IDEA

Innovations Deserving Exploratory Analysis Programs

Rail Safety IDEA Program

Using Light to Reduce Fatigue and Improve Alertness in Railway Operations

Final Report for
Rail Safety IDEA Project 40

Prepared by:
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Using Light to Reduce Fatigue and Improve Alertness in Railway Operations

IDEA Program Final Report

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Glossary

CCT	Correlated color temperature
RCC	Rail Control Center
E_V	Vertical illuminance (i.e., on the vertical plane at eye level)
EEG	Electroencephalogram
EOG	Electrooculogram
GNG	Go/NoGo task performance test
HP	Hit Percent
KSS	Karolinska Sleepiness Scale
LMM	Linear mixed-effects model
LRC	Lighting Research Center
MCTQ	Munich Chronotype Questionnaire
NTSB	National Transportation Safety Board
PSQI	Pittsburgh Sleep Quality Index
PVT	Psychomotor Vigilance Task performance test
RT	Response time
TLA	Transportation Lighting Alliance
λ_{max}	Peak wavelength of energy emission

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Investigator Profile

Principal Investigator Dr. Mariana G. Figueiro has over 20 years of experience conducting research in the field of lighting. She has pioneered the study of the health effects of light, including groundbreaking work in the area of lighting and circadian entrainment. She is currently leading research funded by the National Institutes of Health studying the effects of lighting on health, depression, sleep quality, and alertness. She is also working with the Office of Naval Research studying the effects of lighting on alertness and circadian entrainment on war fighters and submariners. Dr. Figueiro has served as principal investigator on over $20 million dollars of sponsored research, successfully managing both laboratory and field studies. Dr. Figueiro holds a bachelor's in architectural engineering from the Federal University of Minas Gerais, Brazil, and a master's in lighting and a doctorate in multidisciplinary science from Rensselaer. Her master's and Ph.D. dissertation research focused on the human circadian response to light. Dr. Figueiro is the recipient of the 2007 NYSTAR James D. Watson Award, the 2008 Office of Naval Research Young Investigator Award, and the 2010 Rensselaer James M. Tien '66 Early Career Award. In 2013 she was elected Fellow of the Illuminating Engineering Society. She is the author of more than 80 scientific articles in her field of research.

Co-Principal Investigator Dr. Levent Sahin is a senior lighting scientist at the Lighting Research Center at Rensselaer Polytechnic Institute and focuses his research in the area of the alerting effects of light. He holds a bachelor's degree in engineering, a master's degree in industrial product design, and Ph.D. in architectural sciences with a concentration in lighting. Prior to joining the LRC, Dr. Sahin worked for 17 years as a design engineer for Metro Istanbul Co., the only railway operator in Istanbul, Turkey. He first held roles in several design projects including heavy rail, mass transit, and monorail systems. He led the interior design phase of the first locally manufactured tramway vehicle renovation project for the city of Istanbul. He founded the department of lighting, simulation and visualization at Metro Istanbul and served as its manager, during which time he directed several lighting design and research projects for railway stations and facilities.

Executive Summary

With the advent and increasing prevalence of driverless train operation, dispatch centers are becoming more central to reliable and safe transportation worldwide. Dispatchers are, however, highly susceptible to the detrimental effects of sleepiness and related impairment of work performance. A novel approach to mitigate the effect of sleepiness on duty is the use of red light, which can elicit an acute alerting response from humans at any time of day or night.

The primary objective of this research project was to test and demonstrate the effectiveness and acceptability of combined red and white light for increasing acute alertness and improving performance in a simulated dispatch work environment laboratory study using objective (i.e., electroencephalography) and subjective (i.e., Karolinska Sleepiness Scale) measures of alertness and objective measures of short-term performance (i.e., auditory–visual performance testing).

We exposed 18 and 19 participants, respectively, during the daytime and nighttime to four lighting conditions: (1) white light, (2) red light, (3) combined (red + white) light, and (4) a dim control condition. The white light condition served to simulate the lighting characteristics observed in the NYC Rail Control Center (RCC). Our previous work demonstrated that red light, which does not suppress nocturnal melatonin production, can elicit a strong alerting effect on people. However, the use of red light in real life spaces, such as a dispatch center, would have to be in combination with white light in order to consolidate high visual performance. We hypothesized that, both during the day and at night, the combined condition would be less effective than red light only condition and more effective than dim light and white light only conditions.

The present results indicated that all lighting conditions, compared to a dim light condition, significantly increased objective alertness, demonstrating the efficacy of light's alerting effects irrespective of time of day. More specifically, the red and combined conditions significantly increased alertness during nighttime, where the effect of the white condition was not statistically significant. Participants' performance score (i.e., how fast they respond correctly) was significantly higher under combined condition than under white condition after 25 min of exposure. We also found a significant improvement in participants' hit percent (i.e., rate of correct responses) under the red condition during the performance test. The current findings also indicated that nighttime participants were significantly slower than daytime participants irrespective of lighting condition, suggesting a strong time-of-day effect on response times. Results of the lighting appraisal questionnaire evaluation revealed an agreement from both nighttime and daytime participants that the combined condition was visually more comfortable and more acceptable for performing office work compared to red condition alone.

The IDEA project demonstrated that the red and combined lighting conditions increased certain measures of alertness compared to dim condition. Except for the performance score variable, however, we did not find any significant differences between lighting conditions, suggesting that the red and combined light conditions were not always more effective than white light condition alone. It should be noted that the study ran in the early part of the night and that later the effect of the red and combine lights may have been greater in a typical night shift, close to the minimum core body temperature, when the sleep pressure is higher.

A noteworthy limitation of the current IDEA project is that participants followed a regular sleep schedule which required them go to sleep no later than 23:00 and wake up no later than 08:00. The main reason for keeping participants on a regular sleep schedule was to investigate the "acute effects" of the combined (i.e., red and white) light exposure on subjective and objective measures of alertness rather than its long-term effects (e.g., shifting the circadian rhythm's phase). However, future real-world application research projects should be conducted where dispatchers follow their regular shift schedules during the data collection periods.

The current IDEA project demonstrated that red light in combination with white light has a potential to be an effective countermeasure to increase alertness and performance in the workplace, without compromising the visual comfort of the occupant. We will work with our project partner, New York City Transit, to seek opportunities to test and demonstrate a prototype lighting system in an actual control center setting. We will also explore working with lighting manufacturers to develop simple, cost-effective lighting solutions that can be readily implemented in a variety of railway environments.

IDEA Product

Safety is the foremost quality indicator of any transportation system. Despite advances in technology, however, human error is estimated to be a causal or contributing factor in most accidents, in contexts ranging from nuclear power plants (45%) to road traffic (> 90%) (*2*). Acute or chronic sleep deprivation resulting in increased feelings of fatigue (*3*) is one of the leading causes of human error and accidents in the workplace, and carries broad social and economic impacts in terms of loss of life, liability, and property damage.

Several major concerns are pertinent to sleepiness and railroad safety.

- Railway operation is highly susceptible to the detrimental effects of sleepiness:
  - National Transportation Safety Board (NTSB) research indicates that railway staff performing safety-critical functions were often impaired by fatigue stemming from insufficient or poor-quality sleep, and cited fatigue as a probable cause in nearly 20% of accidents investigated between 2001 and 2012 (*4*).
  - Approximately 75% of all train accidents are attributable to fatigue-related human error (*5*) and drivers can experience difficulty staying awake (*6,7*).
- Sleepiness can negatively affect train drivers' performance:
  - Reduced alertness affects train drivers' ability to negotiate speed restrictions and perform proper braking (*8*).
  - Sleepy driving is associated with inefficient and unsafe operation, as shown by a group of high-fatigue train drivers tracked in a 2006 Australian study who used 9% more fuel and less throttle, engaged in heavier braking, and committed a greater number of maximum speed violations compared to low-fatigue drivers (*9*).
- Railway traffic controllers are also prone to fatigue:
  - Studies show that 61% of dispatchers report severe nighttime fatigue and 13% report fatigue-related impairment of nighttime work performance (*10*).
  - A recent study of 132 male control center workers in Portugal found that tasks such as reading graphic information, opening traffic signals, and assigning train passage priorities were affected by a high prevalence of sleepiness (*11*).
  - With the advent and increasing prevalence of automatic train operation systems (*12*), control staff are becoming more central to railway transportation worldwide. It is expected that by 2025, the global total length of automated metro lines will increase to over 1,430 miles from the current total distance of 500 miles (*12*).
- Efforts to mitigate the effect of sleepiness on safety have primarily been directed toward worker behavior and prevention, including napping (*13, 14*) and the use of caffeine while on duty to avoid sleepiness (15, 16).
  - Although naps are proven to be beneficial (*13, 14*), impaired performance and alertness upon waking (i.e., sleep inertia) (*17*) remain major concerns in real work settings.
  - Caffeine can indeed elicit an acute alerting response, but studies have observed that a temporary improvement was followed by excessive sleepiness and reduced sleep duration in subjects who received caffeine compared to those who received a placebo (*18*).

A novel alternative to napping and caffeine is the use of light, which can elicit an acute alerting response from humans at any time of day or night. Laboratory research conducted by the Lighting Research Center (LRC) at Rensselaer Polytechnic Institute has demonstrated that both short-wavelength (peak wavelength [λ_{max}] = 470 nm) "blue" light (*19*) and longer wavelength (λ_{max} = 630 nm) "red" light (*20*) administered in the middle of the night increased subjective and objective measures of alertness. Relevant to the current project, the objective measurements of light's acute alerting effect in those studies were obtained using electroencephalographic (EEG) recordings and auditory performance testing. In cognitive electrophysiological research, frequencies are grouped into spectral bands with distinct functional associations: theta (5–7 Hz), alpha-theta (5-9 Hz), alpha (8–12 Hz), and beta (13–30 Hz), where increased beta range and reduced theta, alpha-theta, and alpha ranges associate with increased alertness. In both studies, the EEG data showed a reduction in alpha power and an increase in beta power. A third nighttime study using the same protocol showed that compared to a dim-light light control condition, power in the alpha and alpha-theta ranges was significantly reduced by exposure to red light, and participants demonstrated significantly faster reaction times during performance testing after exposure to both red and white light (2568 K) (*21*).

Daytime studies have also demonstrated that red light administered during the mid-afternoon drop in alertness and performance known as the "post-lunch dip" decreased power in subjects' alpha, alpha theta, and theta brain activity., suggesting a strong alerting effect of red light during the afternoon hours (*22*). The results of the study also showed an effect of blue light on measures of alertness, but the effect was not as strong as with red light. A subsequent study further investigated the effects of red light and white light (2568 K) exposures on performance and alertness during the daytime, demonstrating for the first time that red light can improve short-term performance as shown by significantly reduced response times and higher throughput in performance testing (*23*). The findings also demonstrated significant reductions in power in the alpha and alpha-theta ranges after exposure to white light and a reduction in power in the alpha range after exposure to the red light.

A key aspect of the current project was the use of red light, which has been shown to promote acute alertness without suppressing the hormone melatonin, in combination with white light. Melatonin is an important regulator of sleep and circadian rhythms that has demonstrated oncostatic effects, and its chronic suppression has been linked to increased cancer risks in shift workers (*24, 25*). Short-wavelength "blue" light is maximally effective for stimulating the circadian system, and while receiving high levels of blue light early in the solar day can be helpful for promoting alertness and synchronizing circadian rhythms, exposure to the same light later in the day and into the evening can lead to circadian disruption and the development of chronic diseases.

