An omnibus comparison across the three light conditions was performed using a dependent-samples F-statistic, followed by pairwise post-hoc contrasts using dependent-samples t-statistics. It included data collected with the various electrodes across the full 15 minutes and in the frequency range from 0.5 to 30 Hz bands. Monte Carlo p-values were estimated using 2000 permutations. For time-averaged analyses, EEG power was first averaged across the full 15-minute recording interval prior to statistical testing, thereby reducing the temporal dimension of the data. Similarly, spectral resolution was varied by comparing results obtained from averaging across predefined frequency bands with those derived from analyses at the level of individual 1Hz frequency bins, allowing for a more fine-grained assessment of frequency-specific effects. These complementary approaches ensured that both broad trends and more localized temporal and spectral patterns in the data were examined. Lastly, for sensitivity analysis, we examined whether mean alpha power varied as a function of the order of the light conditions. We fitted a linear mixed-effects model including light condition and order as fixed effects and participant as a random intercept.

Results

Comparisons Across All Light Conditions

To examine global effects of the light conditions on EEG spectral activity, we first performed non-parametric cluster-based permutation tests across the full time–frequency space (all frequencies [0 30] Hz), all electrodes, and second-length bins for the entire 15-minute uninterrupted light exposure. The omnibus F-statistic was computed to quantify differences across the three light conditions (high melanopic, low melanopic, and dim light). As illustrated in Fig. 4A, the Time x Frequency representation of the omnibus F-statistic averaged across electrodes suggested potential modulations within the alpha and beta ranges. Likewise, the spatial distribution of the omnibus F statistic across the full 15-minute window (Fig. 4B) showed numerically elevated F values over frontal, central, and occipital electrodes. Sample-wise omnibus statistics ranged from $F(2, 36) = < 0.01$ to 25.17, corresponding to effect sizes of partial eta squared (η_p^2) ranging from $< .001$ to .583. However, no significant cluster-level differences were identified across the three light conditions following cluster-based permutation correction (cluster-level Monte Carlo $p = .190$).

To further characterize the spectral distribution of the omnibus effect averaged over time, we examined the frequency-resolved F-statistic for each electrode (Fig. 5). The butterfly plot demonstrated a consistent elevation of F-values within the alpha and low beta (12–20 Hz) frequency range, spread across nearly all electrodes. In contrast, adjacent frequency bands showed comparatively lower and less consistent F-values across channels.

Alpha and Beta Frequency band resolved comparisons

Although our unconstrained spatio-spectro-temporal analysis yielded no significant results after correction for multiple comparisons, this null result is difficult to interpret unambiguously. One contributing factor may be the high variability of the EEG signal: band-limited power in the alpha and beta ranges fluctuates spontaneously over the course of a recording, and these fluctuations differed across participants and conditions. In a test that spans all time points, frequencies, and electrodes simultaneously, such variability inflates the noise against which any condition effect must be detected, reducing sensitivity to small or transient effects. To reduce this source of variance, we therefore conducted a targeted analysis restricted to time-averaged power in the canonical alpha and beta bands.

A cluster-based permutation test conducted across all electrodes within the alpha band (8–12 Hz) revealed a significant main effect of light condition (cluster-level Monte Carlo $p = .006$). Within the significant cluster, sample-wise F statistics ranged from $F(2, 36) = 3.26$ to 8.07 , corresponding to η_p^2 values of .154 to .309. A similar analysis in the beta band (13–30 Hz) did not reveal a significant cluster; the lowest cluster-level Monte Carlo (p)-value was .214 (Supplementary Fig. S1). Within this nonsignificant cluster, sample-wise (F) statistics ranged from $F(2,36) = 3.29$ to 5.26 , corresponding to partial η_p^2 values of .154 to .226. Mean alpha power also differed across block position, $F(2,36) = 8.09$, $p = .001$, with lower power in the first block than in the second and third blocks. Importantly, the main effect of light condition remained significant after accounting for block position in a mixed-effects model, $F(2,38) = 8.79$, $p < .001$.

As shown in Fig. 6A, the Channel x Frequency matrix of the F-statistic demonstrated a broad distribution of electrodes displaying light-induced modulations in alpha activity. The largest nominal cluster, i.e., the largest spatially contiguous set of electrodes whose uncorrected p-value was < 0.05 , encompassed the majority of electrodes reflecting alpha power density differences across the three light conditions (high melanopic, low melanopic, dim light). The spatial distribution of this effect is illustrated in Fig. 6B. The topography of the largest cluster indicated that the effect of light condition was primarily centered over central and occipital electrodes, although it extended more broadly across the scalp.

Contrast analyses between Dim, Low and High melanopic light

To further understand the source of the alpha-band modulation observed in the omnibus analysis, we conducted pairwise cluster-based permutation tests between the dim and low melanopic light

conditions. Within the alpha frequency range, this comparison revealed a significant positive cluster, with higher alpha power in the dim relative to the low melanopic condition ($F(1, 18) = 2.10\text{--}3.57$, $\eta_p^2 = 0.105\text{--}0.166$; cluster-level Monte Carlo $p = 0.004$). As illustrated in Fig. 7A, the largest cluster (highlighted by white circles) was widespread, and was primarily distributed over frontal and central electrodes, but parietal and occipital electrodes were involved as well. This topography indicates that the difference in alpha power between dim and low melanopic light did not only originate from the visual cortical system, but also may have had a more frontocentral origin. In the beta frequency range, the same comparison did not reach statistical significance, with the largest cluster showing a cluster-level Monte Carlo $p = .059$, $F(1, 18) = 4.42\text{--}8.36$, corresponding to $\eta_p^2 = .197\text{--}.317$.

We next performed the same cluster-based permutation analysis to compare the dim and high melanopic light conditions. Within the alpha frequency range, this comparison revealed a significant difference, with higher alpha power for the dim versus the high melanopic condition ($F(1, 18) = 2.10\text{--}4.06$, $\eta_p^2 = 0.105\text{--}0.184$; cluster-level Monte Carlo $p = 0.016$). As illustrated in Fig. 7B, the largest cluster (highlighted by white circles) was again spatially widespread, with less prominence (as compared to the previous comparison) for fronto-central electrodes. Also here, the beta-band analysis did not reveal any statistically significant difference - the cluster-based paired-samples permutation test did not identify any positive or negative cluster-, indicating the absence of reliable beta power differences between dim and high melanopic light conditions. Finally, the direct comparison between the high and low melanopic light conditions did not yield a statistically significant difference in the alpha-frequency range (cluster-level Monte Carlo $p = .168$, $F(1, 18) = 4.56\text{--}6.73$, corresponding to $\eta_p^2 = .202\text{--}.272$).

Taken together, these analyses indicate that light-induced spectral modulation during daytime was, if present, predominantly confined to the alpha frequency band. Significant alpha power differences were observed in comparisons involving dim light, with a spatially widespread distribution. No robust beta-band effects were detected, and no significant differences in alpha or beta power emerged between the two melanopic light conditions.

