**Influence of Daytime Short-Wavelength Enriched Electric Light Exposure on Human Alertness and Cognitive Performance**

Mushfiqul Anwar Siraji1,2, Yi Jiau Saw2,3, Vineetha Kalavally2,3, & Shamsul Haque\*,1,2

1 Department of Psychology, Jeffrey Cheah School of Medicine and Health Sciences, Monash University, Malaysia

2 Intelligent Lighting Lab, Monash University Malaysia

3 Department of Electrical and Computer Systems Engineering, Monash University, Malaysia

\*Correspondence concerning this article should be addressed to Shamsul Haque, Monash University Malaysia, Jalan Lagoon Selatan, 47500 Bandar Sunway, Selangor Darul Ehsan, Malaysia. E-mail: [shamsul@monash.edu](mailto:shamsul@monash.edu).

**Declarations**

**Declarations of interest:** None

**Author contributions:** *Mushfiqul Anwar Siraji:* Conceptualization, Methodology, Data curation, Investigation, Formal analysis, Visualization, Writing - original draft preparation, Writing - review and editing. *Yi Jiau Saw:* Conceptualization, Data curation. *Vineetha Kalavally and Shamsul Haque*: Conceptualization, Writing - review and editing, Supervision.

**Data Availability:** All data, analysis code underlying this article and an R-markdown reproducible manuscript have been made publicly available on GitHub and can be accessed at https://github.com/ILLMMU/Study3.

**Ethical considerations:** The study obtained ethics clearance from the Monash University Human Research Ethics Committee (Project ID: 14786), and participants provided written informed consent prior to the study.

**Abstract**

We tested the influence of electric daytime short-wavelength-enriched white light exposure on alertness and cognitive performance while respecting the lighting guidelines and standards. Twenty-four participants (n = 24; Agemean±sd =23.96±2.42; 16F) were randomized to a two-hour daytime exposure to one of three light conditions with different melanopic daylight efficacy ratios (High MDER= 0.85; Neutral MDER= 0.60; Low MDER= 0.43). For all light conditions, the photopic illuminance was maintained at ~250 lx (238.12±27.4 lx) measured at the horizontal plane (80cm) and 130 lx (128.45.12±13.11 lx) measured at eye level vertical plane (120cm).

Karolinska sleepiness scale, auditory psychomotor vigilance task (aPVT), digit span task, tower of London and n-back task were used to measure subjective alertness, objective alertness, short-term memory span, planning ability, and working memory, respectively.

Results indicated a trend of improved subjective alertness under the High MDER light condition. No significant influence of light on the performance outcome of aPVT was observed. Further, light’s beneficial influences were dependent on the cognitive domain. A higher memory span in the forward digit span task was observed for the neutral MDER light condition compared to the low MDER light condition (*p*=0.04). In contrast, participants had faster execution time in the Tower of London task under the low MDER light than those under neutral MDER light (*p*=0.04).

These results demonstrate that short-wavelength-enriched light exposure within the lighting standards can improve alertness. Improvement in cognitive performance is dependent on the cognitive domain. Collectively, these results will guide us in designing a rewarding light environment within the lighting standards and guidelines.

*Keywords:* light exposure, IIL responses, non-visual effects, alertness, cognition.

# Introduction

In addition to its primal role in human vision, light also influences different physiological and psychological aspects, including modulation of our sleep-wake cycle, alertness, and cognitive performance (Cajochen et al., 2022; Lockley, 2008; Siraji et al., 2022; Spitschan, 2019). These responses are guided mainly by a group of photoreceptors- intrinsically photosensitive retinal ganglion cells (ipRGCs; Berson et al., 2002), which are highly sensitive to short-wavelength-enriched light exposure (Hankins & Lucas, 2002). ipRGCs receive light signals and send them to different regions of the brain, including the suprachiasmatic nucleus (SCN)-the master clock of our body and other areas related to the modulation of alertness and cognitive functioning, such as locus coeruleus and hypothalamus (Lok, Smolders, et al., 2018). Hence, these light-induced non-visual responses are collectively known as ipRGCs influenced light (IIL) responses (CIE, 2018).

With the modern advancement of lighting technology and building architecture, humans are exposed to electric light at night and during the day. Nighttime electric light exposure induced IIL responses have been widely investigated. Studies reported improvement in alertness and a significant phase shift in human circadian rhythm due to evening and nighttime electric light exposure (Cajochen et al., 2005; Chellappa et al., 2011; Lockley et al., 2006). However, less focus is given to investigate the influence of daytime electric light exposure induced IIL responses. A few studies have shown that daytime short-wavelength-enriched light exposure has the potential to improve the alertness (Alkozei. et al., 2016; Viola et al., 2008). However, the majority of these studies reporting the beneficial influence of light have used very low photopic illuminance as a comparison condition (≤10 lx) and/or unrealistically high experimental illuminances (≥1000 lux). It is important to note that most current lighting standards and guidelines suggest a daytime illuminance ranging between 200-700 lux for typical office, classroom, and indoor works (CIE, 2002; DOSH, 2018; IES, 2018; Malaysian Standard, 2014). Whether the lab-based beneficial influences of light can be generalized in light environments with photopic illuminances mimicking real-world light environments while respecting the lighting standards and guidelines is less explored. Further, a recent consensus-based recommendation on healthy light exposure suggested having at least 250 melanopic EDI (a SI unit to quantify light’s ability to elicit IIL responses) at eye level (Brown et al., 2022). A technical difficulty in providing 250 melanopic EDI is that typical “off the shelf” tuneable white LEDs would require at least a 50% increase in horizontal illuminances (Brown et al., 2022), thus increasing the energy expenditure. More research is needed to investigate whether the beneficial influences of electric light can be incorporated into a real-world light environment that rewards alertness and cognitive performance while balancing energy expenditure.

Further, findings of the studies investigating the influence of daytime light exposure on cognitive performance lack consensus and reported positive-(Askaripoor et al., 2019; Cajochen et al., 2019; Grant et al., 2021; Huiberts et al., 2015; Lok et al., 2022; Mills et al., 2007; Viola et al., 2008), negative-(Smolders & de Kort, 2017; Smolders & de Kort, 2014; Smolders et al., 2012) and no-(Leichtfried et al., 2016) influence. The cognitive tasks used in those studies varied highly in terms of task complexity and cognitive domain. Huiberts et al. (2015), in their research (n=64), indicated that electric light’s beneficial influence on task performance depended on task difficulty. Further, Lok et al. (2022), while investigating the beneficial influence of daytime electric light exposure (n=9) using a comprehensive set of cognitive tasks, hinted towards a possible cognitive domain dependency of the beneficial influence of daytime electric light. More studies are needed to understand the impact of daytime electric light exposure on cognitive performance and its dependency on task complexity.