Concept and Innovation

The results of our lab studies suggest that red light can be used to increase alertness during the day and night without increasing the risk for nocturnal melatonin suppression. However, in the context of train drivers and dispatchers, it is challenging to utilize only red light without compromising their visual performance (e.g., color discrimination on the dashboard of the train cabin or monitoring screens in the control center). Because of this challenge, the transportation industry, and railways in particular, have not fully benefitted from the acute alerting effects of red light. An effective way to cope with this challenge could be using the red in combination with the white light in dispatch centers. This innovative strategy, however, has not been tested in laboratory settings to date.

Here, we tested the effectiveness and the acceptability of combined red and white light (the combined condition) for increasing alertness and improving performance in a simulated work environment laboratory study. We hypothesized the combined light would be less effective than red light alone and more effective than dim condition and white light alone, both during the day and at night. If shown that combined condition was effective at increasing alertness during the day and night, finding could be of great interest for railway operations. Our study provides potential benefits that can be translated to support accident prevention strategies and policies that may help reduce the social and economic consequences of sleep-related accidents.

Investigation

Materials and Methods

Participants

We recruited 18 and 19 participants, respectively, for the daytime and nighttime experiments who met the following criteria: (1) no color blindness, as screened by the Ishihara for color blindness test (*26*), (2) no reports of head injury or neurological disease like epilepsy, seizures, migraines, or any other form of psychological disorder, (3) no reports of eye disease, eye surgery, or a history of eye injury or trauma, (4) not taking any type of daily medication, (5) neither extreme late (i.e., a score of 6) nor early (i.e., a score of zero) chronotypes according to their responses on the Munich Chronotype Questionnaire (MCTQ) (*27*), (6) no reports of sleep problems indicated by scores < 5 in Pittsburgh Sleep Quality Index (PSQI), and (7) no experience of shift work or travel across one or more time zones before or during the weeks of the experiment.

Participants were asked to abstain from alcohol and caffeine for 12 h before the start of the experimental sessions. They were also asked to maintain a regular sleep-wake schedule throughout the experiment, requiring bedtimes by 23:00 and wake times by 07:00, and refrain from napping on the day of the experiment. To verify compliance, the participants wore an actigraph (Actiwatch Spectrum Plus, Philips Respironics, Murrysville, PA) on their non-dominant wrist and maintained a sleep log beginning 1 week prior to their first session and continuing through to the end of the experiment.

Two participants had withdrawn from the study before data collection started. We excluded four participants from the study who failed to comply with the sleep schedule. We did not include their data in the analyses. Thus, we reported results for 15 (10 females) and 16 (8 females) participants, respectively, for the daytime and nighttime experiments. We provided participants' average age, PSQI, and MCTQ scores in Table 1.

Table 1. Participants' mean ± standard deviation (SD) age, PSQI, and MCTQ scores.

Time of day	Mean (SD) age	Mean (SD) PSQI scores	Mean (SD) MCTQ scores
Daytime	21.0 (2.2)	2.9 (0.8)	3.5 (0.8)
Nighttime	22.6 (9.3)	3.0 (0.8)	3.7 (0.9)

The study was conducted in accordance with the Declaration of Helsinki and was approved by the Institutional Review Board at Rensselaer Polytechnic Institute. There was minimal risk of harm to the participants, as no known safety risks are associated with the devices used in the study and all comply with federal regulations regarding electromagnetic and radio interference.

Lighting Conditions

We specified the experimental conditions based on the lighting specifications investigated during our site visit to the NYC Rail Control Center (RCC) as well as our previous daytime and nighttime studies (*21,22*). Our site measurements showed a mean ± standard deviation (SD) vertical illuminance (E_V) of 56 ± 24 lux at participants' eye level. Measurements also indicated a mean ± SD correlated color temperature (CCT) of 2857 ±209 K for the ceiling fixtures. Since the light was distributed from an indirect light source, its CCT appears to have been affected by light reflected from surrounding surfaces (e.g., walls, furniture). Taking the reflection into account, the measured CCT of 2818 K suggests that the specified CCT of the fluorescent lamps was 2700 K. Thus, the intervention for the present study consists of four lighting conditions: red (λ_{max} = 630 nm, mean E_V=50 lux), white (2700 K, mean E_V=50 lux), combined conditions where red and white utilized simultaneously (100 lux) and a dim condition (E_V<5 lux).

The white condition was designed to resemble the present lighting environment of the RCC, providing a mean E_V of 50 lux using 2700 K LED troffers (Evokit model, Philips, Andover, MA, USA). The light exposure in the red condition was delivered via RGB color-tunable linear recessed luminaires (L4R model, Ketra, Austin, TX, USA).

We employed four experimental conditions: (1) white light (E_V = 50 lux, 2700 K), (2) red light (E_V = 50 lux, λ_{max} = 630 nm), (3) combined (red + white) light (E_V = 100 lux, 2000 K), and a dim control condition (E_V < 5 lux). Figure 1 shows the setup of the laboratory and the corresponding SPDs of the lighting system for red, white, and combined lighting conditions.

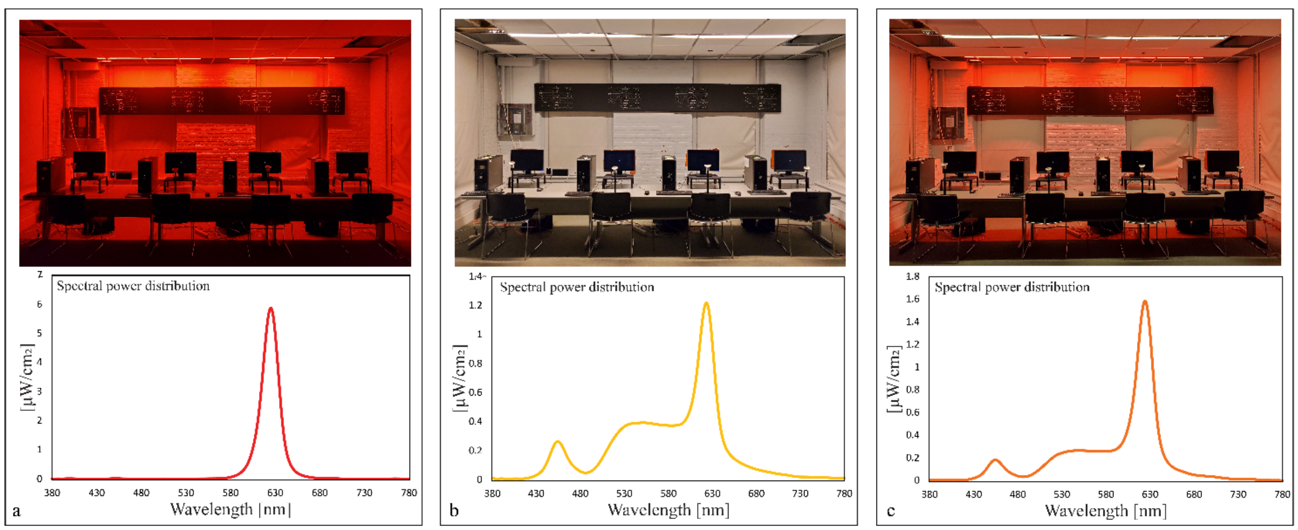


Figure 1: Laboratory settings and SPDs of the lighting system for red (a), white (b), and combined (c) conditions.

Outcomes

EEG

We recorded EEG four times per experimental session using a BioSemi ActiveTwo system (BioSemi, Amsterdam, NL). Prior to each session, we applied electrodes to the participants' scalps according to the international 10-20 system. We placed four electrodes along the midline of participants' crania at locations Fz (frontal), Cz (central), Pz (parietal), and Oz (occipital). We placed the reference electrodes on the earlobes at locations A1 and A2. The common mode sense and driven right leg electrodes were placed on participants' foreheads, forming a feedback loop that drove the average potential of the participant (common mode voltage) as close as possible to the analog-to-digital reference voltage in the analog-digital-box. To record blinking, we placed an electrode under each participant's right eye for electrooculographic (EOG) measurements.

Performance Tests

PVT

To provide assessments of sustained attention while experiencing the lighting conditions, participants underwent a series of 4-min PVT. During the PVT, we instructed participants to monitor a light grey rectangular box frame on the computer screen and press a response button as soon as a black stimulus counter in milliseconds (ms) appears on the screen and stops the counter. The inter-stimulus interval (i.e., the period between the last response and the appearance of the next stimulus) was generated between 1 s and 4 s. We instructed participants to press the button as soon as each stimulus appears. Responses without a stimulus or RT < 100 ms were counted as false starts. We registered response times ≥ 500 ms as lapses. If no response was given, the millisecond counter stopped after 10,000 ms. We counted this stimulus as valid with an RT of 10,000 ms. Pressing the wrong button or failing to release the response button were counted as errors and excluded from the analyses.

GNG Task

The GNG task requires participants to listen for two distinct tones: a target ("go") tone and a higher pitched inhibitor ("no-go") tone. All auditory stimuli were generated using the beep function of Winsound, with each computer's Sound Mixer level set at 50. The volume of the stimuli was designed to be audible but not easily detectable. All auditory stimuli, called "trials" in this study, were presented for a duration of 150 ms. Inter-stimulus intervals were randomly generated between 600 ms and 2300 ms. Participants were instructed to respond to target stimuli as quickly as possible by pressing the computer keyboard's space bar. Participants were explicitly instructed not to respond to inhibitory stimuli.

KSS

We asked participants to rate a Karolinska Sleepiness Scale (KSS) score four times per experimental session (see Procedure). The KSS outcome prompts participants to rate how sleepy or alert they are feeling on a scale ranging from 1 to 9, where 1 = "very alert," 3= "rather alert," 5= "neither alert nor sleepy," 7= "sleepy, but no difficulty remaining awake," and 9 = "very sleepy, fighting sleep, an effort to remain awake."

Lighting Appraisal Questionnaire

Participants evaluated the lighting in the simulated office environment on four items using a five-point Likert-scale. We instructed participants to rate their level of agreement or disagreement (+2: completely agree, +1: agree, 0: neither agree nor disagree, -1: disagree, -2: completely disagree) with the following statements about the lighting in each condition:

Q1: The amount of illumination in this space is adequate.

Q2: The amount of illumination on the desk top is adequate.

Q3: The lights are glaring.

Q4: The lighting in this space is acceptable for performing office work.

Q5: Overall, the space is visually comfortable.

For the last question, we asked participants to complete a final statement by inserting "increase," "decrease" or "keep the same" in the following sentence:

Q6: I would prefer to _____ the light level in this space.

We asked participants to look at the four identical fictitious railway track diagram that were mounted on the wall facing them before they provided their ratings. Figure 2 shows one of the four identical fictitious railway track diagrams.