Discussion

The present study tested acute effects of daytime exposure to light with different melanopic content on EEG spectral density estimates. It used a 15-minute exposure to artificial light of high and low melanopic-equivalent daylight illuminance (melanopic EDI) and dim light conditions. We statistically evaluated the EEG response without initial restrictions on the spatial, spectral, and time dimensions. In addition, we performed statistical comparisons of time-averaged spectral power in predefined frequency bands.

While no broadband effect of light was observed across the full channel-time-frequency space, targeted analyses revealed band-specific effects in the alpha range. Significant differences in alpha-band power across the three lighting conditions were observed, which were driven by the contrasts of dim versus metamer light conditions. The pairwise comparisons between the dim light condition and either the

high or low melanopic conditions showed distinct spatial patterns. Fronto-central differences seemed more prominent in the low melanopic versus dim light comparison (Fig. 7A), in addition to parieto-occipital observed in both comparisons (Fig. 7A and B). No statistically significant effects were observed within the beta frequency range. The results partly support our hypothesis that exposure to high melanopic light produced greater suppression of alpha power compared to the dim light condition. In contrast to our expectations, no significant difference was observed between the low melanopic versus high-melanopic metameric light conditions. We did not find evidence that high melanopic light played a different role than low melanopic light when we looked at the nominal EEG band powers. We could say that, irrespective of the melanopic EDI, both metameric light scenarios were associated with changes in alpha-band power during the daytime.

In this paper, we introduce two key methodological innovations that aimed to substantially advance the precision with which NIF effects of light can be studied. First, the study employs a novel metameric light pair calculated based on an optimized algorithm with 11 primaries,²⁵ as opposed to earlier silent-substitution studies that used eight or fewer primaries.^{31,43} This approach allowed us to manipulate melanopic activation while tightly controlling for cone-mediated visual responses and illuminance, thereby isolating NIF effects with greater specificity than has previously been possible. Also, the melanopic contrast in the present dataset (with a ~ 3.2 -fold difference between high and low conditions) exceeds that used in prior work such as (such as ~ 1.7 -fold difference³⁸), indicating a stronger manipulation of melanopsin-weighted input and potentially enhanced sensitivity for detecting NIF effects. Second, we applied Monte Carlo-based, cluster-level permutation analysis to high-dimensional EEG data. This analysis approach effectively addresses the multiple-comparisons problem inherent to high-dimensional EEG recordings. Together, these methodological advances enabled us to systematically investigate - in an unbiased fashion - light-induced changes in the EEG across cortical regions and frequency bands over time (0–15 minutes since experimental light onset), offering improved sensitivity and interpretability relative to conventional stimulus designs and analysis pipelines. Under these tightly controlled and comprehensively analysed conditions, we did not find indications of purely ipRGC-induced modulations in EEG activity: the only differences observed in alpha power emerged in comparisons between the dim and brighter conditions, i.e., the visually contrasting ones.

The observed effects in alpha power in this study are consistent with the broader EEG literature on NIF responses to light. Recent systematic reviews revealed that alpha is the most consistently reported EEG frequency band sensitive to light manipulations.³ Specifically, several studies have reported decreases in alpha power under higher light intensity levels, whereas the findings for the other frequency bands have been less consistent.^{15,21,23,48}

In this study, we observed a similar pattern where brighter conditions suppressed alpha compared to dim light conditions. Suppression of alpha power (or alpha desynchronization) is commonly interpreted as a marker of cortical activation and increased alertness.^{49,50} The modulation of alpha power is also often interpreted in the context of sensory processing and cortical inhibition, where a reduction of alpha

(relative to a properly defined baseline) in a specific region reflects increased excitability and attentional readiness.^{51,52} The topographically widespread nature of the observed differences in alpha power may reflect changes in activity beyond visual cortical areas.

The alpha band differences were spatially widespread, and could be observed at multiple electrodes. Part of this widespread topography may be explained by the fact that the intrinsic spatial resolution of EEG is somewhat limited, because focal differences generated at the neural source-level lead to widespread scalp-level differences due to volume conduction. Yet, our EEG recordings were of relatively high spatial resolution compared to what is custom in the field, and thus a tentative topographical interpretation can be given. Our results showed occipital electrode dominance in the clusters whilst comparing dim versus high melanopic light. Alpha oscillations in parieto-occipital regions are known to be sensitive to basic visual stimulus properties such as brightness or contrast, and our findings are in line with that. However, tentatively, similar modulations in alpha power have also been observed in rare blind individuals with outer retinal degeneration, who lack rod/cone function but retain ipRGC-mediated responses, to blue light.⁵³ This modulation could be a sign of early visual processing mediated by ipRGCs-pathway.⁵⁴

The observed widespread distribution in the dim versus low melanopic light conditions could suggest the involvement of sensorimotor or perhaps even more prefrontal areas. Frontal alpha activity has previously been linked to executive control and attentional regulation.^{55–57} The observed effects may thus in part reflect changes in top-down attentional engagement. In contrast to occipital alpha modulations, modulations in frontal alpha are less likely to be driven solely by low-level visual properties and might instead indicate more global changes in the cognitive state.^{58,59}

In this study, contrary to our initial hypothesis, no statistically significant differences were observed between the high and low melanopic light conditions. This null finding contrasts with other work, which reported improvements in attention assessed with EEG spectral power and ERP measures under exposure to short-wavelength (blue) light versus longer-wavelength light.^{48,60,61} However, it should be noted that very few studies to date have employed metameric lighting conditions. One study which compared three metameric light conditions (≈ 55 , ≈ 93 , and ≈ 165 melanopic lux) observed a difference in EEG alpha measures obtained using alpha attenuation test, at lower illuminance (100 photopic lux at eye level), but reported no significant difference between the metameric light conditions for higher illuminances (200, 600, and 1200 lux at eye level).¹⁶ We set the photopic illuminance at 200 lux at eye level to match typical daytime conditions in office environments. Yet, there is a chance that saturation level of the ipRGCs was already met at the low melanopic condition, reducing sensitivity to the melanopic contrast between the metamers.

Consistent with our results, systematic reviews have noted that the relationship between the melanopic stimulation and EEG markers of alertness is not well established.⁶² Studies employing spectral manipulations, such as changing CCT or the color of narrowband light sources, have reported inconsistent and sometimes contradictory effects on alpha power, with several high-quality studies

finding no significant differences between short- and long-wavelength light conditions. Where significant differences did emerge, they mainly occurred between dim-light conditions and brighter experimental light conditions.^{3,63,64} Our data follow the same pattern: the difference we observed was between the dim and the melanopic conditions, not between the two metameric conditions.

This pattern has an important interpretive consequence. Our low- versus high-melanopic comparison was placebo controlled through metamerism: the two conditions were matched in photopic illuminance, so cone signals and perceived brightness were held near-constant and any difference could be attributed to melanopic content. In that cleanly controlled contrast, we observed no statistically significant effect. The effect that did emerge appeared only in the dim-versus-metamer comparisons, which were not matched in illuminance and differed in perceived brightness. We therefore see a response consistent with melanopic drive, but because it arose only where overall illumination and brightness were not controlled, it cannot be attributed unequivocally to ipRGC activation. It may reflect melanopsin activation, cone-mediated (image forming) contributions, or expectation and awareness effects associated with the visibly brighter conditions. A stronger claim is difficult given the sparse reporting of melanopic light qualities in the existing literature. Future studies employing metameric lights across a range of illuminance levels would allow the contribution of melanopic content to be dissociated from overall retinal illumination and from expectation effects, and would best clarify the relationship between light quality and alertness.