The current study aims to identify an optimal light spectrum that would reward our alertness and cognitive performance without drastically increasing horizontal illuminances. We composited a light spectrum with high short-wavelength-enrichment- (measured using the new standardized SI unit to express the ratio of melanopic over photopic drive: melanopic daylight efficacy ratio) while keeping the horizontal illuminance within the suggested guidelines (~250 lx). To gain insight into whether the beneficial influences of light exposure can be utilized to improve alertness and cognitive performance in real-world light environments, we compared the alerting effects and cognitive performance induced by this in-house developed high short-wavelength-enriched light spectrum (MDER=0.85) against another two light spectrums with comparatively lower short-wavelength enrichment (MDER=0.60 and 0.43 respectively) but with similar horizontal illuminance (~250 lx). We hypothesized that light exposure with the highest short-wavelength enrichment would improve the alertness highest (H1).

The second aim of this study is to investigate the possible task and cognitive domain dependency of the beneficial influence of light on cognitive performance. We hypothesized that the beneficial effect of light would be the cognitive domain (H2) and task complexity (H3) dependent.

# Materials and Methods

## Participants

Twenty-four healthy university students, ages ranging between 20-29 (Agemean±sd =23.96±2.42)- 16 females (Agemean±sd=23.88±2.64) and 8 males (Agemean±sd=24.00±2.39) were studied in our lab. Table 1 presents the demographic characteristics of the participants. All participants reported to be free from medical and psychological conditions and had no color blindness (tested by Ishihara Blindness Test; Clark, 1924). Most were poor sleepers (62%) and had intermediate chronotypes (71%).

Table 1. Demographic characteristics of the participants (*N*=24)

| Variable | **Overall1**,  N = 24 | **Low1**,  N = 7 | **Neutral1,**  N = 7 | **High1**,  N = 10 |
| --- | --- | --- | --- | --- |
| Age | 23.96 (2.42) | 25.00 (2.52) | 23.29 (2.87) | 23.70 (2.00) |
| Gender |  |  |  |  |
| Female | 8 (33%) | 1 (14%) | 4 (57%) | 3 (30%) |
| Male | 16 (67%) | 6 (86%) | 3 (43%) | 7 (70%) |
| Marital Status |  |  |  |  |
| Single | 24 (100%) | 7 (100%) | 7 (100%) | 10 (100%) |
| Education |  |  |  |  |
| Bachelor’s Degree | 22 (92%) | 7 (100%) | 5 (71%) | 10 (100%) |
| Master’s Degree | 2 (8.3%) | 0 (0%) | 2 (29%) | 0 (0%) |
| Sleep Quality |  |  |  |  |
| Good | 9 (38%) | 3 (43%) | 3 (43%) | 3 (30%) |
| Poor | 15 (62%) | 4 (57%) | 4 (57%) | 7 (70%) |
| Chronotype |  |  |  |  |
| Definite Evening | 1 (4.2%) | 0 (0%) | 0 (0%) | 1 (10%) |
| Intermediate | 17 (71%) | 6 (86%) | 5 (71%) | 6 (60%) |
| Moderate Evening | 5 (21%) | 1 (14%) | 2 (29%) | 2 (20%) |
| Moderate Morning | 1 (4.2%) | 0 (0%) | 0 (0%) | 1 (10%) |

## 1Mean (SD); n (%)

## Measures

### Subjective Measures of Alertness

We used Karolinska Sleepiness Scale (Åkerstedt & Gillberg, 1990) to measure subjective sleepiness. Participants rated their sleepiness hourly using the KSS, a 10-point scale from 1- "very alert" to 10 - "Extremely sleepy, cannot keep wake".

### Auditory Psychomotor Vigilance Task (aPVT)

Participants’ sustained attention was measured using a 10-minute computer-based auditory psychomotor vigilance task (aPVT). In this task, an auditory signal was presented at a random interval (1-9s), and the participants were asked to press the keyboard's spacebar as fast as possible after hearing the sound.

### Digit Span Task

Three variations of the verbal Digit Span Task: (a) forward, (b) backward, and (c) sequential were used to measure participants’ short-term memory span. In the forward-span variant, participants attempted to recall the digits in the same order they were presented. In the backward-span variant, participants attempted to recall the digits in the reverse order. In the sequential-span variant, at the end of each list, participants attempted to recall the digits in sequential order. In each variation, there were eight iterations with two trials per iteration. In each iteration, the number of digits was incremented by one digit.

### Tower of London

The Tower of London test (Shallice, 1982) was used to measure the planning ability of the participants. This task had 16 trials with no imposed time constrain. Participants were presented with a board with three poles carrying three colored balls: red, green, and blue. In each trial, authors arranged the ball in a certain arrangement and participants were asked to rearrange the balls to attain a goal state with as few moves and as quickly as possible. They were instructed to preplan their moves and execute them as quickly as possible.

### N-Back Task

Two variations of the auditory n-back task, (a) one-back (easy) and (b) three-back (difficult), were used to measure the working memory and executive functions of the participant's (Jonathan et al., 1997). Both variations contain 72 trials each (24 target trials and 48 nontarget trials). Each trial lasted for approximately two seconds. The sequence of target and non-target trials were randomized. Both variations started with a presentation of a fixation screen from 1000 ms. In both variations, random English one-digit numbers were presented successively. The participants were instructed to judge whether the current digit matches the digit heard one digit previously (one-back) or three-digit previously (three-back) and press the assigned keys (labeled "Yes" and "No") on the keyboard.

## Environmental and Light Settings

The lab () was furnished with one rectangular working desk with three chairs. The lab walls were covered with grey curtains, and blackout blinds covered all glass windows. The room temperature was set to 25°C. The three light conditions were generated using 12 Phillips tuneable LED ceiling-mounted luminaries (9W, 7.58.86.5 cm; CCT: 2000K–6500K). Figure 1 (A-B) depicts the luminaire arrangement of the lab. We measured the light sources at the horizontal plane at desk level (80 cm) and the vertical plane at eye level of the participants seated at the desk (120 cm). Figure 1-C depicts the spectral composition of the three light conditions. Spectral measurements were conducted using a Konica Minolta CL-500A illuminance spectrophotometer (Konica Minolta Sensing Americas., NJ, USA).