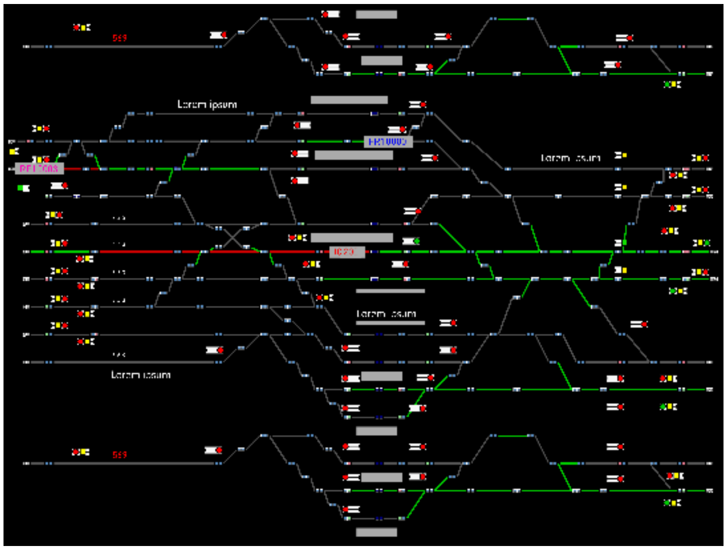


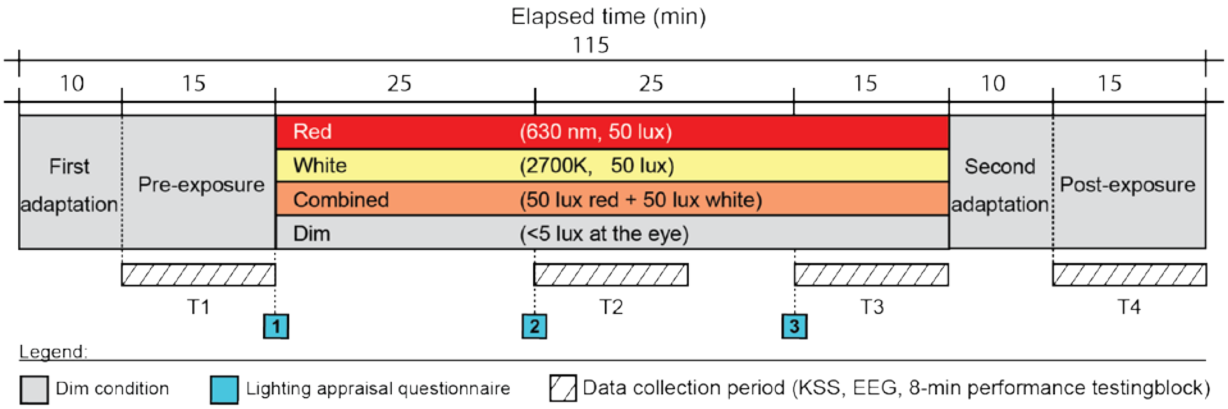
Figure 2: One of the four identical fictitious railway track diagrams.

Procedure

We gave an orientation session to all participants at the Lighting Research Center (LRC) laboratory 1 week prior to their first experimental session. We obtained their consent forms and the experimenters explained the EEG preparation procedure and experimental protocol. Participants experienced one of 4 experimental conditions during each experimental session. We separated sessions by 1 week and counterbalanced across participants to avoid order effects. Due to withdrawals and the fact that our laboratory could accommodate four participants with only one condition, the number of participants experiencing the dim, red, white, and combined conditions first were, respectively, five, four, three, and three for the daytime. For the nighttime, the number of participants experiencing the dim, red, white, and combined conditions first were, respectively, five, three, five, and three.

On the day of each session, participants arrived at the LRC laboratory at 13:00 for the daytime session and at 22:00 for the nighttime session for verification of their regular sleep schedules and EEG preparation. After electrode placement, each participant was seated in an office chair at a computer desk furnished with a chinrest. The experimenters instructed participants to adjust the chinrest to a comfortable position and wore a dedicated pair of earphones (MC5 Noise-Isolating in-Ear Stereo Headphones, Etymotic Research, Elk Grove Village, IL) during the entire session to receive auditory prompts.

Sessions started at 14:00 for the daytime and at 23:00 for the nighttime with staggered 6-min intervals between participants' start times. Experimenter asked participants to remain awake and keep their eyes open during the entire session. The experimenters also asked participants to refrain from body movement and excessive blinking during EEG recordings to avoid the occurrence of EOG artifacts in the EEG data. Each experimental session was broken up into 5 segments: (1) first adaptation (10 min), (2) pre-exposure (15 min), (3) intervention/control (65 min), (4) second adaptation (10 min), and (5) post-exposure (15 min). The experimental protocol is shown in Figure 3.



Note: KSS: Karolinska Sleepiness Scale, EEG: electroencephalogram.

Figure 3: The experimental protocol for the 4-week study.

All participants waited in dim condition during the first adaptation, followed by the first data collection trial (T1) (KSS score rating, 3-min EEG recording, and 8-min performance testing block) that occurred during the pre-exposure. Experimenter either turned on the lighting system for red, white, and combined conditions or kept the dim condition and asked participants to fill out their first lighting appraisal questionnaire. Participants underwent 2 additional data collection periods beginning 25 (T2) and 50 (T3) min after pre-exposure data collection period. The experimenters asked participants to rate their second and third lighting appraisal questionnaire at the beginning of T2 and T3, respectively. Participants then experienced the second adaptation, followed by the post-exposure and final data collection period (T4). Figure 4 shows an experimental session with four participants under red condition.

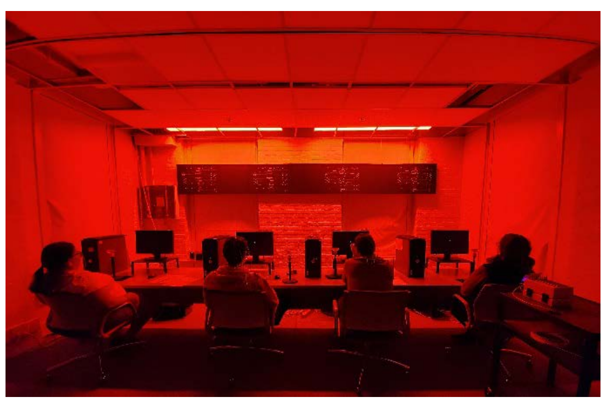


Figure 4: Experimental session with four participants experiencing red condition.

Data Analyses

We used MATLAB (version 2019a, MathWorks, Inc., Natick, MA) to analyze the EEG data. Values from 2 reference electrodes were averaged together and subtracted from all four electrodes positioned on the z line (i.e., Fz, Cz, Pz, Oz). A 0.3–100 Hz bandpass filter was used to remove signals outside of the relevant frequency band.

Data were then grouped into 2-s epochs with a 1-s overlap between each epoch (e.g., epoch 1 is 0–2 s, epoch 2 is 1–3 s, etc.). Any epochs with fluctuations exceeding ±100 µV on the Fz, Pz, Cz, or Oz electrodes or 40 µV on the EOG electrode were removed from the analysis. A 10%

cosine window followed by a fast Fourier transform was then applied to each epoch. This process yielded spectral power distributions from 0.3 to 40 Hz in 0.5 Hz intervals. The power spectra from each epoch were then averaged together to yield average power spectra at theta (4-7 Hz), alpha-theta (5-9 Hz), alpha (8-12 Hz), and beta (13-30 Hz) frequency bands for each electrode site. The outcome measures of the EEG analyses were the reduction in alpha, alpha theta, and theta power, and the increase in beta power at each electrode site.

Performance outcomes included mean hit percent (HP [number of correct responses divided by total trials]), mean response time (RT), mean score [number of correct responses divided by mean RT], mean 10 % best and worst RT, and mean number of lapses.

Statistical Analyses

For all measures except the lighting appraisal questionnaire, we first normalized data to the data obtained during at T1 to obtain the relative change over time within each condition. We conducted a linear mixed-effects model (LMM) to test for main effects and interaction effects for all outcome measures with time of day (daytime/nighttime) as a between-subject factor and condition (dim, red, white, and combined) and trial (T2, T3, T4) as within-subjects factor. For the EEG analyses, electrode site (Fz, Cz, Pz, and Oz) was also registered as a within-subjects factor. Time of day, condition, electrode site, and trial were entered as fix factors where participant was entered as a random factor. For the lighting appraisal questionnaire, we conducted analyses for each time of day separately and did not normalized ratings to T1.

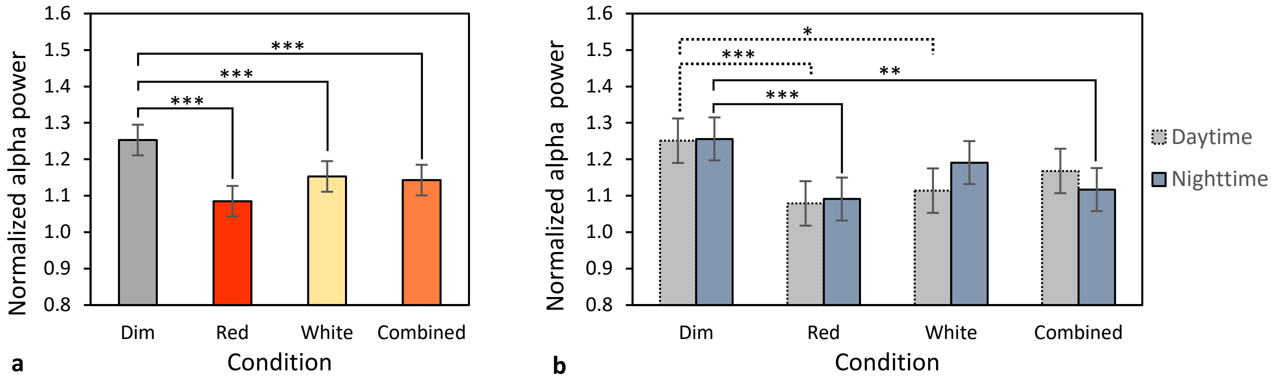
In order to further explore the nature of possible differences due to main factors and/or their interactions, except for the lighting appraisal questionnaire, a post hoc analysis based on the pairwise multiple comparisons with the Sidak correction was performed. Lighting appraisal questionnaire data were analyzed with the non-parametric Wilcoxon signed rank test with Bonferroni correction for multiple paired comparisons.

Results

EEG

Alpha Band

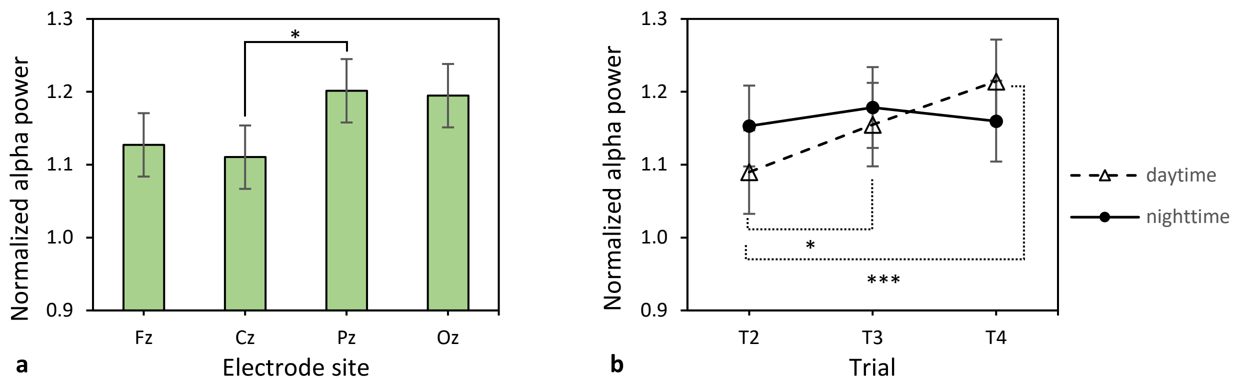
The LMM revealed significant main effects of condition [$F_{3,\,676.860} = 12.478$, $p < 0.001$] and electrode site [$F_{3,\,319.139} = 3.830$, $p = 0.010$], and a significant interaction between time of day and trial [$F_{2,\,885.366} = 3.830$, $p = 0.010$]. Multiple group comparisons showed that all lighting interventions (i.e., red [$t_{795.841} = 5.93$, $p < 0.001$], white [$t_{530.291} = 3.34$, $p = 0.006$], and combined [$t_{699.759} = 3.85$, $p = 0.001$]) reduced alpha power compared to dim condition irrespective of time of day (Figure 5a). We conducted post hoc analyses to further investigate the effect of condition for daytime and nighttime separately, although the interaction between condition and time of day was not statistically significant. Post hoc tests showed that alpha power, compared to the dim condition, was significantly reduced by the red [$t_{795.841} = 4.23$, $p < 0.001$] and white [$t_{530.291} = 3.15$, $p = 0.010$] conditions, but not by the combined [$t_{699.759} = 2.00$, $p = 0.245$] condition during daytime. At night, however, the red [$t_{795.841} = 4.19$, $p < 0.001$] and combined [$t_{699.759} = 3.47$, $p = 0.003$] conditions significantly reduced alpha power compared to dim condition. The difference between the dim and white conditions did not reach statistical significance level at night [$t_{530.291} = 1.52$, $p = 0.559$] (Figure 5b).