Although alpha power showed light-induced differences, no statistically significant effects emerged in the beta band, consistent with prior work.^{16,65} This suggests daytime light may preferentially modulate alpha oscillations linked to vigilance rather than higher-frequency activity tied to core cognitive processing; though beta is less frequently reported in lighting studies, limiting comparison.

Despite the novelty and strengths of the methods demonstrated in this paper, several considerations should be kept in mind when interpreting the present findings. The metameric pair was designed to approximately match cone activations. While the absolute cone activations were quite similar between the two conditions (see Table 1), minor differences remained. These were more pronounced for the rhodopic EDI values. The optimization solver assumed linearity for cone activation and did not model rod activation, assuming saturation; the computed metamers may therefore not be perfectly equivalent in practice, leaving residual differences in photoreceptor stimulations in beyond-melanopsin containing cells. Relatedly, as noted earlier,³⁸ observed metameric differences in alpha only at 100 photopic lux and not at 200, 600, or 1200 lux. Our choice of 200 lux was motivated by ecological validity for office environments, but this places our design at an illuminance range where metameric effects on EEG appear to be, at best, small.

A second consideration concerns the 15-minute exposure. Acute non-image-forming responses to light have a rapid onset: EEG power density can be modulated within the first minute of exposure at room-light melanopic levels, and cortical and subcortical brain responses to blue light can appear within seconds to a few minutes, even without a concurrent cognitive task (Vandewalle et al., 2007; Prayag et

al., 2019). Daytime EEG alerting effects have been reported after exposures as short as 30 minutes,^{33,34} and a recent review concluded that a frequency band's responsiveness does not clearly depend on exposure duration.³ A 15-minute exposure is therefore likely sufficient to capture the onset of these effects. The temporal profile of the effect is dynamic, and this does constrain our design: fast EEG bands can follow a biphasic course (an initial decrease in high-alpha and beta power followed by a gradual increase), slower components such as delta continue to change over tens of minutes, and higher-frequency bands reach half-maximal responses only after roughly ten minutes⁶⁶. Duration and timing also shape which bands respond. In their study, Iskra-Golec et al. (2017) found that 30-minute versus 4-hour exposures produced partially opposite effects on low-frequency power showing that the duration can alter the pattern of the response, not merely its presence. Our single 15-minute exposure therefore likely captured the onset of this trajectory but may have been insensitive to more slowly building components and to spectral contributions that emerge only with longer exposure.

Finally, the sample size, although comparable to previous EEG studies in this domain, may also have limited the statistical power to detect more subtle effects, possibly in other frequency bands than alpha and in direct comparisons between the metameric light conditions. At the same time, the use of a systematically controlled design with a relatively strong melanopic contrast in a continuous time × frequency × spatial orientation approach stands as a methodological advancement and provides a rigorous framework for investigating the melanopsin-specific contributions to light-induced modulations in EEG during daytime.

The findings of the present study have broader implications for future research and the quantification of NIF effects of light using EEG measures. Although the spectral differences between the metameric light conditions did not result in robust changes in frequency specific EEG power, it is still possible that light influences other characteristics of brain activity that are not captured by the conventional power-based metrics.⁶⁷ For example, measures for temporal dynamics of neural fluctuations as well as connectivity between brain regions may provide more sensitive ways to quantify light-induced modulations, otherwise left undetected.^{68,69} The inconsistencies across the daytime-light literature may therefore reflect, in part, the heterogeneity of EEG metrics used: studies that rely solely on canonical band-power measures may miss light induced effects that more sensitive analyses (time-locked measures, microstate sequences, or connectivity) would have detected. Future research could consider incorporating more advanced analytical approaches, such as connectivity and complexity-based metrics to better capture the potentially subtle and distributed effects of light via the ipRGC-pathway.

Conclusion

In conclusion, daytime light exposure modulated EEG activity, primarily within the alpha band, with distinct spatial patterns across conditions. These effects were mainly driven by the differences between dim and brighter conditions rather than between the metameric light conditions, rendering it impossible to establish whether this effect was driven by non-visual or visual pathways. A clearer picture of how

spectral composition and overall illumination interact will require a more systematic manipulation of both. Specifically, future work would benefit from factorial paradigms in which metameric pairs (matched in photopic illuminance and chromaticity but differing in melanopic EDI) are presented at multiple, dose-graded photopic illuminance levels. Such a design would dissociate the melanopic and photopic axes that are confounded in single-pair comparisons, and would allow the shape of the dose-response function for each axis to be estimated. Combining this with sensitive neurophysiological metrics (such as task-evoked ERP components, EEG source localization, and pupillometry) would help reveal whether melanopic and photopic contributions diverge at specific stages of processing (e.g., early sensory versus later attentional ERP components) even when behavioural effects remain subtle. Such paradigms would help to uncover the neural mechanisms through which photoreceptor-specific pathways shape human physiology and behaviour. The findings about the effects of light on alertness and cognition during daytime could have a potential impact on the designing of living spaces, with improved alertness for work and educational settings and optimization of wellbeing for clinical settings.

Declarations

Use of generative AI

Generative AI tools were used for language editing and assistance with debugging analysis code. All outputs were reviewed and verified by the authors, who retain full responsibility for the manuscript and analyses.

Data availability

The datasets generated and analysed during the current study are not currently publicly available. In accordance with the informed consent obtained from participants, de-identified data may be shared for future research upon reasonable request to the corresponding author and, where appropriate, made available through an online data repository.

Competing interests

The authors declare no competing interests.

Author Contribution

E.G.: Conceptualization, Methodology, Investigation, Data curation, Formal analysis, Visualization, Writing the original draft.

K.S: Conceptualization, Methodology, Supervision, Writing: review & editing.

JM.S.: Supervision, Methodology, Visualization, Writing : review & editing.

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References

1. Vetter, N. C. et al. Anterior insula hyperactivation in ADHD when faced with distracting negative stimuli. *Hum. Brain Mapp.* **39**, 2972–2986 (2018).
2. Warthen, D. M. & Provencio, I. The role of intrinsically photosensitive retinal ganglion cells in nonimage-forming responses to light. *Eye Brain* 43–48 (2012).
3. Gecer, E., Smolders, K., Schlangen, L. & Schoffelen, J. M. & de Kort. EEG Effects of Daytime Light: a PRISMA Systematic Review. Submitted manuscript.
4. Gooley, J. J., Lu, J., Fischer, D. & Saper, C. B. A broad role for melanopsin in nonvisual photoreception. *J. Neurosci.* **23**, 7093–7106 (2003).
5. Hattar, S. et al. Central projections of melanopsin-expressing retinal ganglion cells in the mouse. *J. Comp. Neurol.* **497**, 326–349 (2006).
6. Patton, A. P. & Hastings, M. H. The suprachiasmatic nucleus. *Curr. Biol.* **28**, R816–R822 (2018).
7. Vandewalle, G., Maquet, P. & Dijk, D. J. Light as a modulator of cognitive brain function. *Trends Cogn. Sci.* **13**, 429–438 (2009).
8. Foster, R. G. Bright blue times. *Nature* **433**, 698–699 (2005).
9. Hannibal, J. et al. Central projections of intrinsically photosensitive retinal ganglion cells in the macaque monkey. *J. Comp. Neurol.* **522**, 2231–2248 (2014).
10. Mure, L. S. Intrinsically photosensitive retinal ganglion cells of the human retina. *Front. Neurol.* **12**, 636330 (2021).
11. Coull, J. T., Jones, M. E., Egan, T. D., Frith, C. D. & Maze, M. Attentional effects of noradrenaline vary with arousal level: selective activation of thalamic pulvinar in humans. *Neuroimage* **22**, 315–322 (2004).
12. Portas, C. M. et al. A specific role for the thalamus in mediating the interaction of attention and arousal in humans. *J. Neurosci.* **18**, 8979–8989 (1998).
13. Schlangen, L. J. M. & Price, L. L. A. The lighting environment, its metrology and non-visual responses. 24 (2020).