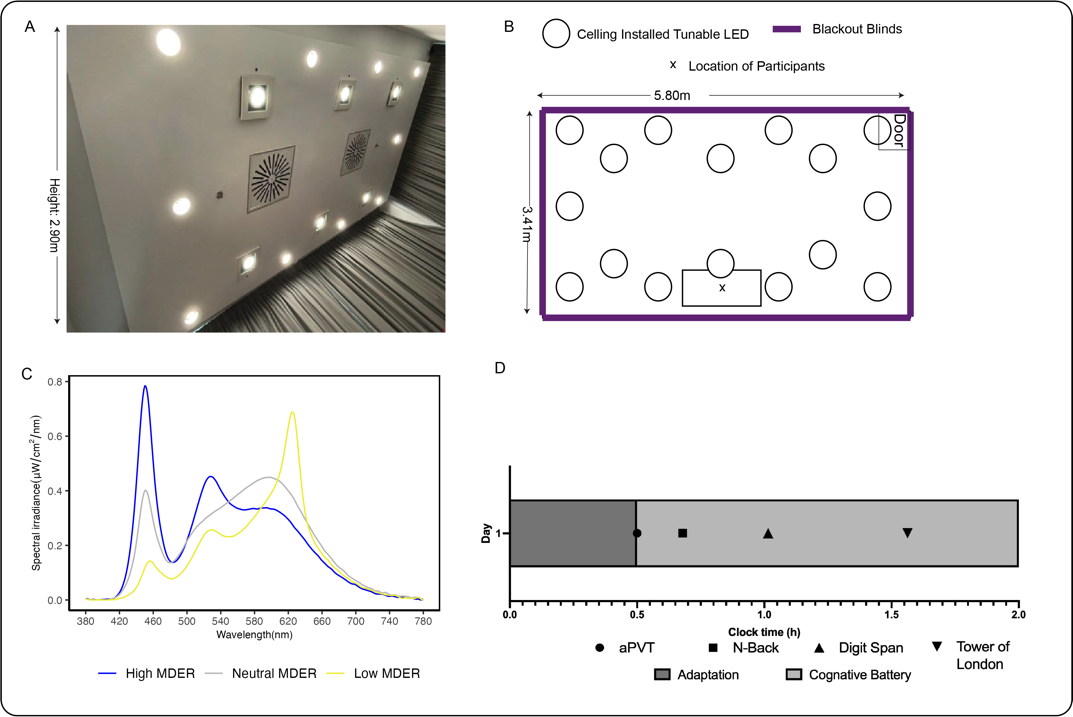


Figure 1: Panels A and B depict the luminaire arrangement. Panel C depicts the spectral power distributions of the three light settings. Panel D presents the timestamped study protocol.

Table 2 presents α-opic melanopic equivalent daylight illuminances (melanopic EDI), and melanopic daylight efficacy ratio (MDER) values both at the desk (80 cm) and eye level (120 cm) for the three light conditions: (a) high MDER light settings: 0.85 MDER, 210.93 MEDI, 6381 K; (b) neutral MDER light settings: 0.6 MDER, 156.09 MEDI, 3875 K; and (c) low MDER light settings: 0.43 MDER, 90.57 MEDI, 2648 K. The photopic lx of three light settings was kept at ~250 lx in the horizontal plane (mean=238; SD=±27.4) and ~130 lx in the vertical plane (mean=128.45; SD=±13.11). Each experimental session started with a 30-minute adaption period, during which the MDER was 0.60 with 250 photopic lx in the horizontal plane (79.23 μW/cm) and 139 photopic lx (42.79 μW/cm) in the vertical plane. The α-opic values and MDER values are obtained using Loux software (Spitschan et al., 2021) and CIE S 026:2018 toolbox (Schlangen, 2018) following the CIE S 026 guidelines (CIE, 2018).

Table 2. α-opic EDI and MDER values of the three light conditions.

|  |  |  |  |  |  |  |  |  |  |
| --- | --- | --- | --- | --- | --- | --- | --- | --- | --- |
| **Horizontal plane (measured at desk level: .80m)** | | | | | | | | | |
| Light Condition | Photopic lx | Irradiance (μW/cm2) | α- opic Equivalent Daylight (D65) Illuminance (lx) | | | | | MDER | CCT (K) |
| S cone | Melanopsin | Rod | M Cone | L Cone |
| High MDER | 247.17 | 81.16 | 242.09 | 210.93 | 221.15 | 239.49 | 243.22 | 0.85 | 6381 |
| Neutral MDER | 259.82 | 79.23 | 137.75 | 156.09 | 174.23 | 226.870257 | 259.43 | 0.60 | 3875 |
| Low MDER | 207.38 | 63.48 | 50.85 | 90.57 | 108.8808562 | 161.9572833 | 211.8043125 | 0.43 | 2648 |
| **Vertical plane (measured at Eye level: 1.2m)** | | | | | | | | | |
| Light Condition | Photopic lx | Irradiance (μW/cm2) | α- opic Equivalent Daylight (D65) Illuminance (lx) | | | | | MDER | CCT (K) |
| S cone | Melanopsin | Rod | M Cone | L Cone |
| High MDER | 131.83 | 43.37 | 125.21 | 110.723337 | 116.40 | 127.00 | 129.83 | 0.84 | 6164 |
| Neutral MDER | 139.53 | 42.73 | 71.68 | 82.62 | 92.47 | 121.15 | 139.49 | 0.60 | 3788 |
| Low MDER | 113.98 | 35.22 | 27.23 | 49.20 | 59.26 | 88.52 | 139.49 | 0.43 | 2606 |

## Study Protocol

The study obtained ethics clearance from the Monash University Human Research Ethics Committee (Project ID: 14786), and written informed consent was collected from all participants. Participation was purely voluntary, and a reward of RM40 was provided upon completion of the study. Participants were asked not to ingest any caffeine or alcohol during the experiment day. Figure 1-D depicts the experimental protocol followed in this study. Each participant spent approximately two hours in our lab in a time-cue-free environment (all doors and windows covered with blinds, no watches, internet, mobile, TV, newspaper and radio). Each session started with an adaption period of 30 minutes, where participants participated in a practice block to familiarize themselves with the cognitive tests. After the adaption period, participants were randomly exposed to one of the three light conditions. Throughout the two-hour protocol, participants remained seated at their desks. Exercising and napping were not allowed. Participants took part in a series of cognitive tests in the following order: aPVT, N-back test, digit span, and Tower of London test. Subjective measures of sleepiness were recorded at the protocol's beginning and end.

## Data analysis

We used R (Team, 2022) for all our analyses using packages including psych (Revelle, 2021), tabledown (Siraji, 2022), and WRS2 (Mair & Wilcox, 2020). Classical ANOVA methods assume normality and homoscedasticity, and any violation of these assumptions raises serious practical concerns. Hence, we used a 10% trimmed mean based robust one-way and/or factorial ANOVA, which were less prone to these assumption violations and outliers (Mair & Wilcox, 2020).

We calculated ΔKSS (ΔKSS = KSS score at the beginning of the light exposure- KSS Score at the end of the light exposure) to assess the influence of light on subjective alertness. In aPVT, we calculated the mean 10% fastest reaction time, attentional laps (reaction time >500 ms), and general reaction time. To assess short-term memory span, we calculated the number of digits correctly recalled in the digit span task. For the ToL task, we calculated execution time (time elapsed to attain the goal state), efficiency (total number of moves-number of the optimal number of moves) and planning time (time elapsed to plan the moves). We investigated the influence of light on these outcomes using a robust one-way ANOVA. “t1way” function from the package “WRS2” (Mair & Wilcox, 2020) was used to conduct the robust one-way ANOVA.

We calculated general accuracy, hit ratio, false alarm, sensitivity index (), and bias (c) for the n-back task. The equations are provided in *Supplementary file 1*. We investigated the main and interaction effects of light conditions, time and task complexity on the n-back performances using robust factorial ANOVA. “bwtrim” functions from the package “WRS2” (Mair & Wilcox, 2020) were used to conduct the robust factorial ANOVA respectively.