Note: The error bars represent standard error of the means (SEMs); (*) p < 0.05, (**) p < 0.01, (***) p < 0.001.

Figure 5: Normalized alpha power by condition (a) and by condition for each time of day (b).

Multiple group comparisons for the main effect of electrode site showed that alpha power was significantly lower at Cz than at Pz [$t_{307.437}$ = -2.74, p = 0.038] (Figure 6a). Analyses also revealed that alpha power significantly increased throughout the experiment during daytime, but not during nighttime. Alpha power was significantly lower at T2 than at T3 [$t_{870.311}$ = -2.55, p = 0.032] and T4 [$t_{917.208}$ = -4.86, p < 0.001] during daytime (Figure 6b).

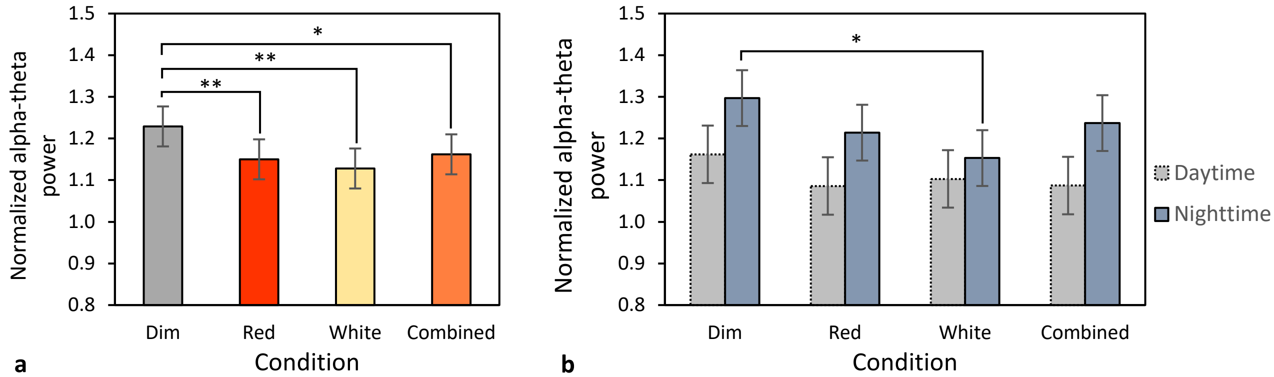


Note: The error bars represent standard error of the means (SEMs); (*) p < 0.05, (***) p < 0.001.

Figure 6: Normalized alpha power by electrode site (a) and by trial for each time of day (b).

Alpha-Theta Band

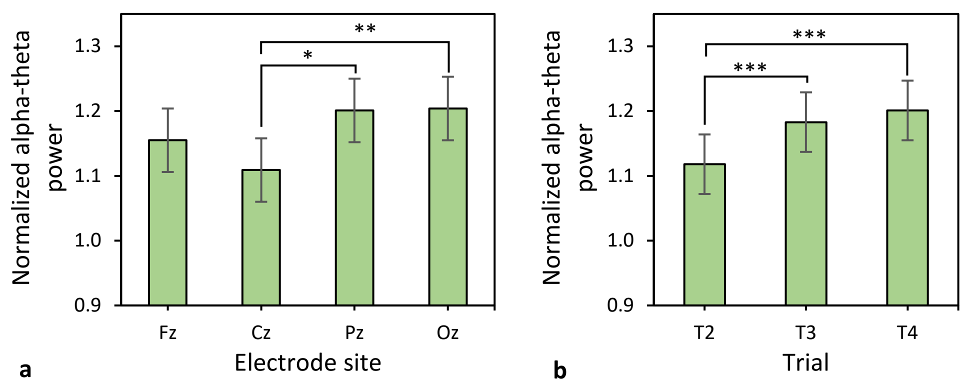
The analyses revealed significant main effects of condition [$F_{3,\ 671.993}$ = 5.802, p = 0.001], electrode site [$F_{3,\ 298.927}$ = 4.686, p = 0.003], and trial [$F_{2,\ 885.366}$ = 3.830, p = 0.010] for alpha-theta band. Multiple group comparisons showed that alpha-theta power were significantly lower in red [$t_{796.081}$ = 3.33, p = 0.006], white [$t_{520.715}$ = 3.88, p = 0.001], and combined [$t_{689.398}$ = 2.68, p = 0.039] conditions than the power in dim condition where daytime and nighttime data were aggregated (Figure 7a). We conducted post hoc analyses to further investigate the effect of condition for daytime and nighttime separately, although the interaction between condition and time of day was not statistically significant. Post hoc tests showed that alpha-theta power, compared to dim condition, was significantly reduced by the white condition [$t_{520.715}$ = 3.97, p = 0.001] during nighttime. Although alpha-theta power was lower in the red [$t_{796.081}$ = 2.52, p = 0.078] and combined [$t_{689.398}$ = 1.74, p = 0.413] conditions than the power in dim condition at night, none of the differences reached statistical significance after Sidak correction (Figure 7b).



Note: The error bars represent standard error of the means (SEMs); (*) $p < 0.05$, (**) $p < 0.01$.

Figure 7: Normalized alpha-theta power by condition (a) and by condition for each time of day (b).

Multiple group comparisons for the main effect of electrode site showed that alpha power was significantly lower at Cz than at Pz [$t_{287.219}$ = -3.17, p = 0.010] and Oz [$t_{287.219}$ = -3.28, p = 0.007] (Figure 8a). Analyses for the main effect of trial revealed that alpha-theta power was significantly lower at T2 than at T3 [$t_{870.910}$ = -4.49, $p < 0.001$] and T4 [$t_{924.858}$ = -5.67, $p < 0.001$] irrespective of time of day (Figure 8b).



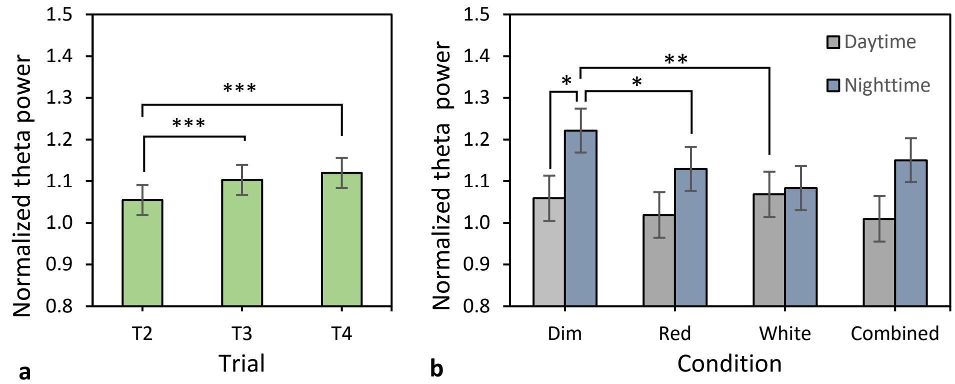
Note: The error bars represent standard error of the means (SEMs); (*) $p < 0.05$, (***) $p < 0.001$.

Figure 8: Normalized alpha-theta power by electrode site (a) and by trial for each time of day (b).

Theta Band

The analyses revealed significant main effects of electrode site [$F_{3, 286.466}$ = 2.657, p = 0.049] and trial [$F_{2, 904.913}$ = 14.277, $p < 0.001$], and a significant interaction between condition and time of day [$F_{3, 678.479}$ = 4.054, p = 0.007] for the theta band. Multiple group comparisons for the main effect of electrode site did not show statistically significant differences between any of the electrode site when corrected for multiple comparisons using Sidak correction. Analyses for the main effect of trial, however, revealed significantly lower theta power at T2 than at T3 [$t_{888.044}$ = -3.84, $p < 0.001$] and T4 [$t_{940.935}$ = -5.13, $p < 0.001$] irrespective of time of day (Figure 9a).

Post hoc multiple group comparisons showed that theta power was significantly lower in the red [$t_{806.934}$ = 3.06, p = 0.013] and white [$t_{522.856}$ = 4.20, $p < 0.001$] conditions than the power in the dim condition during nighttime. The difference between the combined and dim conditions, however, did not reach statistical significance after Sidak correction [$t_{689.329}$ = 2.30, p = 0.120]. The paired comparison also did not reveal significant difference between conditions for the daytime. Analyses also showed that theta power was significantly lower during daytime than during nighttime in the dim condition [$t_{38.394}$= -2.14, p = 0.038] (Figure 9b).

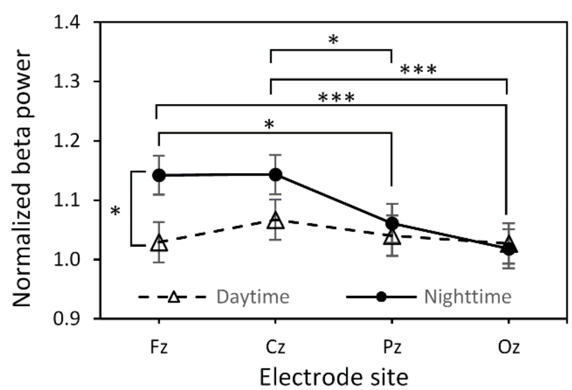


Note: The error bars represent standard error of the means (SEMs); (*) $p < 0.05$, (***) $p < 0.001$.

Figure 9: Normalized theta power by trial (a) and by condition for each time of day (b).

Beta Band

The analyses revealed a significant interaction between channel and time of day [$F_{3, 276.677}$ = 3.537, p = 0.015] for the beta band. Post hoc multiple group comparisons showed that theta power at Fz was significantly higher than at Pz [$t_{264.595}$ = 2.79, p = 0.032] and Oz [$t_{288.899}$ = 4.46, p < 0.001] electrode sites during the nighttime. It was also found that power in Cz was significantly higher than at Pz [$t_{264.502}$ = 2.83, p = 0.030] and Oz [$t_{264.505}$ = 4.31, p < 0.001] during the nighttime. Comparison did not reveal significant difference between any of the variables for the daytime. Analyses also showed that beta power was significantly lower during daytime than nighttime at Fz electrode site [$t_{54.342}$ = -2.35, p = 0.022] (Figure 10).



Note: The error bars represent standard error of the means (SEMs); (*) $p < 0.05$, (***) $p < 0.001$.

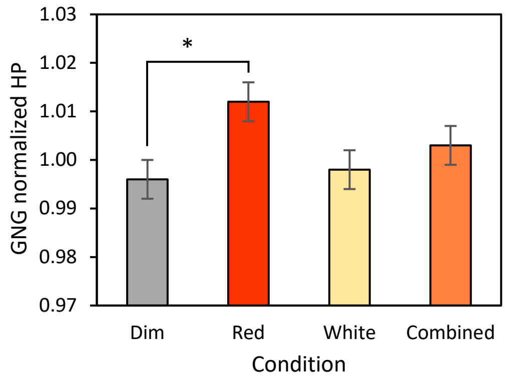
Figure 10: Normalized beta power by electrode site for each time of day.