14. Askaripoor, T. et al. The parallel effect of correlated color temperature and illumination level on alertness and cognitive performance: a multi-measure study. *J. Health Saf. Work.* **11**, 674–678 (2021).
15. Smolders, K., De Kort, Y. & Cluitmans, P. Higher light intensity induces modulations in brain activity even during regular daytime working hours. *Light Res. Technol.* **48**, 433–448 (2016).
16. Zeeuw, J. et al. Living in Biological Darkness: Objective Sleepiness and the Pupillary Light Responses Are Affected by Different Metameric Lighting Conditions during Daytime. *J. Biol. Rhythms.* **34**, 410–431 (2019).
17. Aeschbach, D. et al. Two circadian rhythms in the human electroencephalogram during wakefulness. *Am. J. Physiol. -Regul Integr. Comp. Physiol.* **277**, R1771–R1779 (1999).
18. Cajochen, C., Brunner, D. P., Krauchi, K., Graw, P. & Wirz-Justice, A. Power Density in Theta/Alpha Frequencies of the Waking EEG Progressively Increases During Sustained Wakefulness. *Sleep* **18**, 890–894 (1995).
19. Klimesch, W. EEG alpha and theta oscillations reflect cognitive and memory performance: a review and analysis. *Brain Res. Rev.* **29**, 169–195 (1999).
20. Askaripoor, T. et al. Non-Image Forming Effects of Light on Brainwaves, Autonomic Nervous Activity, Fatigue, and Performance. *J. Circadian Rhythms.* **16**, 9 (2018).
21. Askaripoor, T. et al. Effects of light intervention on alertness and mental performance during the post-lunch dip: A multi-measure study. *Ind. Health.* **57**, 511–524 (2019).
22. Kuller, R. & Wetterberg, L. Melatonin, cortisol, EEG, ECG and subjective comfort in healthy humans: Impact of two fluorescent lamp types at two light intensities. *Light Res. Technol.* **25**, 71–80 (1993).
23. Li, Y., Fang, W., Qiu, H. & Wang, J. The non-visual effects of correlated color temperature on the alertness, cognition, and mood of fatigued individuals during the afternoon. *Int. J. Ind. Ergon.* **101**, 103589 (2024).
24. Park, J. Y., Ha, R. Y., Ryu, V., Kim, E. & Jung, Y. C. Effects of Color Temperature and Brightness on Electroencephalogram Alpha Activity in a Polychromatic Light-emitting Diode. *Clin. Psychopharmacol. Neurosci.* **11**, 126–131 (2013).
25. Gecer, E. Designing Metameric Light: Advanced Methods for Isolated Photoreceptor Response and Testing NIF Effects of Light. in *IEEE Sustainable Smart Lighting World Conference & Expo (LS24)* (IEEE, 2024). (IEEE, 2024). (2024).
26. Conus, V. & Geiser, M. A review of silent substitution devices for melanopsin stimulation in humans. in *Photonics* vol. 7 121MDPI, (2020).
27. Spitschan, M. & Woelders, T. The Method of Silent Substitution for Examining Melanopsin Contributions to Pupil Control. *Front. Neurol.* **9**, 941 (2018).
28. De Zeeuw, J. et al. Living in Biological Darkness: Objective Sleepiness and the Pupillary Light Responses Are Affected by Different Metameric Lighting Conditions during Daytime. *J. Biol. Rhythms.* **34**, 410–431 (2019).

29. Qin, B. et al. Lighting-based alertness enhancement in low-light environments: Spectral modulation effects and psychophysiological evidence. *Build. Environ.* **285**, 113589 (2025).
30. Schöhlhorn, I. et al. Melanopic irradiance defines the impact of evening display light on sleep latency, melatonin and alertness. *Commun. Biol.* **6**, 228 (2023).
31. Zele, A. J., Feigl, B., Adhikari, P., Maynard, M. L. & Cao, D. Melanopsin photoreception contributes to human visual detection, temporal and colour processing. *Sci. Rep.* **8**, 3842 (2018).
32. Baek, H. & Min, B. K. Blue light aids in coping with the post-lunch dip: an EEG study. *Ergonomics* **58**, 803–810 (2015).
33. Iskra-Golec, I. et al. Daytime effect of monochromatic blue light on EEG activity depends on duration and timing of exposure in young men. *Adv. Cogn. Psychol.* **13**, 241–247 (2017).
34. Okamoto, Y., Rea, M. S. & Figueiro, M. G. Temporal dynamics of EEG activity during short- and long-wavelength light exposures in the early morning. *BMC Res. Notes.* **7**, 113 (2014).
35. Smolders, K. C. H. J., de Kort, Y. A. W. & Cluitmans, P. J. M. Higher light intensity induces modulations in brain activity even during regular daytime working hours. *Light Res. Technol.* **48**, 433–448 (2016).
36. Blume, C. et al. Melatonin suppression does not automatically alter sleepiness, vigilance, sensory processing, or sleep. *Sleep* **45**, zsac199 (2022).
37. Cao, D., Nicandro, N. & Barrionuevo, P. A. A five-primary photostimulator suitable for studying intrinsically photosensitive retinal ganglion cell functions in humans. *J. Vis.* **15**, 27 (2015).
38. de Zeeuw, J. et al. Living in biological darkness: Objective sleepiness and the pupillary light responses are affected by different metameric lighting conditions during daytime. *J. Biol. Rhythms.* **34**, 410–431 (2019).
39. Fazlali, F. et al. Lack of strong evidence for cone photoreceptors' contribution to human melatonin suppression and alerting response to light. *J Pineal Res* (2025).
40. Schöhlhorn, I. et al. Melanopic irradiance defines the impact of evening display light on sleep latency, melatonin and alertness. *Commun. Biol.* **6**, 228 (2023).
41. Souman, J. L. et al. Spectral tuning of white light allows for strong reduction in melatonin suppression without changing illumination level or color temperature. *J. Biol. Rhythms.* **33**, 420–431 (2018).
42. Spitschan, M., Luu, L., Datta, R., Brainard, D. H. & Aguirre, G. K. Melanopsin-driven responses in the human brain. *J. Vis.* **14**, 1188 (2014).
43. Zandi, B. et al. Optimising metameric spectra for integrative lighting to modulate the circadian system without affecting visual appearance. *Sci. Rep.* **11**, 23188 (2021).
44. Maris, E. & Oostenveld, R. Nonparametric statistical testing of EEG- and MEG-data. *J. Neurosci. Methods.* **164**, 177–190 (2007).
45. Oostenveld, R., Fries, P., Maris, E., Schoffelen, J. M. & FieldTrip Open source software for advanced analysis of MEG, EEG, and invasive electrophysiological data. *Comput. Intell. Neurosci.* 156869