We reported as the explanatory measure of the effect size where 0.10, 0.30, and 0.50 correspond to small, medium and large effect sizes. The confidence interval of the effect size was estimated using 1000 bootstrap samples (Wilcox & Tian, 2011). In the case of significant *F* statistics, we conducted robust pairwise post-hoc tests to compare the three light conditions using the “lincon” function with Bonferroni correction from the WRS2 package.

# Results

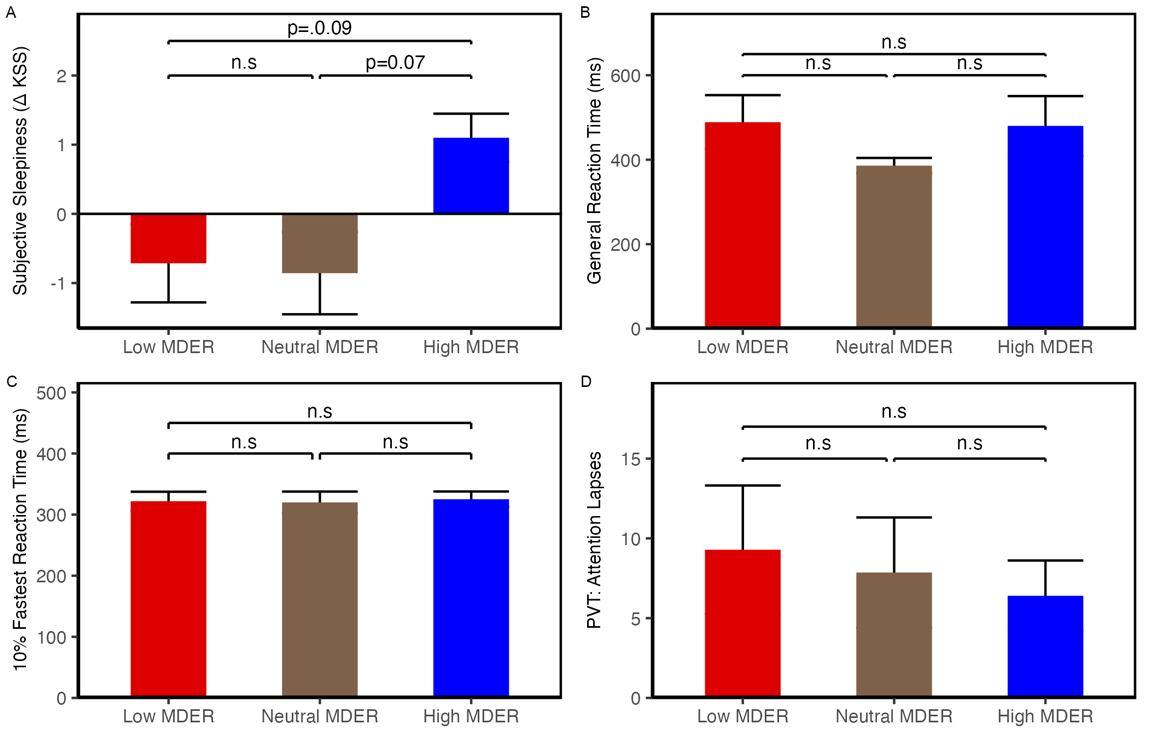
## Alerting effects

Table 3 presents the ANOVA results on the performance outcome. We observed a significant difference in subjective sleepiness across the three light settings [*F(2,11.7)=*4.85, *p*=0.03, = 0.69 (CI: 0.42-1.04); Figure 2-A]. Post-hoc tests revealed that there was a trend of decreased subjective sleepiness (beginning of the protocol vs. end of the protocol) in high MDER conditions compared to low MDER ( =–1.71; *p*=0.09) and neutral MDER ( =–1.86; *p*=0.07) light conditions. No significant difference between the low MDER and neutral MDER light conditions was observed (*p*=1.0).