Performance

Go-NoGo (GNG) Task

Hit Percent (HP)

The LMM revealed significant main effects of color [$F_{3,\ 184.692}$ = 3.868, p = 0.010] for the HP. Multiple group comparisons showed that participants had significantly higher correct response rate in red condition than in dim condition [$t_{233.644}$ = -3.20, p = 0.016] (Figure 11).

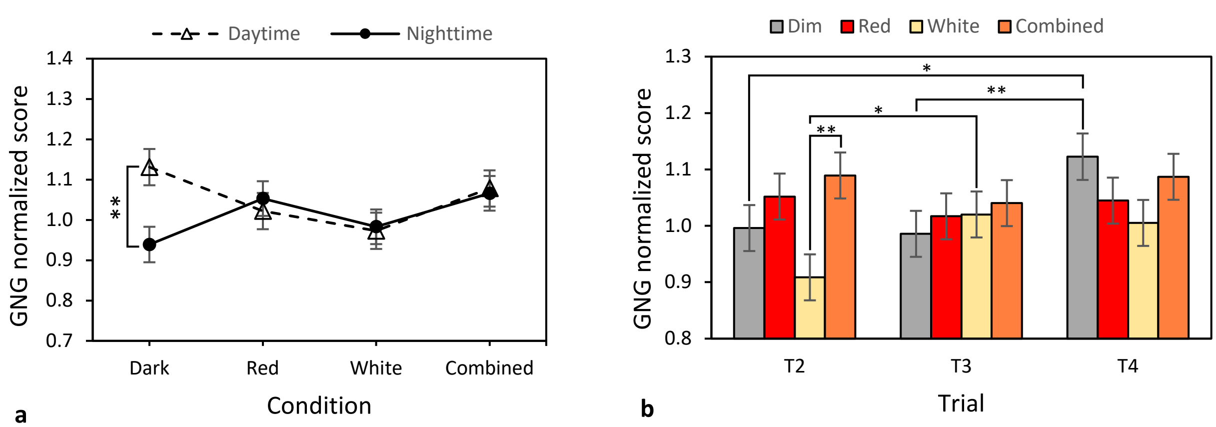


Note: The error bars represent standard error of the means (SEMs); (*) $p < 0.05$

Figure 11: GNG normalized hit percent by condition.

Score

The analyses for score showed significant interactions between color and time of day [$F_{3,\ 174.918}$ = 3.119, p = 0.027] and between color and trial [$F_{6,\ 291.371}$ = 2.291, p = 0.035]. Multiple group comparisons showed that participants' scores during daytime were significantly higher than their scores during nighttime [$t_{118,851}$ = 3.05, p = 0.003] (Figure 12a). It was also shown that participants' scores significantly increased during T4 than during T2 [$t_{345.290}$ = 2.47, p = 0.043] and T3 [$t_{277.188}$ = 3.21, p = 0.005] in the dim condition and significantly increased during T3 than during T2 [$t_{277.396}$ = 2.62, p = 0.026] in the white condition (Figure 12b). The scores in combined condition were also significantly higher than scores in white condition at T2 [$t_{329.214}$ = 3.31, p = 0.006] (Figure 12b).

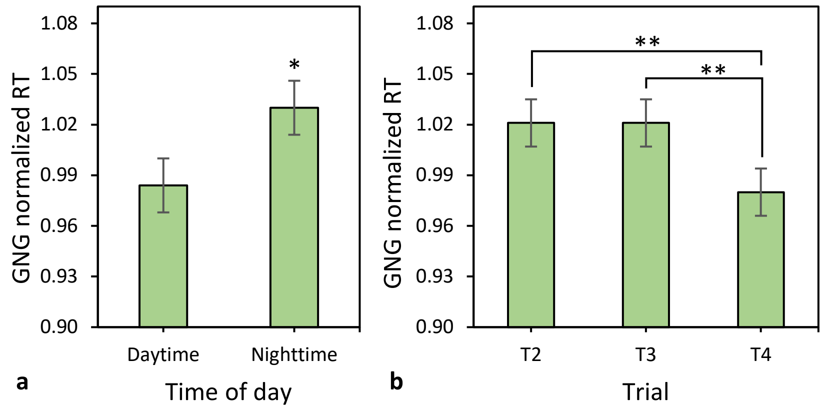


Note: The error bars represent standard error of the means (SEMs); (*) $p < 0.05$, (**) $p < 0.01$.

Figure 12: GNG normalized score by condition for each time of day (a), and by trial for each condition (b).

Response Time (RT)

The LMM revealed significant main effects of time of day [$F_{1,67.375}$ = 4.169, p = 0.045] and trial [$F_{2,\ 248.007}$ = 6.373, p = 0.002] for the RT. Multiple group comparisons showed that participants responded significantly faster during daytime than during nighttime [$t_{67.375}$ = -2.04, p = 0.045] (Figure 13a). Participants' RTs were also significantly lower at T4 than at T2 [$t_{287.664}$ = -2.93, p = 0.009] and T3 [$t_{233.836}$ = -3.15, p = 0.004] (Figure 13b).

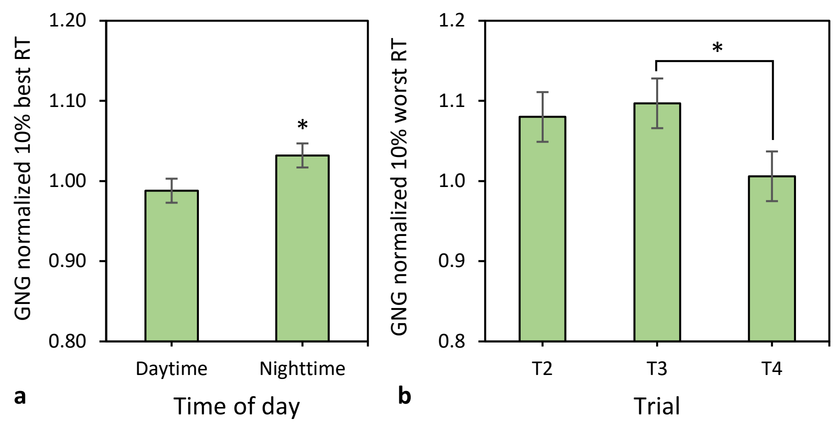


Note: The error bars represent standard error of the means (SEMs); (*) $p < 0.05$, (**) $p < 0.01$.

Figure 13: GNG normalized RT by time of day (a) and by trial (b).

10% Best and 10% Worst RT

The LMM revealed significant main effects of time of day [$F_{1,67.024}$ = 4.157, p = 0.045] for the 10% best RT and trial [$F_{2, 232.247}$ = 3.568, p = 0.030] for the 10% worst RT. Multiple group comparisons showed that participants 10% best RTs were significantly lower during the daytime than during the nighttime [$t_{67.024}$ = -2.05, p = 0.045] (Figure 14a) and 10% worst RTs were significantly lower at T4 than at T3 [$t_{220.068}$ = -2.53, p = 0.034] (Figure 14b).

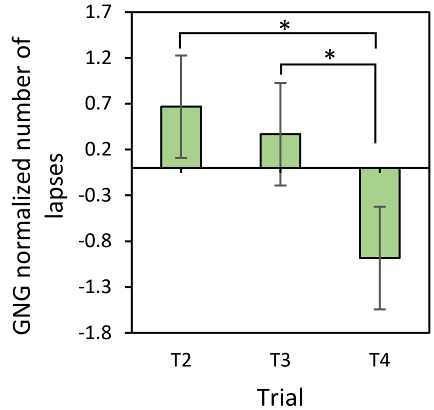


Note: The error bars represent standard error of the means (SEMs); (*) $p < 0.05$.

Figure 14: GNG normalized 10% best RT by time of day (a) and normalized 10% worst RT and by trial (b).

Number of Lapses

The LMM for the number of lapses revealed a significant main effect of trial [$F_{2,239.969}$ = 4.908, p = 0.008]. Multiple group comparisons showed that participants had significantly less lapses at T4 than at T2 [$t_{277.016}$ = -2.91, p = 0.012] and T3 [$t_{226.261}$ = -3.15, p = 0.037] (Figure 15).



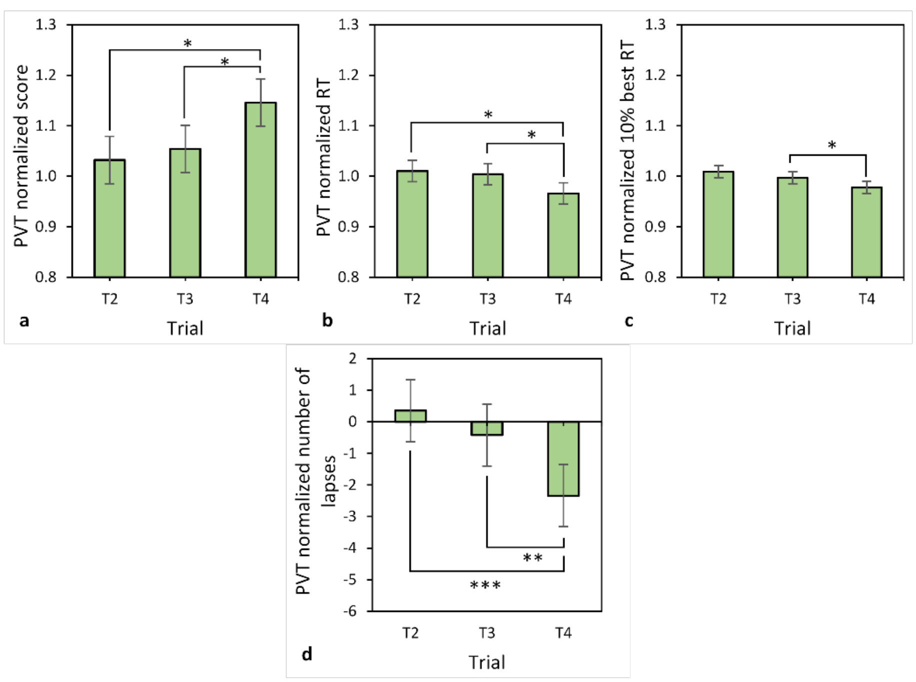
Note: The error bars represent standard error of the means (SEMs); (*) $p < 0.05$, (**) $p < 0.01$.

Figure 15: GNG normalized number of lapses by trial.

Psychomotor Vigilance Task (PVT)

The LMM for the PVT did not reveal significant main effects or interactions in any of the variables for the HP and 10% worst RT. The analyses, however, showed a significant main effect of trial for score [$F_{2, 252.205} = 4.606$, $p = 0.011$], RT [$F_{2, 257.782} = 6.073$, $p = 0.003$], 10% best RT [$F_{2, 2} = 4.584$, $p = 0.011$], and number of lapses [$F_{2, 251.505} = 8.342$, $p < 0.001$].

Multiple group comparisons showed that participants had significantly higher scores (Figure 16a), lower RTs (Figure 16b) and number of lapses (Figure 16c) at T4 than at T2 and T3. Participants 10% best RTs, however, were lower at T4 than T3, but not at T2 (Figure 16d). The *p* and associated *t* values are presented for each Multiple group comparisons in Table 2.



Note: The error bars represent standard error of the means (SEMs); (*) $p < 0.05$, (**) $p < 0.01$, (***) $p < 0.001$.

Figure 16: PVT normalized score (a), RT (b), 10% best RT (c), and number of lapses (d) by trial.