- (2011). (2011).
46. Smolders, K., De Kort, Y. & van den Berg, S. M. Daytime light exposure and feelings of vitality: Results of a field study during regular weekdays. *J. Environ. Psychol.* **36**, 270–279 (2013).
 47. Maris, E. & Oostenveld, R. Nonparametric statistical testing of EEG-and MEG-data. *J. Neurosci. Methods.* **164**, 177–190 (2007).
 48. An, M., Huang, J., Shimomura, Y. & Katsuura, T. Time-of-day-dependent Effects of Monochromatic Light Exposure on Human Cognitive Function. *J. Physiol. Anthropol.* **28**, 217–223 (2009).
 49. Klimesch, W., Sauseng, P. & Hanslmayr, S. EEG alpha oscillations: the inhibition–timing hypothesis. *Brain Res. Rev.* **53**, 63–88 (2007).
 50. Pfurtscheller, G., Stancák, A. & Neuper, C. Event-related synchronization (ERS) in the alpha band – an electrophysiological correlate of cortical idling: a review. *Int. J. Psychophysiol.* **24**, 39–46 (1996).
 51. Jensen, O., Gelfand, J., Kounios, J. & Lisman, J. E. Oscillations in the alpha band (9–12 Hz) increase with memory load during retention in a short-term memory task. *Cereb. Cortex.* **12**, 877–882 (2002).
 52. Klimesch, W., Sauseng, P. & Hanslmayr, S. EEG alpha oscillations: the inhibition–timing hypothesis. *Brain Res. Rev.* **53**, 63–88 (2007).
 53. Vandewalle, G. et al. Light modulates oscillatory alpha activity in the occipital cortex of totally visually blind individuals with intact non-image-forming photoreception. *Sci. Rep.* **8**, 16968 (2018).
 54. Spitschan, M., Bock, A. S., Frazzetta, G., Brainard, D. H. & Aguirre, G. K. Human visual cortex responds to isolated melanopsin-directed stimulation. *J. Vis.* **17**, 20–20 (2017).
 55. Cooper, P. S., Darriba, Á., Karayanidis, F. & Barceló, F. Contextually sensitive power changes across multiple frequency bands underpin cognitive control. *NeuroImage* **132**, 499–511 (2016).
 56. Klimesch, W. Alpha-band oscillations, attention, and controlled access to stored information. *Trends Cogn. Sci.* **16**, 606–617 (2012).
 57. Sadaghiani, S. & Kleinschmidt, A. Brain networks and α -oscillations: Structural and functional foundations of cognitive control. *Trends Cogn. Sci.* **20**, 805–817 (2016).
 58. Sauseng, P. et al. EEG alpha synchronization and functional coupling during top-down processing in a working memory task. *Hum. Brain Mapp.* **26**, 148–155 (2005).
 59. Wang, C., Rajagovindan, R., Han, S. M. & Ding, M. Top-down control of visual alpha oscillations: sources of control signals and their mechanisms of action. *Front. Hum. Neurosci.* **10**, 15 (2016).
 60. Rahman, S. A. et al. Diurnal Spectral Sensitivity of the Acute Alerting Effects of Light. *Sleep* **37**, 271–281 (2014).
 61. Šmotek, M., Vlček, P., Saifutdinova, E. & Kopřivová, J. Objective and Subjective Characteristics of Vigilance under Different Narrow-Bandwidth Light Conditions: Do Shorter Wavelengths Have an Alertness-Enhancing Effect? *Neuropsychobiology* **78**, 238–248 (2019).
 62. Cheshmeh Noor, M., Revell, V., Mehdizadeh Saradj, F. & Yazdanfar, S. A. The impact of wavelength on acute non-visual responses to light: A systematic review and meta-analysis. *Brain Res.* **1816**, 148470 (2023).

63. Bjerrum, L. B. et al. Acute effects of light during daytime on central aspects of attention and affect: A systematic review. *Biol. Psychol.* **192**, 108845 (2024).

64. Lasauskaite, R., Wüst, L. N., Schöllhorn, I., Richter, M. & Cajochen, C. *Non-Image-Forming Effects of Daytime Electric Light Exposure in Humans: A Systematic Review and Meta-Analyses of Physiological, Cognitive, and Subjective Outcomes* LEUKOS,. (2025).

65. Luo, X. et al. Temporal Dynamics of Subjective and Objective Alertness During Exposure to Bright Light in the Afternoon for 5 h. *Front Physiol* **12**, (2021).

66. Prayag, A. S., Jost, S., Avouac, P., Dumortier, D. & Gronfier, C. Dynamics of Non-visual Responses in Humans: As Fast as Lightning? *Front Neurosci* **13**, (2019).

67. Donoghue, T. et al. Parameterizing neural power spectra into periodic and aperiodic components. *Nat. Neurosci.* **23**, 1655–1665 (2020).

68. Killgore, W. D. S. et al. Blue light exposure increases functional connectivity between dorsolateral prefrontal cortex and multiple cortical regions. *NeuroReport* **33**, 236–241 (2022).

69. Sharifpour, R. et al. Light impact on thalamo-cortical connectivity during a cognitive task depends on time of day and is different in teenagers. *bioRxiv* (2025).
<https://doi.org/10.1101/2025.04.03.647005> doi:10.1101/2025.04.03.647005.