Table 3. *MEAN, SEM and ANOVA test results*

|  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |
| --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- |
| Performance outcomes | | | | **High** | | **Neutral** | | | | **Low** | | | **ANOVA Statistics** | | | | | | | |
| **Mean±SEM** | | **Mean±SEM** | | | | **Mean±SEM** | | | **F** | | | **p** | |  | | **Categorization** |
| ΔKSS | | | | 1.1±0.35 | | -0.86±0.60 | | | | -0.71±.057 | | | 4.85 | | | 0.03 | | 0.69 | | Large |
| **Auditory Psychomotor Vigilance Task (aPVT)** | | | | | | | | | | | | | | | | | | | |  |
| Reaction time (ms) | | | | 480±64.1 | | 386±18.3 | | | | 489±64.1 | | | 1.29 | | | 0.32 | | 0.54 | | Large |
| Attentional failures | | | | 6.4±2.21 | | 7.86±3.45 | | | | 9.29±4.03 | | | 0.49 | | | 0.63 | | 0.34 | | Medium |
| 10% fastest reaction time (ms) | | | | 0.33±0.01 | | 0.32±0.02 | | | | 0.32±0.02 | | | 0.09 | | | 0.91 | | 0.29 | | Small |
| **Digit Span Task** | | | | | | | | | | | | | | | | | | | | |
| Forward Digit Span | | | | 7.3±0.52 | | 7.57±0.43 | | | | 6±0.31 | | | 4.99 | | | 0.03 | | 0.59 | | Large |
| Backward Digit Span | | | | 4.9±0.46 | | 5.14±0.55 | | | | 5.14±0.34 | | | 0.33 | | | 0.72 | | 0.37 | | Medium |
| Sequential Digit Span | | | | 6.50±0.43 | | 6.43±0.57 | | | | 5.86±0.34 | | | 0.54 | | | 0.60 | | 0.41 | | Medium |
| **Tower of London Tasks** | | | | | | | | | | | | | | | | | | | |  |
| Execution | | | | 24.8±3.08 | | 30±3.27 | | | | 19.1±1.74 | | | 4.38 | | | 0.04 | | 0.59 | | Large |
| Efficiency | | | | 2.10±0.29 | | 1.85±0.32 | | | | 1.90±0.69 | | | 0.11 | | | 0.90 | | 0.31 | | Medium |
| Planning | | | | 9.23±2.24 | | 14±3.96 | | | | 8.22±1.72 | | | 1.20 | | | 0.34 | | 0.48 | | Medium |
| **N-Back Task** | | | | | | | | | | | | | | | | | | | |  |
| Reaction time (ms) | | | | 1034±60.8 | | 1053±62.7 | | | | 906±64.7 | | | 2.90 | | | 0.10 | | 0.41 | | Medium |
| Accuracy | | | | 83.4±3.55 | | 87.8±3.33 | | | | 82.3±4.90 | | | 1.24 | | | 0.35 | | 0.14 | | Small |
| Hit ratio | | | | 0.72±0.06 | | 0.80±05 | | | | 0.80±0.04 | | | 2.82 | | | 0.13 | | 0.13 | | Small |
| False alarm | | | | 0.11±0.03 | | 0.08±0.02 | | | | 0.16±0.05 | | | 1.28 | | | 0.35 | | 0.24 | | Small |
|  | | | | 1.96±0.30 | | 2.12±0.32 | | | | 1.98±0.36 | | | 1.25 | | | 0.41 | | 0.08 | | Negligible |
| c | | | | 0.39±.07 | | 0.32±0.04 | | | | 0.12±0.05 | | | 3.58 | | | 0.17 | | 0.14 | | Small |
| **Interaction Effect of Light and task complexity** | | | | | | | | | | | | | | | | | | | |  |
|  | **High** | | | | **Neutral** | | | | **Low** | | | | | | **ANOVA Statistics** | | | | | |
| Performance outcomes | **Easy**  **Mean±SEM** | **Difficult**  **Mean±SEM** | | | **Easy**  **Mean±SEM** | | **Difficult**  **Mean±SEM** | | **Easy**  **Mean±SEM** | | | **Difficult**  **Mean±SEM** | | | **F** | | **p** | |  | **Categorization** |
| Reaction time (ms) | 791±33.6 | 1252±50.9 | | | 860±51 | | 1246±45.2 | | 771±66.1 | | | 1040±88 | | | 1.46 | | 0.28 | | 0.41 | Medium |
| Accuracy | 95±1 | 72.9±4.88 | | | 97±0.93 | | 78.6±4.35 | | 94.6±1.50 | | | 70.0±7.17 | | | 0.32 | | 0.74 | | 0.14 | Small |
| Hit ratio | 0.92±0.01 | 0.53±0.07 | | | 0.93±0.02 | | 0.68±0.08 | | 0.92±0.02 | | | 0.68±0.06 | | | 2.24 | | 0.18 | | 0.03 | Negligible |
| False alarm | 0.03±0.01 | 0.17±0.05 | | | 0.008±0.01 | | 0.16±0.03 | | 0.04±0.01 | | | 0.29±0.08 | | | 1.28 | | 0.59 | | 0.24 | Small |
|  | 3.04±0.14 | 1.30±0.41 | | | 3.34±1.59 | | 1.59±0.39 | | 2.98±0.19 | | | 1.27±.50 | | | 0.03 | | 0.97 | | 0.08 | Negligible |
| c | 0.25±0.04 | 0.48±.11 | | | 0.37±.03 | | 0.30±0.07 | | 0.17±0.05 | | | 0.08±0.09 | | | 1.14 | | 0.38 | | 0.71 | Large |
| **Main Effect of Task Complexity of N-back performance** | | | | | | | | | | | | | | | | | | | |  |
|  | | | **Easy (1-back)** | | | | | **Difficult (3-Back)** | | | ANOVA Statistics | | | | | | | | | |
| Performance outcomes | | | **Mean±SEM** | | | | | **Mean±SEM** | | | F | | | p | | |  | | | **Categorization** |
| Reaction time (ms) | | | 806±28 | | | | | 1118±39.59 | | | 45.71 | | | <0.001 | | | 0.88 | | | Large |
| Accuracy | | | 95.5±0.67 | | | | | 73.7±3.12 | | | 44.43 | | | <0.001 | | | 0.94 | | | Large |
| Hit ratio | | | 0.92±0.01 | | | | | 0.62±0.04 | | | 2.24 | | | 0.18 | | | 0.03 | | | Negligible |
| False alarm | | | 0.03±0.01 | | | | | 0.20±0.03 | | | 0.59 | | | 0.58 | | | 0.24 | | | Small |
|  | | | 3.09±0.09 | | | | | 1.38±0.24 | | | 0.03 | | | 0.97 | | | 0.08 | | | Negligible |
| c | | | 0.24±0.03 | | | | | 0.31±0.06 | | | 1.41 | | | 0.38 | | | 0.70 | | | Large |

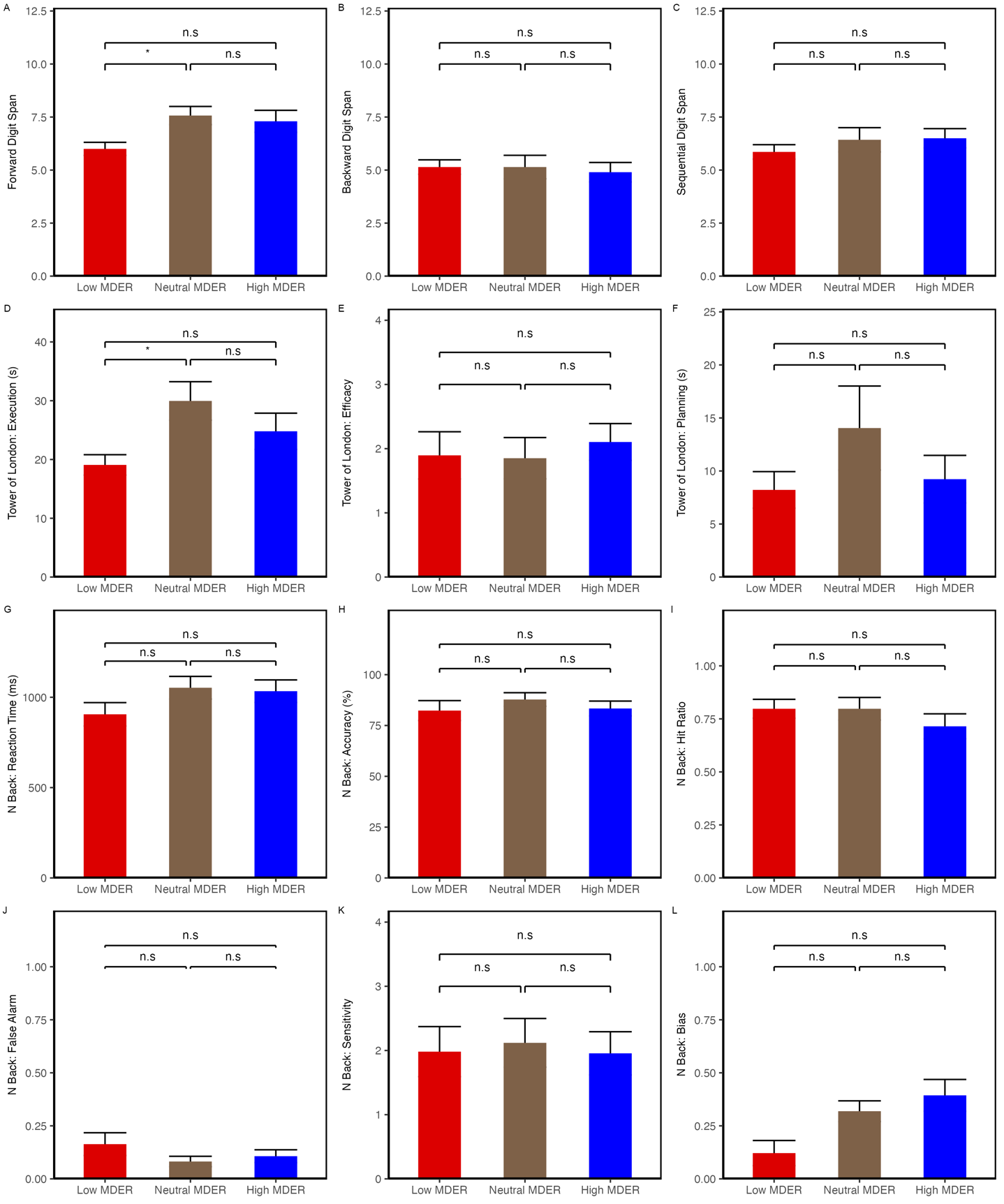
However, we did not observe any significant effect of light conditions on general reaction time [*F(2,10.1)=*1.29, *p*=0.32, = 0.54 (CI: 0.21-1; Figure 2-B)], attention lapses [*F(2,10.99)*=0.49, *p*=0.63, = 0.34 (CI: 0.07-0.73); Figure 2-C], and 10% fastest reaction time [F*(2,12.21)*=0.09, *p*=0.91, = 0.29 (CI: 0.06-0.66); Figure 2-D] in aPVT task.