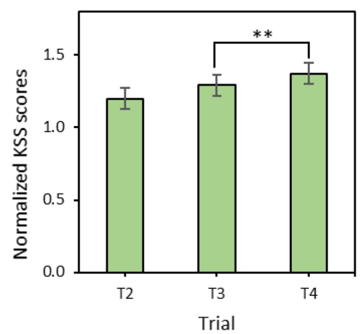
Table 2: Multiple group comparison results for each dependent variable.

Variable	Pairs			Error	*p*	*t*
Score	T4	-	T2	294.167	0.015*	2.85
	T4	-	T3	237.300	0.046*	2.42
RT	T4	-	T2	302.504	0.005*	-3.21
	T4	-	T3	242.765	0.012*	-2.92
10% best RT	T4	-	T2	308.419	0.009*	-3.10
	T4	-	T3	245.815	0.133	-2.11
Number of lapses	T4	-	T2	300.068	0.000*	-3.94
	T4	-	T3	235.543	0.008*	-3.04

Note: (*) statistically significant

Karolinska Sleepiness Scale (KSS)

The LMM for the KSS revealed a significant main effect of trial [$F_{2,\,261.238} = 6.483$, $p = 0.002$]. Multiple group comparisons showed that participants felt sleepier as time passed and that the difference between T3 and T4 reached statistical significance [$t_{311.241} = 3.58$, $p = 0.001$] (Figure 17).



Note: The error bars represent standard error of the means (SEMs); (**) $p < 0.01$.

Figure 17: Normalized KSS score by trial.

Lighting Appraisal Questionnaire

We conducted statistical analyses to assess the impacts of condition (i.e., dim, red, white, and combined) on responses to the subjective rating statements for the six questions. We also evaluated the effect of time (i.e., trial) on the subjective rating statements within each condition.

Question 1 (Q1): The Amount of Illumination in This Space Is Adequate

Participants, as expected, significantly disagreed that dim condition provided adequate illumination compared to the red, white and combined conditions during both daytime and nighttime. Wilcoxon signed ranks test also revealed a significant reduction in agreement that the red condition provided adequate illumination compared to the white condition at T3 (i.e., after 50 min of exposure) during daytime and at T2 (i.e., after both 25 min of exposure) and at T3 during nighttime. Table 3 shows z and associated *p* values for each multiple group comparisons at each trial.

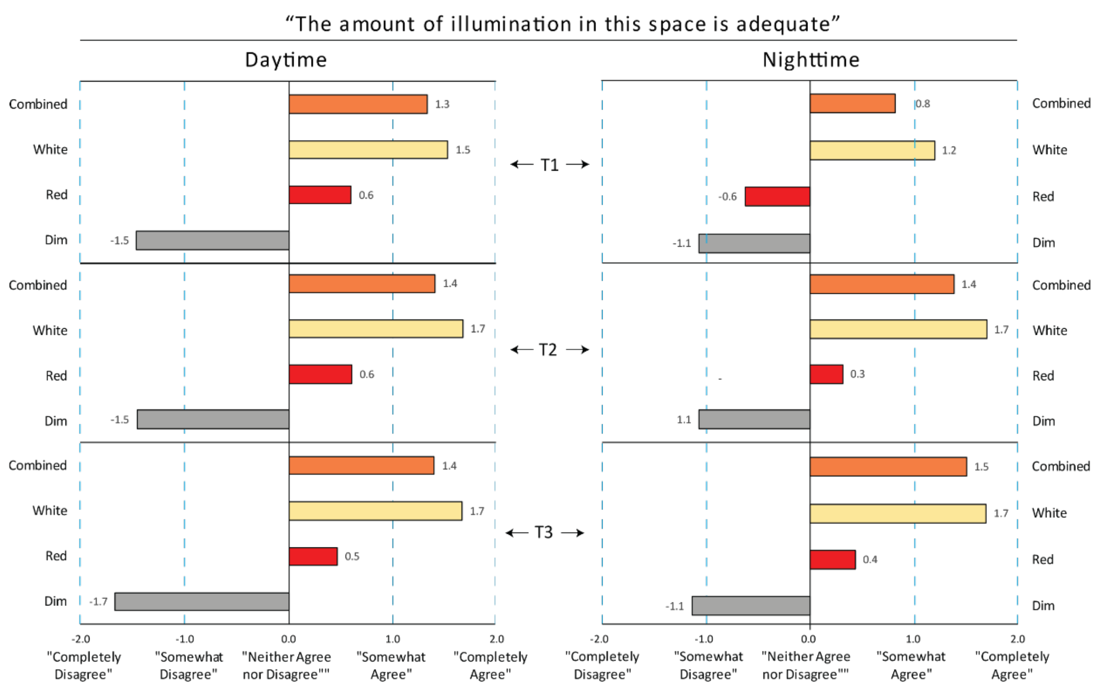
We also investigated the change in agreement within each condition as time progressed and found that, although the participants' rate of agreement changed direction at T2 [z = -0.90, $p = 0.371$] and at T3 [z = -0.79, $p = 0.435$], the differences did not reach statistical significance.

Figure 18 shows the level of agreement that the illumination in the space were adequate under each condition for each time of day and trial.

Table 3: Wilcoxon signed ranks test results for each time of day for Q1.

Time of day	Pairs			T1		T2		T3	
				z	p	z	p	z	p
Daytime	Dim	-	Red	3.12*	0.012	3.07*	0.013	3.13*	0.010
	Dim	-	White	3.45*	0.006	3.45*	0.003	3.50*	0.003
	Dim	-	Combined	3.35*	0.006	3.44*	0.004	3.45*	0.003
	Red	-	White	2.29	0.132	2.49	0.078	3.07*	0.013
	Red	-	Combined	1.91	0.336	2.31	0.126	2.59	0.058
	White	-	Combined	0.60	1.000	0.71	1.000	2.00	1.000
Nighttime	Dim	-	Red	3.33*	0.006	3.54*	0.002	3.56*	0.002
	Dim	-	White	3.66*	0.000	3.63*	0.002	3.62*	0.002
	Dim	-	Combined	3.57*	0.000	3.60*	0.002	3.61*	0.002
	Red	-	White	3.11	0.012	2.72*	0.039	2.92*	0.021
	Red	-	Combined	2.46	0.084	2.23	0.154	2.74*	0.037
	White	-	Combined	1.90	0.348	1.00	1.000	0.00	1.000

Note: (*) statistically significant



Note: Dashed blue line represents limits of four levels of agreement from "completely disagree" to "completely agree".

Figure 18: Average ratings of acceptability of illumination in the space for each lighting condition by trial (T1, T2, and T3) and time of day.

Q2: The Amount of Illumination on My Desk Top is Adequate

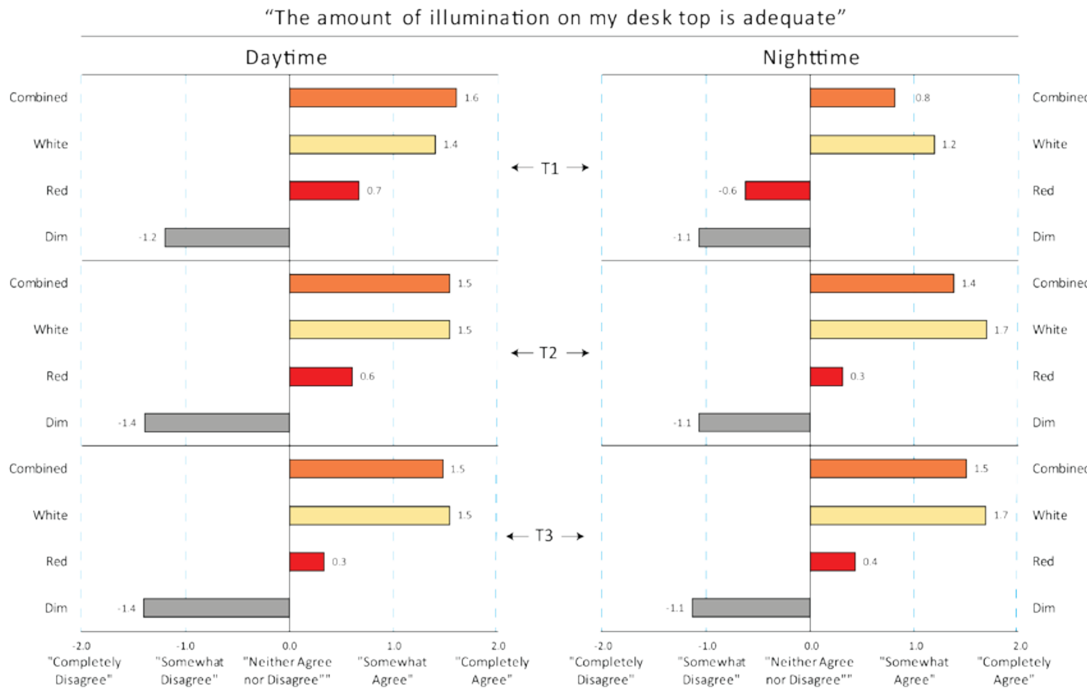
Participants, as reported for Q1, significantly disagreed that the dim condition provided adequate illumination on the desktop compared to the red, white and combined conditions during both the daytime and nighttime. The Wilcoxon signed ranks test also revealed a significant reduction in agreement that the red condition provided adequate illumination on the desktop compared to combined condition at T2 and at T3 during daytime and nighttime. The rating differences between the red and white conditions were also significant at T1 and T3 during nighttime. Table 4 shows z and associated *p* values for each multiple group comparisons at each trial.

We also investigated the change in agreement within each condition as time progressed and found that, although nighttime participants' rate of agreement changed direction for the red condition from negative to positive agreement at T2 [z = -0.00, *p* = 1.000] and T3 [z = -1.732, *p* = 0.083] the differences did not reach statistical significance. Figure 19 shows the level of agreement that the illumination on the desk top were adequate under each condition for each time of day and trial.

Table 4: Wilcoxon signed ranks test results for each time of day for Q2.

Time of day	Pairs			T1		T2		T3	
				z	p	z	p	z	p
Daytime	Dim	-	Red	2.82*	0.030	3.05*	0.014	3.03*	0.015
	Dim	-	White	3.33*	0.006	3.24*	0.007	3.35*	0.005
	Dim	-	Combined	3.46*	0.006	3.34*	0.005	3.46*	0.003
	Red	-	White	1.51	0.786	1.81	0.420	2.58	0.060
	Red	-	Combined	2.23	0.156	2.81*	0.030	2.91*	0.021
	White	-	Combined	0.68	1.000	0.33	1.000	0.71	1.000
Nighttime	Dim	-	Red	3.44*	0.006	3.44*	0.004	3.55*	0.002
	Dim	-	White	3.62*	0.000	3.59*	0.002	3.52*	0.003
	Dim	-	Combined	3.57*	0.000	3.60*	0.002	3.61*	0.002
	Red	-	White	3.00*	0.018	2.72*	0.039	2.48	0.078
	Red	-	Combined	2.36	0.108	2.88*	0.024	2.76*	0.034
	White	-	Combined	1.63	0.612	0.58	1.000	0.58	1.000

Note: (*) statistically significant



Note: Dashed blue line represents limits of four levels of agreement from "completely disagree" to "completely agree".

Figure 19: Average ratings of acceptability of illumination on the desk top for each lighting condition by trial (T1, T2, and T3) and time of day.

