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Daylight exposure has a positive carryover effect on nighttime performance and subjective sleepiness

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Two studies were designed to investigate the carryover effects of daylight on performance and self-reports of sleepiness. The effects of daylight and of darkness were compared independent of the effects of simultaneous periodic, 1-hour exposures to narrow-band blue and red lights over the course of 26-hour sessions. Nighttime performance on a 54-minute tracking task, but not subjective sleepiness, was significantly better following exposure to daylight. There was no differential effect on performance or sleepiness from exposure to the blue or red lights. Eight of the participants returned to experience a completely dark session and a replication of the daylight and intermittent blue light session. Nighttime performance and subjective sleepiness were significantly worse for the dark session than for daylight-plus-blue sessions in both studies.

1. Background

Light stimulating the retina can potentially affect human performance through three neural mechanisms: the visual, psychological, and circadian systems.[1–4] The effects of light on the visual system are well understood. There are, for example, a variety of computational algorithms that predict on-axis[5] and off-axis visual performance,[6–7] colour matching,[8] colour appearance,[9–11] and brightness.[12,13] All of these models utilise the spectral power distribution of the stimulus, with no special benefit given to daylight.

Many studies have tried to show a reliable relationship between daylight and improved psychological well-being and, thus, improved performance through the psychological system. Although these ideas are certainly appealing (e.g. biophilia hypothesis or access to view), the daylight stimulus is generally undefined and the underlying neural mechanisms are not well characterised.[14] Without an ability to specify the valence (good or bad) or the magnitude of a daylight stimulus as it might affect human performance, and with no clear understanding of the neural mechanisms underlying the potential benefits of daylight on human performance, it is very difficult to systematically apply daylight to reliably affect performance through the psychological system.

A fruitful line of research has been recently directed in examining the impact of daylight on performance as it might affect the circadian system. The circadian system utilises the 24-hour light–dark pattern incident on the retina to synchronise our diurnal (day-active, night-rest) behaviour and physiology to our local time on earth. Over the past decade, the spectral sensitivity of the human circadian system has been developed and the neural mechanisms underlying both acute and phase responses to light have been elucidated.[15–20]

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Evidence is also accumulating showing that light mediated by the circadian system can impact hormone production, performance, objective and subjective measures of alertness, and brain activity.[21–23] Some evidence also suggests that more than one non-visual pathway, perhaps associated with the circadian system, can affect hormones and performance.[22–24]

Daylight is potentially the ideal light source for synchronising our circadian systems to local time – it provides the right amount, spectrum, distribution, duration, and timing needed for circadian entrainment. Indeed, for millennia this was the only light source used by terrestrial species for circadian entrainment. In a modern, 24-hour society populated by people who spend most of their time indoors, it is quite reasonable to suppose that electric lighting, operated during the day and during the night, blurs the distinction between day and night, compromising our entrainment to the local time. In other words, without access to daylight (or electric lighting providing comparable amount, spectrum, distribution, duration, and timing), human performance and well-being may be compromised.

It has been clearly demonstrated that light exposure during the day has no impact on modulating the already-low levels of melatonin.[21,22] There is evidence that light exposure during the day can affect objective and subjective markers of alertness – e.g. as measured by functional magnetic resonance imaging (fMRI), electroencephalogram (EEG), or the Karolinska Sleepiness Scale (KSS).[25–27] Morning light has been shown to improve performance in more extreme environments, such as during the polar winter in Antarctica.[28] However, one study of the non-visual effects of light exposure suggests that the effect of light on daytime performance is more modest than its effect on nighttime alertness.[22] Light exposure at night has been shown to reliably increase alertness, as measured by EEG brain activity,[29,30] increase core body temperature,[29,31] and improve performance on some cognitive tasks.[32,33] Although the pathways mediating these non-visual effects of light at night are often associated with melatonin suppression, Figueiro *et al.*[34] recently showed that both long-wavelength (red) light and short-wavelength (blue) light increased alertness at night, as measured by EEG. One-hour exposure to 40 lux of red light, which does not suppress nocturnal melatonin, was just as effective as 1-hour exposure to 40 lux of blue light, which does reliably suppress nocturnal melatonin, for increasing alertness, as inferred from heart rate and from EEG recordings. Both light stimuli increased heart rate and increased beta power while reducing alpha power in the EEG recordings.[34] As converging evidence for non-visual retinal pathways that affect alertness at night other than those that modulate nocturnal melatonin, both nighttime exposures to both red and blue lights increase cortisol levels.[21] Subsequent research also showed that subjective alertness was elevated after exposure to both light spectra.[23,34] Regarding daytime light exposures when melatonin is at its naturally lowest concentrations, Sahin and Figueiro[25] showed that red-light exposure in the afternoon reduced measures of sleepiness, as demonstrated by a reduction in power in the alpha, alpha–theta, and theta ranges. These data further demonstrate that light can increase alertness independent of light-induced melatonin modulation.