*Figure* *2.*  Panel A-D depicts the one-way ANOVA results comparing the light conditions’ effect on (A) subjective sleepiness, (B) general reaction time, (C) attention lapses and (D) 10% fastest reaction time. Each bar represents the mean ± standard error of measurements.

## Working Memory and Executive Functioning

We observed a significant difference in forward digit span across the three light settings [*F(2,12.14)*=4.99, *p*=0.03, =0.59 (CI: 0.34-0.82); Figure 3-A]. Post-hoc tests revealed that participants had significantly higher memory span in the neutral MDER condition compared to the low MDER light condition (=-1.57, *p*=0.04). No other pair-wise comparison in the forward digit span was significant. We did not observe any significant differences in backward [*F*(2,12.11)=0.33, *p*=0.72, = 0.37 (CI: 0.07-0.88); Figure 3-B] and sequential digit span task performance [*F*(2,12.05)=0.54, *p*=0.60, = 0.41 (CI: 0.1-0.74); Figure 3-C].



*Figure* *3.*  ANOVA results comparing the light conditions’ effect on digit span (A-C), tower of London (D-F), and n-back (G-L) task. Each bar represents the mean ± standard error of measurements.

In the ToL task, we observed a significant effect of light condition on execution time [*F(2,11.47)*=4.38, *p*=0.04, = 0.59 (CI: 0.31-0.85); Figure 3-D]. Participants under the low MDER light condition had significantly faster execution time than participants under the neutral MDER light condition (=-10.89, *p*=0.04). We did not observe any significant influence of light on efficiency [*F*(2,12.56)=0.11, *p*=0.90, = 0.31 (CI: 0.06-0.68; Figure 3-E)] and planning time [*F*(2,10.57)=1.20, *p*=0.34, = 0.48 (CI: 0.16-1.04); Figure 3-F] in the ToL task.

In the N-back task, we observed a significant main effect of task difficulty where participants had significantly faster reaction time [*F*(1,11.76)=45.71, *p*<0.001, = 0.88 (CI: 0.78-0.98)] and higher accuracy [*F*(1,6.72)=44.43, *p*<0.001, = 0.94 (CI: 0.75-0.99)] in the easy blocks (one back) compared to difficult blocks (two-blocks). However, we did not observe any significant effect of light condition on reaction time [*F*(2,9.26)=2.90, *p*=0.10, = 0.41 (CI: 0-0.79); Figure 3-G], accuracy [*F*(2,6.11)=1.24, *p*=0.35, = 0.14 (CI: 0-0.68); Figure 3-H], hit ratio [*F*(2,7.05)=2.82, *p*=0.13, = 0.13 (CI: 0-0.60); Figure 3-I], false alarm [*F*(2,5.7)=1.28, *p*=0.35, = 0.24 (CI: 0-0.81); Figure 3-J], sensitivity [*F*(2,2.91)=1.22, *p*=0.41, = 0.08 (CI: 0-0.61); Figure 3-K], bias [*F*(2,2.67)=3.68, *p*=0.17, = 0.14 (CI: 0-0.68); Figure 3-L].

Further, we observed no significant interaction effect of light condition and task complexity on N back reaction time [*F*(2,9.25)=1.46, *p*=0.28, = 0.41 (CI: CI: 0-0.79)] and accuracy [*F*(2,6.11)=0.32, *p*=0.74, = 0.14 (CI: 0-0.68)], hit ratio [*F*(2,7.05)=2.24, *p*=0.18, = 0.03 (CI: 0-0.56)], false alarm [*F*(2,5.7)=1.28, *p*=0.59, = 0.24 (CI: 0-0.78)], sensitivity [*F*(2,2.91)=0.03, *p*=0.97, = 0.08 (CI: 0-0.55)], bias [*F*(2,2.67)=1.41, p=0.38, = 0.71 (CI: 0.18-0.91)].

# Discussion

We investigated the effect of daytime light exposure varying in short-wavelength enrichment with approximately equal photopic lux on alertness and cognitive performance. Results indicated a trend of reduced sleepiness under short-wavelength-enriched light exposure. However, we observed that the beneficial influence of light exposure on cognitive performance was cognitive domain dependent. More specifically, exposure to neutral MDER light conditions led to a higher memory span in the forward-digit span task. In contrast, exposure to low MDER light condition led to a faster execution time in the tower of London task.

Our findings on the light’s alerting effect align with the literature. Previously, several studies have reported reduced subjective sleepiness under short-wavelength dominant light exposure. Grant et al. (2021) reported that short-wavelength-enriched light exposure (MDER=0.76) reduced sleep-restricted students’ subjective sleepiness in comparison to conventional light exposure (MDER=0.48). However, their study's photopic lux (50 lx) was below the illuminances required for typical daytime office or indoor activities (CIE, 2002; IES, 2018; Malaysian Standard, 2014). The current study provides additional evidence that short-wavelength-enrichment has the potential to reduce daytime subjective sleepiness when incorporated in light environments that respect the illuminance guidelines.