Q3: The Lights are Glaring

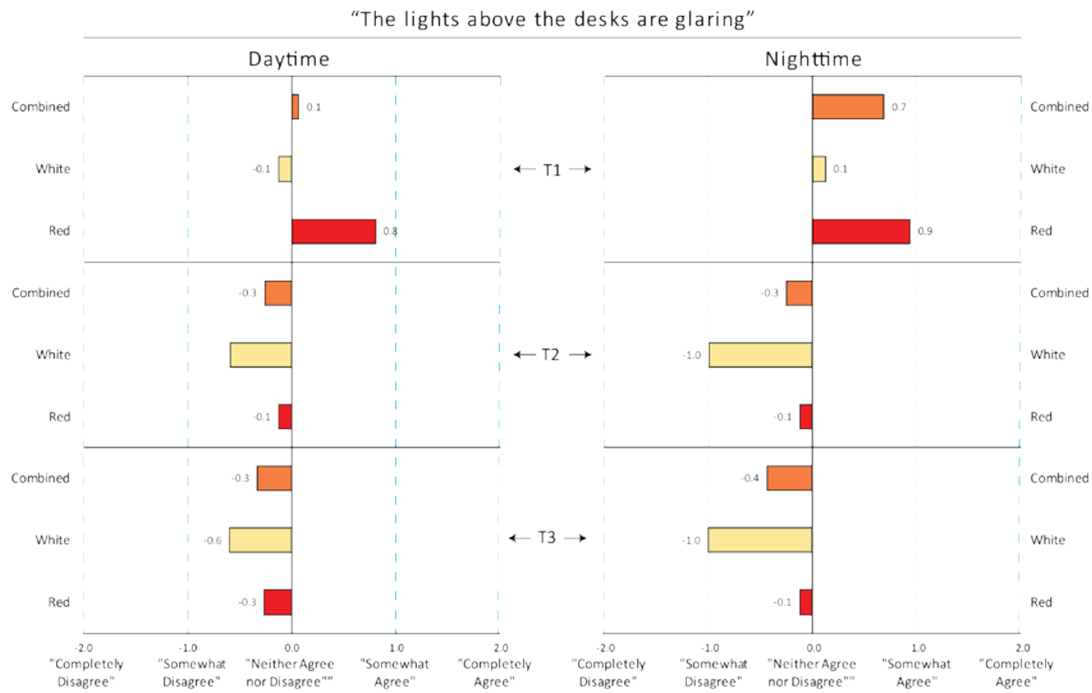
Regarding the level of glare perceived from the light sources, none of the conditions were rated as being glary except at T1 where ratings were given as soon as lights were turned on. During the daytime, participants agreed that red condition was significantly glary than white condition at this first rating. Table 5 shows z and associated p values for each of the multiple group comparisons at each trial.

As time progressed, however, interpolating for a rating value of zero, which occupants would neither agree nor disagree, glare ratings for the red condition dropped to negative values at T2 [z = -2.401, p = 0.016] and at T3 [z = -2.911, p = 0.004]. The higher glare ratings obtained at T1 suggest that participants' eye became more visually sensitive to the light exposure at the beginning of the experiment after remaining in darkness for a 10-min adaptation. Figure 20 shows the level of agreement on the glare ratings under each condition for each time of day and trial.

Table 5: Wilcoxon Signed Ranks Test Results for Each Time of Day for Q3.

Time of day	Pairs			T1 z	T1 *p*	T2 z	T2 *p*	T3 z	T3 *p*
Daytime	Red	-	White	2.91*	0.012	0.91	1.000	1.41	0.479
	Red	-	Combined	1.62	0.315	0.47	1.000	0.31	1.000
	White	-	Combined	0.73	1.000	0.36	1.000	0.92	1.000
Nighttime	Red	-	White	1.95	0.153	1.93	0.161	2.12	0.101
	Red	-	Combined	1.16	0.744	0.49	1.000	1.06	0.871
	White	-	Combined	1.89	0.177	2.07	0.115	2.00	0.137

Note: (*) statistically significant



Note: Dashed blue line represents limits of four levels of agreement from "completely disagree" to "completely agree".

Figure 20: Average glare ratings for each lighting condition by trial (T1, T2, and T3) and time of day

Q4: The Lighting in This Space is Acceptable for Performing Office Work

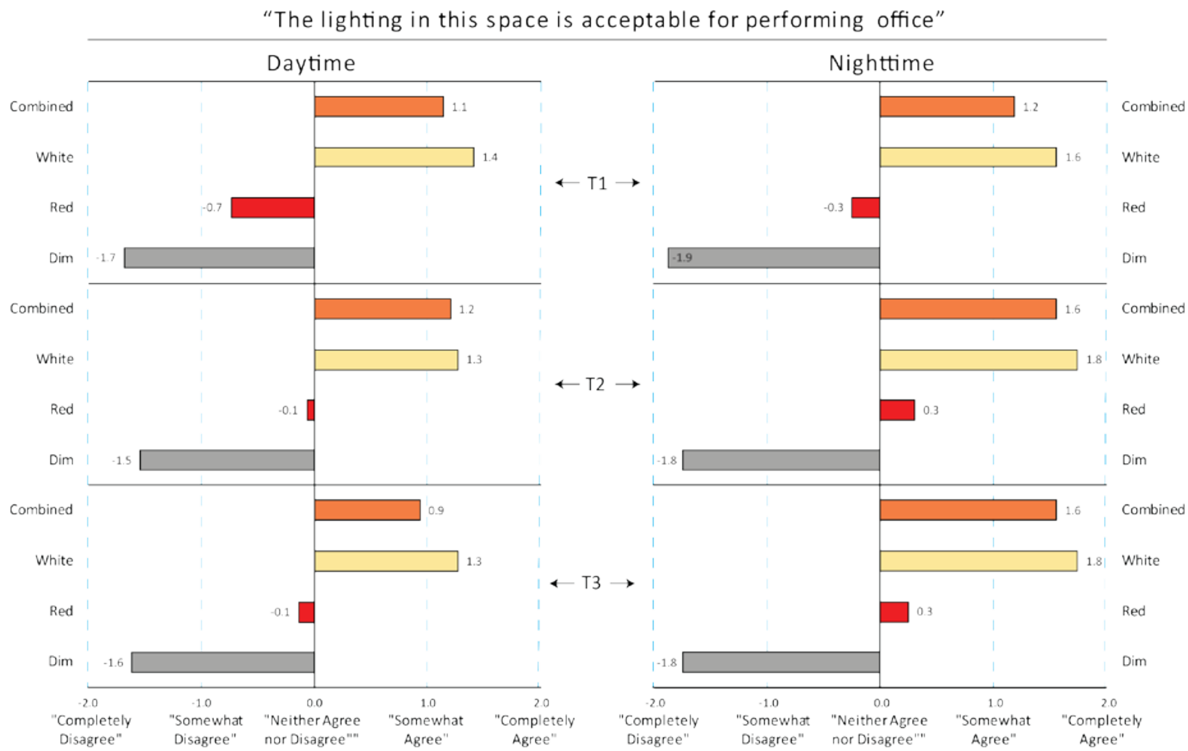
The dim condition, as expected, resulted in statistically significant complete disagreement for each time of day at each trial that the lighting was acceptable for performing office work. Daytime participants also significantly disagreed that the red condition provided lighting condition acceptable for performing office work compared to the white condition at T1 and at T3, and compared to combined condition at T1, T2, and T3. Although nighttime participants' level of agreement for acceptability under the red condition tended toward "somewhat agree", the red condition was rated significantly less acceptable than the white and combined conditions at each trial. Table 6 shows z and associated *p* values for each of the multiple group comparisons at each trial. Results suggest that combining the red with white light increased participants' level of agreement on the acceptability of the red light as being part of general illumination. Figure 21 shows the level of agreement on the acceptability of the lighting under each condition for each time of day and trial.

Table 6: Wilcoxon Signed Ranks Test Results for Each Time of Day for Q2.

Time of day	Pairs			T1		T2		T3	
				z	*p*	z	*p*	z	*p*
Daytime	Dim	-	Red	2.75*	0.036	2.84*	0.027	2.98*	0.017
	Dim	-	White	3.37*	0.006	3.33*	0.005	3.34*	0.005
	Dim	-	Combined	3.33*	0.006	3.44*	0.004	3.43*	0.004
	Red	-	White	3.01*	0.018	2.55	0.065	2.86*	0.026
	Red	-	Combined	3.10*	0.012	3.17*	0.009	2.70*	0.041
	White	-	Combined	0.95	1.000	0.07	1.000	1.04	1.000
Nighttime	Dim	-	Red	3.25*	0.006	3.46*	0.003	3.46*	0.003

Time of day	Pairs			T1		T2		T3	
				z	p	z	p	z	p
	Dim	-	White	3.60*	0.000	3.59*	0.002	3.63*	0.002
	Dim	-	Combined	3.58*	0.000	3.54*	0.002	3.59*	0.002
	Red	-	White	3.34*	0.006	3.31*	0.006	3.37*	0.005
	Red	-	Combined	2.98*	0.018	2.81*	0.030	3.14*	0.010
	White	-	Combined	1.86	0.378	0.00	1.000	1.34	1.000

Note: (*) statistically significant



Note: Dashed blue line represents limits of four levels of agreement from "completely disagree" to "completely agree".

Figure 21: Average acceptability ratings for each lighting condition by trial (T1, T2, and T3) and time of day.

Q5: Overall, the Space is Visually Comfortable

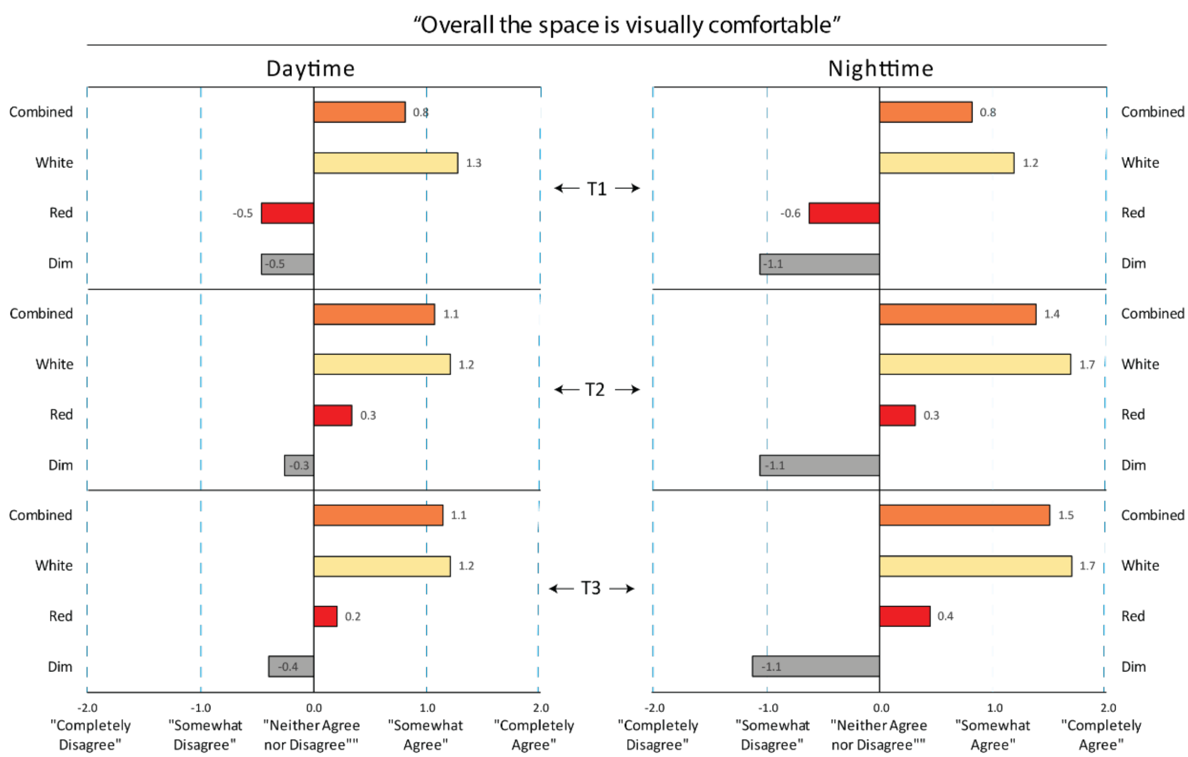
Daytime participants rated the dim condition significantly less visually comfortable compared to the white and combined conditions at T1 and T3. On the other hand, there was not a significant difference between the dim and red conditions in terms of visual comfort (Table 7). The Wilcoxon signed ranks test of within-condition comparisons showed that the agreement level of daytime participants for the red condition significantly trended toward "somewhat agree" at T2 [z = -2.360, p =0.018] and at T3 [z = -1.998, p =0.046] compared to T1.