Figures

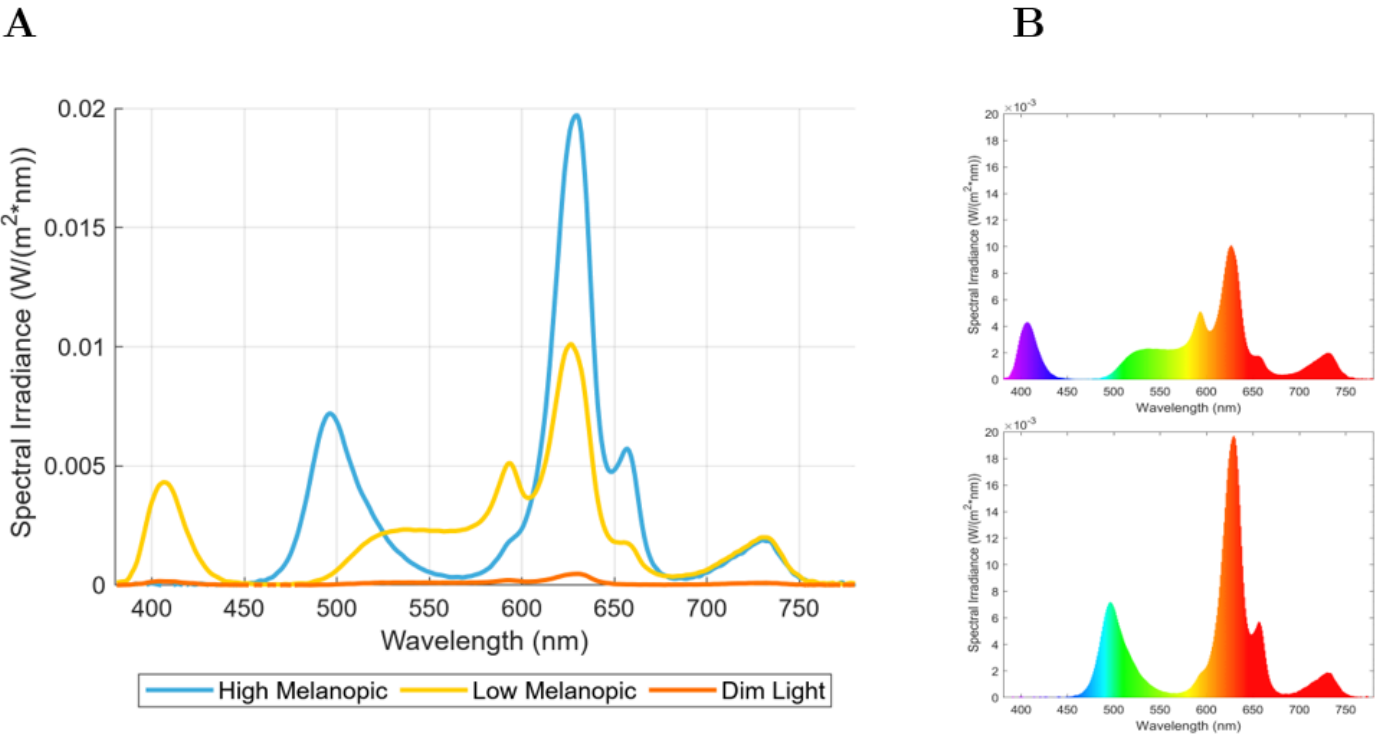


Figure 1

a. Spectra of the metameric light conditions and dim light condition. Blue: High Melanopsin, Yellow: Low Melanopsin, Orange: Dim Light Conditions. **b.** Colour spectra of high melanopsin (top) and low melanopsin (bottom) conditions.

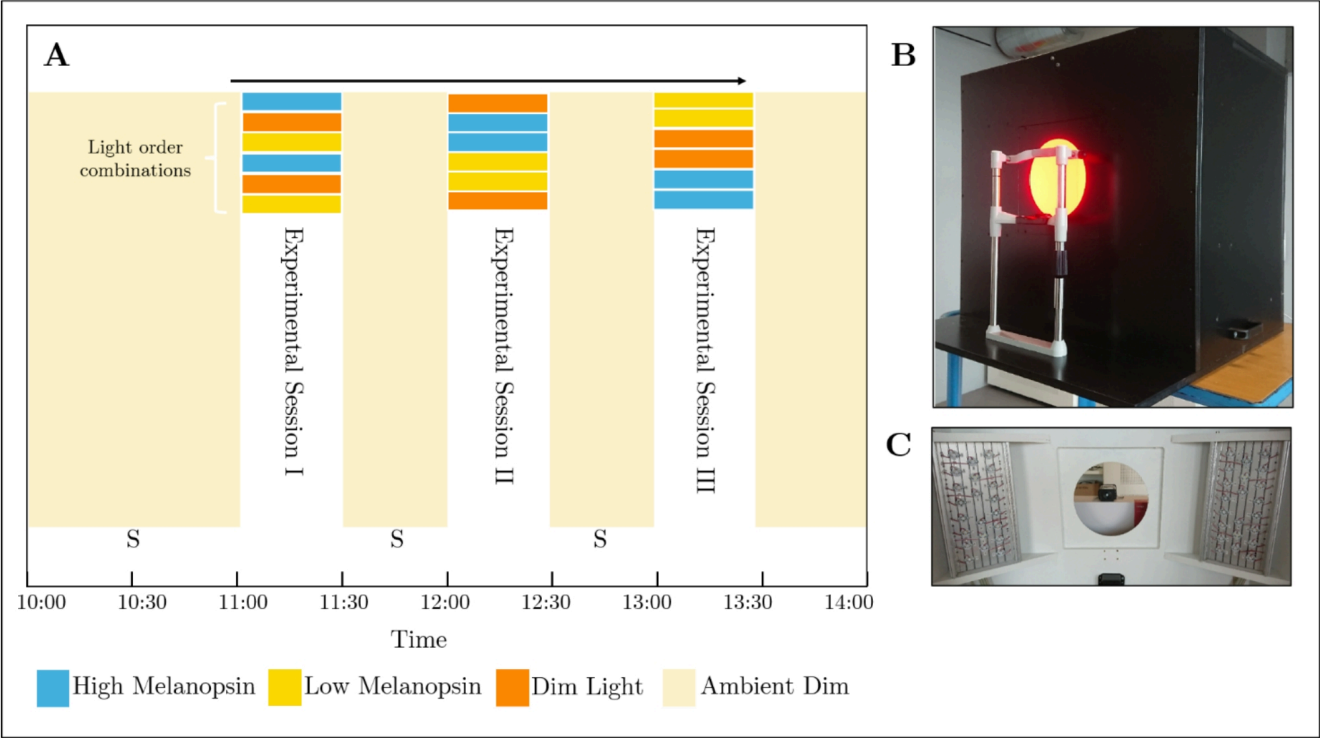


Figure 2

a. Visualization of the experimental protocol with different light conditions (High Melanopic, Low Melanopic and Dim Light, and Ambient Dim Light administered during blocks I, II and III). Each light condition lasted 30 minutes. Participants were exposed to 60 minutes of ambient dim light before the first light condition and 30 minutes between the light conditions. The order of the experimental light conditions was counterbalanced across subjects.

b. Boschman Light Box. 2C. Eleven types of LEDs within the box on each side of the opening.