In the current study, although we have matched the photopic illuminances for the three light conditions, they had differences in their spectral power distribution, which might lead to differences in visual perceptions in the three light conditions. Hence, we used an acoustic version of the psychomotor visual test (aPVT) to control for the non-specific impacts caused due to visual perception processes. We did not observe any significant influence of short-wavelength dominance on aPVT outcomes. Similar results were also reported in previous studies, where no significant influence of short-wavelength-dominance on aPVT was reported (Lok et al., 2022; Rahman et al., 2014; Segal et al., 2016). However, a few studies reported a beneficial influence of short-wavelength-dominance on visual PVT performances (Burattini et al., 2019; Rodriguez-Morilla et al., 2018). However, these studies used dim light conditions (<10 lx) as their comparison group. It might be possible that light’s alerting effect measured using visual PVT tasks is dependent on short-wavelength dominance and illuminances. Lok, Woelders, et al. (2018) indicated a possible saturation of light-induced alertness at a light intensity of 75 lx. However, Grant et al. (2021), while comparing the influence of short-wavelength-dominance on visual PVT performances, kept the photopic illuminances of all light conditions fixed (50 lx) and reported no beneficial influence on visual PVT, indicating that the possible saturation point might be even lower. It is possible and rationale to assume that such a saturation point might exist for the light’s influence on aPVT task performances. However, further in-depth studies are required to understand this relationship.

Further, we aimed to investigate whether the beneficial influence of light on cognitive performance was cognitive domain and task complexity dependent. We employed a comprehensive cognitive battery that utilized visual (Tower of London) and auditory (Digit span task, N-back task) modalities to assess working memory and executive functioning. The n-back task had two variations based on task complexity: one-back (easy) and three-back (difficult). In the N-back task, we observed a significant effect of task complexity, as expected. Performance was better in the easy variation (one-back) than the difficulty variation (three-back). However, no significant effect of light conditions and interaction of light conditions and task complexity was observed in N-back task performances.

Interestingly, we observed an increased performance in the forward digit span in the neutral MDER light condition compared to the low light condition with a large effect size. Further, faster execution time in the tower of London tasks was observed under low MDER light (short-wavelength-depleted) light condition. We did not observe any significant influence of light on backward and sequential digit span task performance and efficiency and planning time in the tower of London task. Altogether, based on these results, it is safe to confer that the beneficial influence of daytime electric light exposure is cognitive domain-specific, and each domain requires a separate investigation to quantify the beneficial influence of light.

Collectively our results partially supported our first hypothesis (H1), where we observed that short-wavelength-enriched white light exposure improved subjective alertness but had no influence on objective alertness. In our second hypothesis (H2), we assumed that the beneficial influence of short-wavelength-enriched light exposure on cognitive performance would be cognitive domain-specific. Our results supported this hypothesis where we observed differential improvement in task performance based on the cognitive task used. However, our third hypothesis (H3) was not supported, as we observed no significant interaction between light conditions and task complexity on task performance.

## Limitations

First, due to the sample size, this study deviates from satisfactory statistical power. However, the significant effects of light exposure on alertness and cognitive performance reported here had a large effect size (>0.50), thus providing more confidence in the conclusion drawn from this study. Second, the present study's sample is female-dominant, which poses a potential challenge to generalizing our findings. Third, no prior sleep schedule was imposed to synchronize the participant’s circadian rhythm to rule out the influence of possible differences in circadian rhythm on alertness and cognitive performances.

# Conclusion

Daytime short-wavelength-enriched white light exposure improved alertness. More studies are strongly required to identify the illuminance range of possible saturation of the alerting effects of daytime electric light exposure. Further research is necessary targeting specific cognitive domains to quantify these influences.

# References

Åkerstedt, T., & Gillberg, M. (1990). Subjective and objective sleepiness in the active individual. *International Journal of Neuroscience*, *52*(1-2), 29-37.

Alkozei., Smith, R., Pisner, D. A., Vanuk, J. R., Berryhill, S. M., Fridman, A., Shane, B. R., Knight, S. A., & Killgore, W. D. S. (2016). Exposure to blue light increases subsequent functional activation of the prefrontal cortex during performance of a working memory task. *Sleep*, *39*(9), 1671-1680. <https://doi.org/10.5665/sleep.6090>

Askaripoor, T., Motamedzade, M., Golmohammadi, R., Farhadian, M., Babamiri, M., & Samavati, M. (2019). Effects of light intervention on alertness and mental performance during the post-lunch dip: A multi-measure study. *Industrial Health*, *57*(4), 511-524. <https://doi.org/10.2486/indhealth.2018-0030>

Berson, D. M., Dunn, F. A., & Takao, M. (2002). Phototransduction by retinal ganglion cells that set the circadian clock. *Science (New York, N.Y.)*, *295*(5557), 1070-1073.

Brown, T. M., Brainard, G. C., Cajochen, C., Czeisler, C. A., Hanifin, J. P., Lockley, S. W., Lucas, R. J., Münch, M., O’Hagan, J. B., Peirson, S. N., Price, L. L. A., Roenneberg, T., Schlangen, L. J. M., Skene, D. J., Spitschan, M., Vetter, C., Zee, P. C., & Wright, K. P., Jr. (2022). Recommendations for daytime, evening, and nighttime indoor light exposure to best support physiology, sleep, and wakefulness in healthy adults. *PLoS Biology*, *20*(3), e3001571. <https://doi.org/10.1371/journal.pbio.3001571>

Burattini, C., Piccardi, L., Curcio, G., Ferlazzo, F., Giannini, A. M., & Bisegna, F. (2019). Cold LED lighting affects visual but not acoustic vigilance. *Building and Environment*, *151*, 148. <https://doi.org/http://dx.doi.org/10.1016/j.buildenv.2019.01.022>

Cajochen, C., Freyburger, M., Basishvili, T., Garbazza, C., Rudzik, F., Renz, C., Kobayashi, K., Shirakawa, Y., Stefani, O., & Weibel, J. (2019). Effect of daylight LED on visual comfort, melatonin, mood, waking performance and sleep. *Lighting Research & Technology*, *51*(7), 1044-1062.

Cajochen, C., Munch, M., Kobialka, S., Krauchi, K., Steiner, R., Oelhafen, P., Orgul, S., & Wirz-Justice, A. (2005). High sensitivity of human melatonin, alertness, thermoregulation, and heart rate to short wavelength light. *Journal of Clinical Endocrinology & Metabolism*, *90*(3), 1311-1316.

Cajochen, C., Stefani, O., Schöllhorn, I., Lang, D., & Chellappa, S. L. (2022). Influence of evening light exposure on polysomnographically assessed night-time sleep: A systematic review with meta-analysis. *Lighting Research & Technology*, 14771535221078765.

Chellappa, S. L., Steiner, R., Blattner, P., Oelhafen, P., Götz, T., & Cajochen, C. (2011). Non-Visual Effects of Light on Melatonin, Alertness and Cognitive Performance: Can Blue-Enriched Light Keep Us Alert? *PLoS One*, *6*(1). <https://doi.org/http://dx.doi.org/10.1371/journal.pone.0016429>

CIE. (2002). *LIGHTING OF WORK PLACES - PART 1: INDOOR*.

CIE. (2018). *CIE international Standard (CIE S 026/E:2018) "System for Metrology of Optical Radiation for ipRGC-Influenced Responses to Light"*. <http://www.cie.co.at/publications/international-standards>

Clark, J. (1924). The Ishihara test for color blindness. *American Journal of Physiological Optics*.

DOSH. (2018). *Guidlines on OSH for Lighting at Workplace*.