Nighttime participants had a significant level of disagreement that the dim condition was more visually comfortable than the white and combined conditions at all trials and more comfortable than the red condition at T2 and at T3. Participants' level of agreement on visual comfort for the red condition was also significantly lower compared to the white and combined conditions (Table 7:), although as time progressed ratings for the red condition advanced to positive ratings at T2 [z = -2.803, p =0.005] and T3 [z = -2.859, p = 0.004] compared to T1 during the nighttime. Figure 22 shows the level of agreement on the visual comfort under each condition for each time of day and trial.

Table 7: Wilcoxon Signed Ranks Test Results for Each Time of Day for Q4.

Time of day	Pairs			T1		T2		T3	
				z	p	z	p	z	p
Daytime	Dim	-	Red	2.75*	0.036	2.84*	0.027	2.98*	0.017
	Dim	-	White	3.37*	0.006	3.33*	0.005	3.34*	0.005
	Dim	-	Combined	3.33*	0.006	3.44*	0.004	3.43*	0.004
	Red	-	White	3.01*	0.018	2.55	0.065	2.86*	0.026
	Red	-	Combined	3.10*	0.012	3.17*	0.009	2.70*	0.041
	White	-	Combined	0.95	1.000	0.07	1.000	1.04	1.000
Nighttime	Dim	-	Red	3.25*	0.006	3.46*	0.003	3.46*	0.003
	Dim	-	White	3.60*	0.000	3.59*	0.002	3.63*	0.002
	Dim	-	Combined	3.58*	0.000	3.54*	0.002	3.59*	0.002
	Red	-	White	3.34*	0.006	3.31*	0.006	3.37*	0.005
	Red	-	Combined	2.98*	0.018	2.81*	0.030	3.14*	0.010
	White	-	Combined	1.86	0.378	0.00	1.000	1.34	1.000

Note: (*) statistically significant



Note: Dashed blue line represents limits of four levels of agreement from "completely disagree" to "completely agree".

Figure 22: Average agreement level on visual comfort for each lighting condition at each trial (T1, T2, and T3) and each time of day.

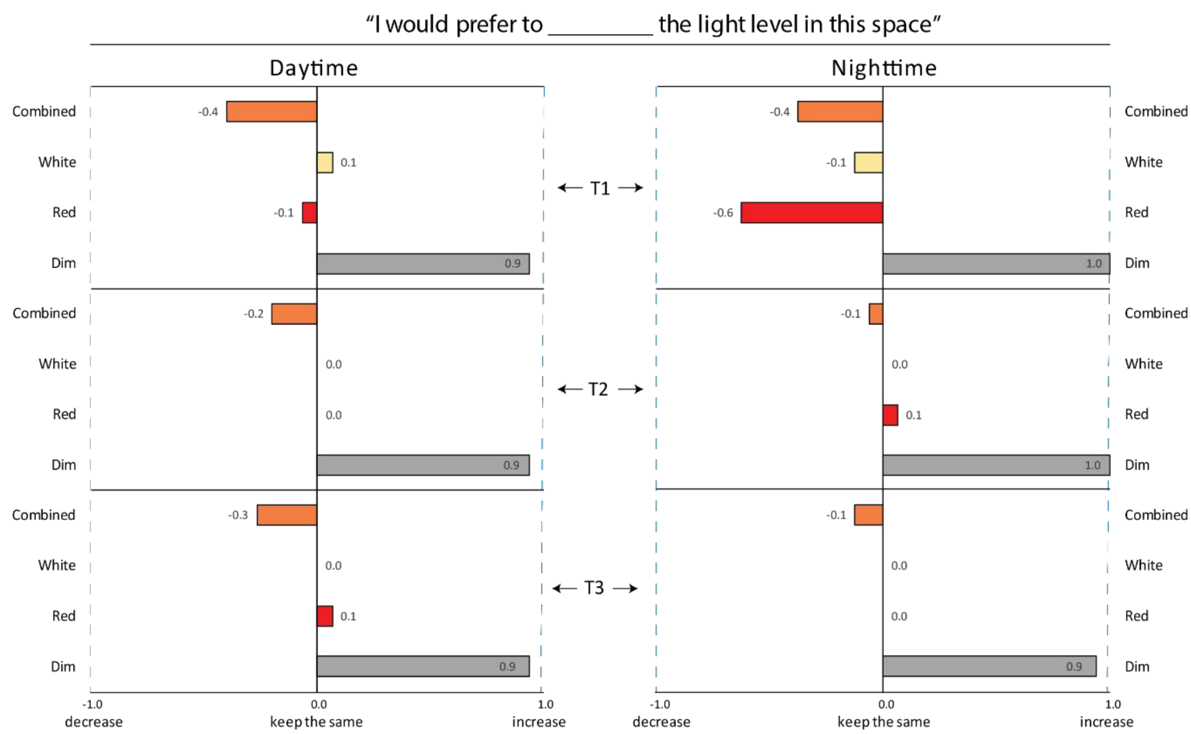
Q6: I Would Prefer To ___________ The Light Level In This Space

Both daytime and nighttime participants, as expected, significantly preferred to increase light levels for the dim condition compared to other conditions. Although the Wilcoxon signed ranks test did not reveal any significant differences between the red, white, and combined conditions (Table 8), both daytime and nighttime participants preferred decreased light levels for the combined condition. Figure 23 shows the level of agreement on the preferred light level under each condition for each time of day and trial.

Table 8: Wilcoxon Signed Ranks Test Results for Each Time of Day for Q4.

Time of day	Pairs	T1 z	T1 p	T2 z	T2 p	T3 z	T3 p
Daytime	Dim - Red	2.88*	0.024	2.89*	0.023	2.74*	0.037
	Dim - White	3.61*	0.002	3.28*	0.006	3.28*	0.006
	Dim - Combined	3.40*	0.004	3.31*	0.006	3.29*	0.006
	Red - White	0.63	1.000	0.00	1.000	0.28	1.000
	Red - Combined	2.24	0.152	1.34	1.000	1.67	0.573
	White - Combined	2.65	1.000	1.13	1.000	1.63	0.612
Nighttime	Dim - Red	3.56*	0.002	3.04*	0.014	3.22*	0.008
	Dim - White	3.63*	0.002	3.74*	0.001	3.87*	0.001
	Dim - Combined	3.51*	0.003	3.69*	0.001	3.69*	0.001
	Red - White	2.00	0.273	0.38	1.000	0.00	1.000
	Red - Combined	1.16	1.000	0.82	1.000	0.82	1.000
	White - Combined	1.41	0.944	1.73	0.498	1.41	0.942

Note: (*) statistically significant



Note: Dashed blue line represents limits of four levels of agreement from "completely disagree" to "completely agree".

Figure 23: Average agreement level on preferred light level for each lighting condition at each trial (T1, T2, and T3) and each time of day.

Plans for Implementation

The current IDEA project successfully demonstrated the effective use of the lighting intervention to increase alertness and performance in a simulated work laboratory condition. The next step will be to work with our project partner, New York City Transit, to seek opportunities for testing and demonstrating a prototype lighting system in an actual control center setting. We will also explore collaborating with lighting manufacturers to develop simple, cost-effective lighting solutions that can be readily implemented in a variety of railway environments. In a potential follow-up field study, we will propose to test the effectiveness of lighting to promote alertness and reduce fatigue among train operation personnel, during both daytime and nighttime shifts.

We will also widely disseminate the results of the current project among lighting decision makers for railways. This will include the development of a model lighting performance specification, publishing articles, and holding seminars to show railway system managers, operators, and designers simple ways to apply the concept of using red and white light in railway settings to improve alertness, performance, and safety in rail operations.

Conclusions

The current IDEA project demonstrated that red light in combination with white light has a potential to be an effective countermeasure to increase alertness and performance in the workplace, without compromising occupants' visual comfort. Although we attempted to replicate field conditions in this laboratory study, we still kept subjects on a fixed sleep-wake schedule and we did not sleep deprive them, which may be more representative of real-life circumstances. Future real-world application research projects should be conducted where dispatchers follow their regular shift schedules.

Lighting Research Center

The LRC is part of Rensselaer Polytechnic Institute, the oldest technical university in the US, and is the world's leading center for lighting research and education. Established in 1988, the LRC has been pioneering research in solid-state lighting, light and health, transportation lighting and safety, and energy efficiency for over 30 years. LRC lighting scientists with multidisciplinary expertise in research, technology, design, and human factors collaborate with a global network of leading manufacturers and government agencies, developing innovative lighting solutions for projects that range from the Boeing 787 Dreamliner to U.S. Navy submarines to hospital neonatal intensive-care units. LRC researchers conduct independent, third-party testing of lighting products in the LRC's state of the art photometric laboratories. In 1990, the LRC became the first university research center to offer graduate degrees in lighting and today provides M.S. and Ph.D. programs to educate future leaders in lighting. With 35 full-time faculty and staff, and six graduate students, the LRC is the largest university-based lighting research and education organization in the world. The interdisciplinary research model is carried through to the graduate education programs, which provide students with a broad education in lighting while allowing them to focus their research in a particular area of lighting research.

The LRC is housed in a 30,000 sq. ft. facility with state-of-the-art equipment and the ability to perform research in diverse areas of lighting. The LRC has a large investment in research facilities and equipment, including:

- A fully equipped *light and health laboratory*, with a light- and sound-controlled space dedicated to light and health experiments, including sleeping studies
- A fully equipped biomarker assay analyses room
- A fully equipped *photometry* laboratory, including limited goniometric capabilities
- Four climate-controlled lamp and *electrical testing* laboratories
- Fully equipped and reconfigurable *human factors* research laboratory capable of accommodating large groups of subjects for a variety of experimental setups, including 20 computer workstations
- Two *lighting application* laboratory spaces
- *Mechanical workshop* able to produce fully functional prototypes and models.

The LRC has a dedicated Transportation Lighting Group that is committed to explore lighting and visibility issues associated with transportation. This includes research and educational programs in such disciplines as optical design, photometry, human factors, vision, product testing, and market assessment. The LRC takes a unique approach to examining roadway visibility by considering all elements: vehicle lighting, fixed roadway lighting, and signal and marking devices, separately and as an interactive system. In order to further its commitment to improving transportation lighting and visibility the LRC has developed the Transportation Lighting Alliance (TLA), a partnership among the LRC, industry market players, standard-setting organizations, and government. Recent TLA members include Automotive Lighting, General Electric, General Motors, Hella, Philips Lighting, OSRAM Sylvania, and Visteon. To facilitate its transportation lighting research, the LRC has relationships with state and municipal authorities to conduct large-scale transportation lighting testing and evaluation.

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