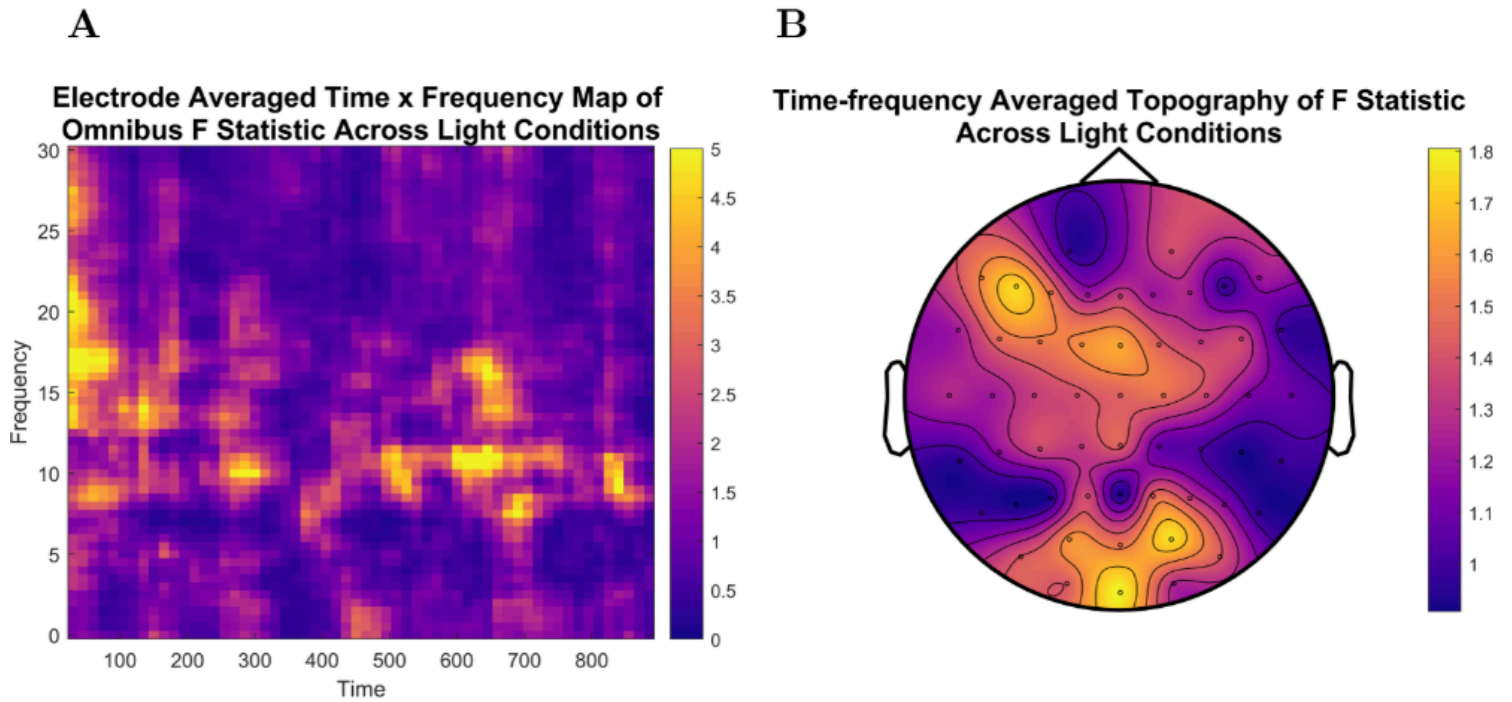


Figure 3

4. a. Time x Frequency map (of the omnibus F-statistic) across the 15-minute uninterrupted light exposure averaged across all electrodes and comparing all three light conditions (High mel, Low mel, Dim light). **b.** Topography of the omnibus F statistic for comparisons across the three experimental light conditions, averaged over the 15 minutes of exposure. There were no statistically significant differences between the three conditions in the clusters. Separate colour scales are used to account for the reduced F-value range after averaging; colours are not directly comparable between panels.

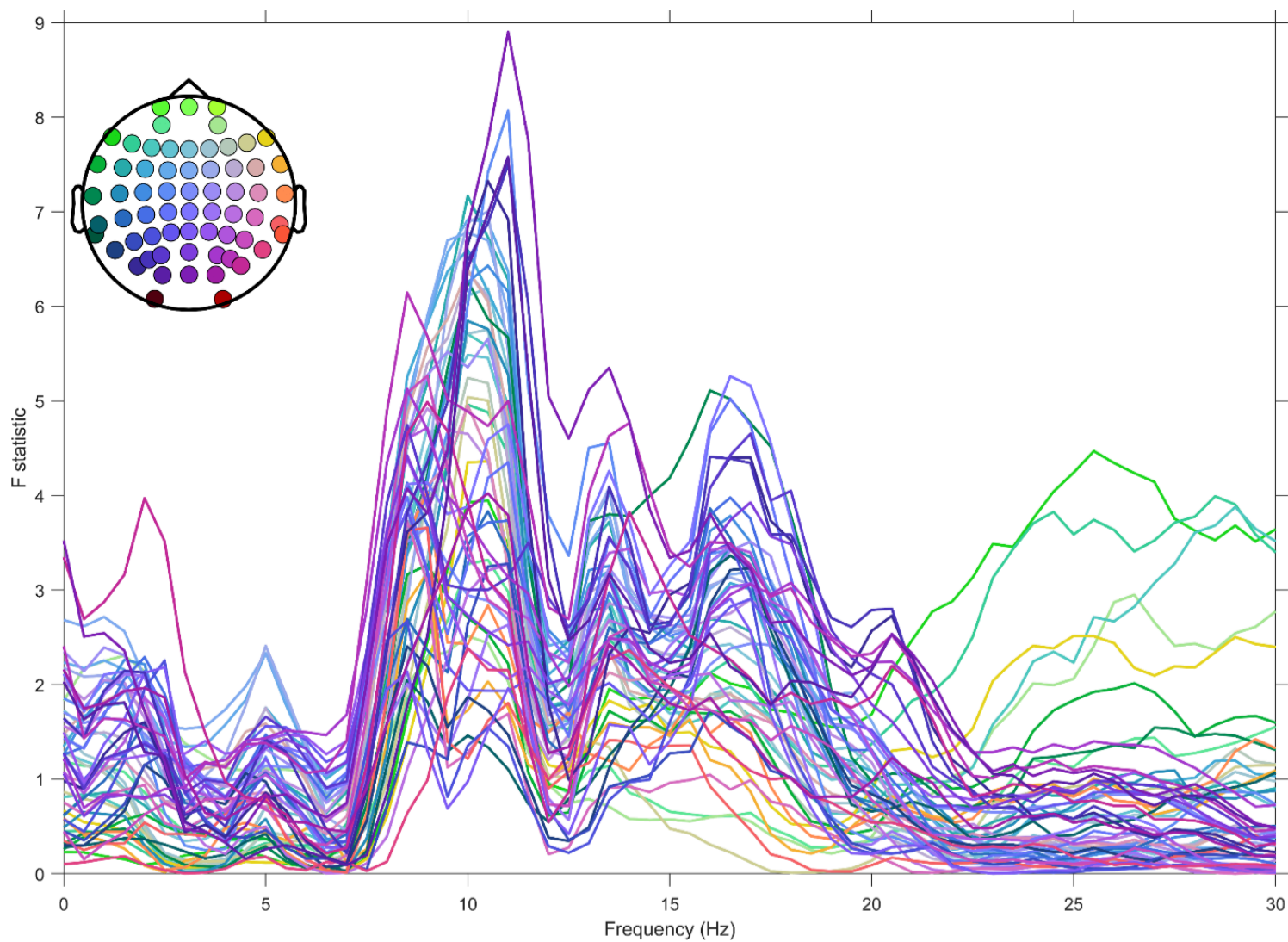


Figure 4

5. Butterfly plot distribution of the F statistic across frequency ranges. Colored traces represent individual electrodes.