Grant, L. K., Kent, B. A., Mayer, M. D., Stickgold, R., Lockley, S. W., & Rahman, S. A. (2021). Daytime exposure to short wavelength-enriched light improves cognitive performance in sleep-restricted college-aged adults. *Frontiers in neurology*, 197.

Hankins, M. W., & Lucas, R. J. (2002). The primary visual pathway in humans is regulated according to long-term light exposure through the action of a nonclassical photopigment. *Current Biology*, *12*(3), 191-198.

Huiberts, L. M., Smolders, K., & De Kort, Y. A. W. (2015). Shining light on memory: Effects of bright light on working memory performance. *Behavioural Brain Research*, *294*, 234-245.

IES. (2018). Light and Human Health: An Overview of the Impact of Optical Radiation on Visual, Circadian, Neuroendocrine and Neurobehavioral Responses.

Jonathan, D. C., William, M. P., Todd, S. B., Leigh, E. N., Douglas, C. N., John, J., & Edward, E. S. (1997). Temporal dynamics of brain activation during a working memory task. *Nature*, *386*(6625), 604. <https://doi.org/10.1038/386604a0>

Leichtfried, V., Hanser, F., Griesmacher, A., Canazei, M., & Schobersberger, W. (2016). Brief morning light exposure, Visuomotor performance, and biochemistry in sport shooters. *Int J Sports Physiol Perform*, *11*(6), 756-762. <https://doi.org/10.1123/ijspp.2015-0553>

Lockley, S. W. (2008). Spectral sensitivity of circadian, neuroendocrine and neurobehavioral effects of light. *Journal of the Human-Environment System*, *11*(1), 43-49.

Lockley, S. W., Evans, E. E., Scheer, F. A. J. L., Brainard, G. C., Czeisler, C. A., & Aeschbach, D. (2006). Short-wavelength sensitivity for the direct effects of light on alertness, vigilance, and the waking electroencephalogram in humans. *Sleep*, *29*(2), 161-168.

Lok, R., Joyce, D. S., & Zeitzer, J. M. (2022). Impact of daytime spectral tuning on cognitive function. *Journal of Photochemistry and Photobiology B: Biology*, *230*, 112439.

Lok, R., Smolders, K., C. H. J., Beersma Domien, G. M., & de Kort Yvonne, A. W. (2018). Light, Alertness, and Alerting Effects of White Light: A Literature Overview. *Journal of Biological Rhythms*, *33*(6), 589-601. <https://doi.org/http://dx.doi.org/10.1177/0748730418796443>

Lok, R., Woelders, T., Gordijn, M. C. M., Hut, R. A., & Beersma, D. G. M. (2018). White Light During Daytime Does Not Improve Alertness in Well-rested Individuals. *Journal of Biological Rhythms*, *33*(6), 637-648.

Mair, P., & Wilcox, R. (2020). Robust statistical methods in R using the WRS2 package. *Behav Res Methods*, *52*(2), 464-488. <https://doi.org/10.3758/s13428-019-01246-w>

Mills, P. R., Tomkins, S. C., & Schlangen, L. J. (2007). The effect of high correlated colour temperature office lighting on employee wellbeing and work performance. *J Circadian Rhythms*, *5*, 2. <https://doi.org/10.1186/1740-3391-5-2>

Rahman, S. A., Flynn-Evans, E. E., Aeschbach, D., Brainard, G. C., Czeisler, C. A., & Lockley, S. W. (2014). Diurnal spectral sensitivity of the acute alerting effects of light. *Sleep*, *37*(2), 271-281.

Revelle, W. (2021). psych: Procedures for Psychological, Psychometric, and Personality Research.

Rodriguez-Morilla, B., Madrid, J. A., Molina, E., Perez-Navarro, J., & Correa, A. (2018). Blue-Enriched Light Enhances Alertness but Impairs Accurate Performance in Evening Chronotypes Driving in the Morning. *Front Psychol*, *9*, 688. <https://doi.org/10.3389/fpsyg.2018.00688>

Schlangen, L. (2018). CIE international Standard (CIE S 026/E:2018) "System for Metrology of Optical Radiation for ipRGC-Influenced Responses to Light" <http://www.cie.co.at/publications/international-standards>.

Segal, A. Y., Sletten, T. L., Flynn-Evans, E. E., Lockley, S. W., & Rajaratnam, S. M. W. (2016). Daytime Exposure to Short- and Medium-Wavelength Light Did Not Improve Alertness and Neurobehavioral Performance. *Journal of Biological Rhythms*, *31*(5), 470-482. <https://doi.org/10.1177/0748730416659953>

Siraji, M. (2022). Tabledown: Create Publication Quality Tables and Plots.

Siraji, M. A., Kalavally, V., Schaefer, A., & Haque, S. (2022). Effects of daytime electric light exposure on human alertness and higher cognitive functions: A systematic review. *Frontiers in psychology*, *12*, 765750-765750.

Smolders, K. C. H. J., & de Kort, Y. A. (2017). Investigating daytime effects of correlated colour temperature on experiences, performance, and arousal. *Journal of environmental psychology*, *50*, 80-93. <https://doi.org/10.1016/j.jenvp.2017.02.001>

Smolders, K. C. H. J., & de Kort, Y. A. W. (2014). Bright light and mental fatigue: Effects on alertness, vitality, performance and physiological arousal. *Journal of environmental psychology*, *39*, 77-91. <https://doi.org/http://dx.doi.org/10.1016/j.jenvp.2013.12.010>

Smolders, K. C. H. J., De Kort, Y. A. W., & Cluitmans, P. J. M. (2012). A higher illuminance induces alertness even during office hours: findings on subjective measures, task performance and heart rate measures. *Physiology & Behavior*, *107*(1), 7-16.

Spitschan, M. (2019). Melanopsin contributions to non-visual and visual function. *Current opinion in behavioral sciences*, *30*, 67-72.

Spitschan, M., Mead, J., Roos, C., Lowis, C., Griffiths, B., Mucur, P., & Herf, M. (2021). luox: novel validated open-access and open-source web platform for calculating and sharing physiologically relevant quantities for light and lighting. *Wellcome open research*, *6*, 1-12. <https://doi.org/10.12688/wellcomeopenres.16595.2>

Standard, M. (2014). *MALAYSIAN STANDARD :Energy efficiency and use of renewable energy for non residential buildings - Code of practice*

Team, R. C. (2022). R: A Language and Environment for Statistical Computing.

Viola, A. U., James, L. M., Schlangen, L. J. M., & Dijk, D.-J. (2008). Blue-enriched White Light in the Workplace Improves self-reported Alertness, Performance and Sleep Quality. *Scandinavian Journal of Work, Environment & Health*, *34*(4), 297-306. <https://doi.org/10.5271/sjweh.1268>

Wilcox, R. R., & Tian, T. S. (2011). Measuring effect size: a robust heteroscedastic approach for two or more groups. *Journal of applied statistics*, *38*(7), 1359-1368. <https://doi.org/10.1080/02664763.2010.498507>