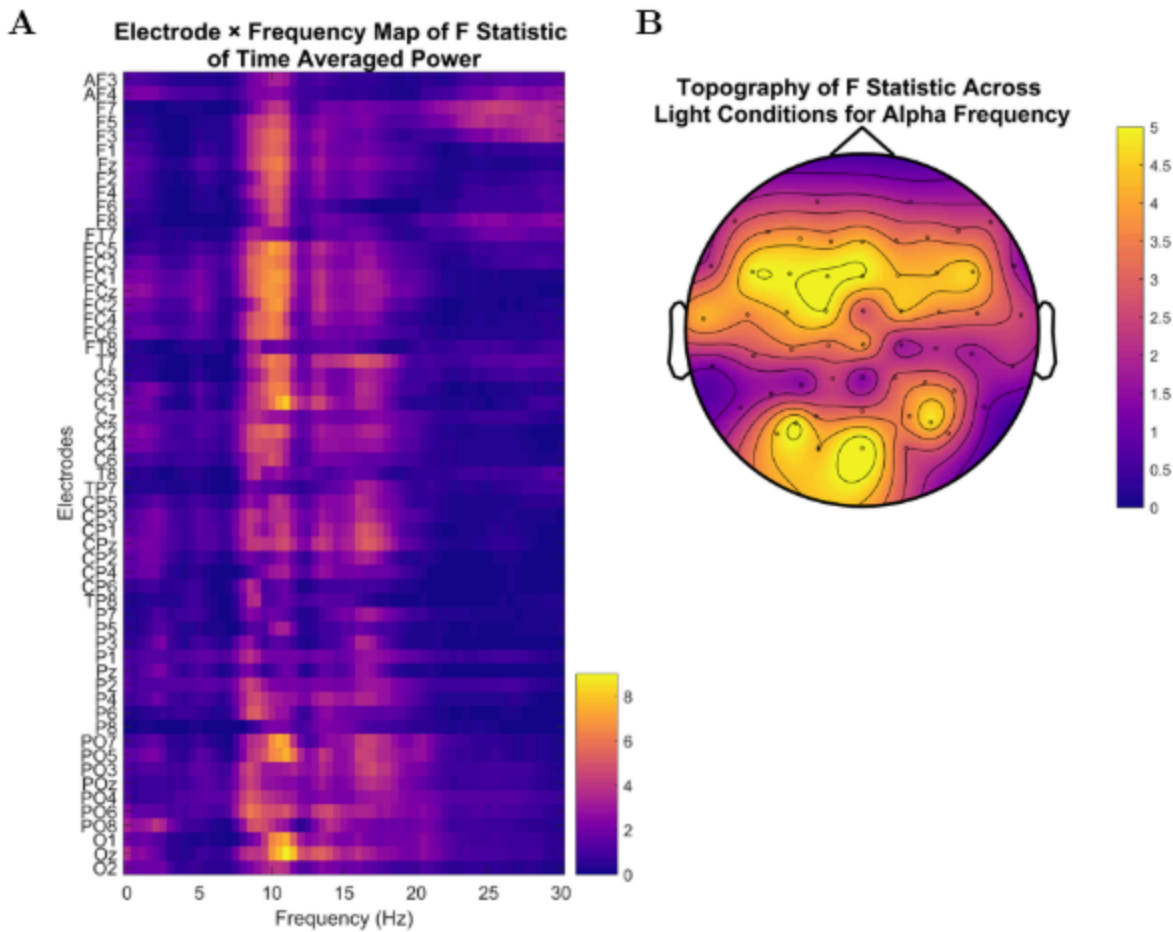


Figure 5

6.a. Channel x frequency distribution of the omnibus F statistic for alpha power density across the three light conditions (high melanopic, low melanopic, and dim light). **b.** Scalp topography of the omnibus F statistic for alpha power density across conditions, averaged across time and alpha-frequency bins. The cluster-based permutation analysis revealed a significant main effect of light condition (cluster-level Monte Carlo $p = .006$). Within the significant cluster, sample-wise F statistics ranged from $F(2, 36) = 3.26$ to 8.07 , corresponding to η_p^2 values of .154 to .309. Separate color scales are used to account for the reduced F-value range after averaging; colors are not directly comparable between panels.

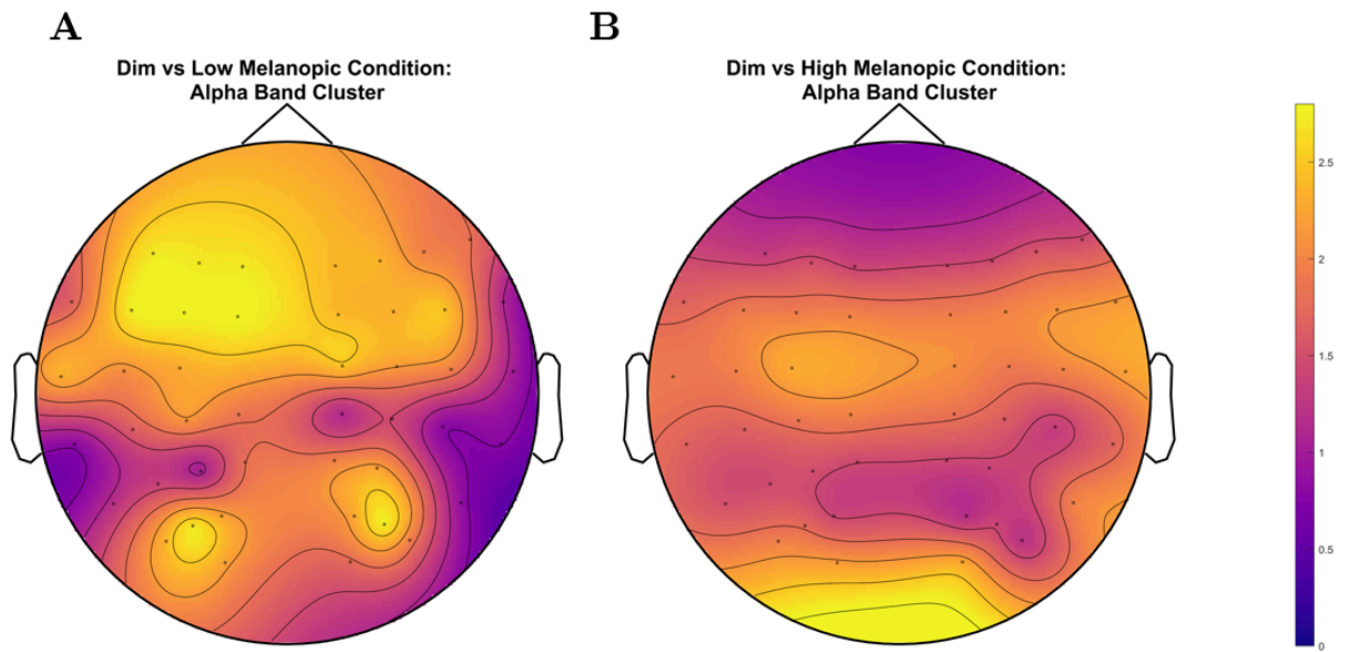


Figure 6

7. Cluster-based Monte Carlo permutation results for pairwise comparisons of alpha-band power between dim and melanopic light conditions. Topographies show the T-statistic averaged across frequency bins contributing to the largest cluster. **a.** Dim vs Low melanopic light, cluster-level corrected $p = .004$. **b.** Dim vs High melanopic light, cluster-level corrected $p = .016$. No significant cluster was observed for Low vs High melanopic light, $p = .168$.

Supplementary Files

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