During our studies examining the impact of light at night on brain activities, hormone production, and performance[21,22,34] we were able to observe individual behaviour throughout prolonged periods of wakefulness. Those participants who had been restricted to darkness during the day had more difficulty staying awake at night than those who had a day of normal activity where they were exposed to much higher levels of ambient light, even though both sets of individuals had been awake for the same amount of time. Here we report the results of two studies designed to systematically investigate whether

there is objective evidence supporting our observations that daytime light exposure has a carryover effect on performance and feelings of sleepiness at night. The first experiment employed a within-subject experimental design comprised of four, 26-hour sessions. All sessions took place in the same room, but half the sessions were conducted in daylight during the day and darkness at night and half were conducted in darkness during the day and night. For two sessions, subjects were exposed every 4 hours to 1 hour of narrow-band blue ($\lambda_{max} = 470$ nm) light and for two sessions to 1 hour of narrow-band red ($\lambda_{max} = 630$ nm) light. This design made it possible to statistically isolate the effects of daylight versus darkness and of blue-light versus red-light exposures on performance and feelings of sleepiness. Based upon earlier work (reviewed above), it was hypothesised that the acute impact of daylight exposure on daytime performance and feelings of sleepiness would be modest but that the daylight exposure would carry over to enhance performance and to reduce feelings of sleepiness at night. Moreover, it was hypothesised that the periodic exposure to red light and to blue light would have no differential effect on performance when used in combination with the daylight and with the dark conditions.

The second experiment was designed to determine whether the results of the first study could be replicated and to extend those findings by including a dark session with no intermittent coloured light exposures. Eight of the same subjects from the previous study were available for the second, two-session study. These subjects were again exposed to one lighting condition used in the first study; namely, they were exposed to the daylight and periodic blue-light exposure condition for one session. Unlike the first experiment, a 26-hour session was conducted in a dark room with no intermittent coloured light exposures. As in the first experiment, performance on a 54-minute tracking task and self-reports of sleepiness were measured every 4 hours in both sessions. It was hypothesised (again) that acute exposure to daylight would have only small effects on performance or feelings of sleepiness during the daytime, but during nighttime subjects experiencing the daylight and periodic blue-light exposure session would perform better and report feeling less sleepiness than when experiencing the completely dark session.

2. Method – Experiment 1

2.1. Subjects

Thirteen participants (2 females) were recruited for this four-session, within-subjects study without sleep. Participants (mean age = 32.7 years, standard deviation (SD) = 13.2 years) were recruited for the study from an electronic posting at Rensselaer Polytechnic Institute in Troy, NY, USA; its institutional review board approved the study. The participants were screened for major health problems and, except for women taking birth control pills, reported they were not taking any pharmaceuticals or medications.

Every screened participant completed a Munich Chronotype Questionnaire (MCTQ)[35] prior to the study; those who were late or extremely late chronotypes were excluded from the experiment. The MCTQ self-description of categories ranges from 0 (extremely early person) to 6 (extremely late person). The participants selected for the study had a mean score of 2.7 (SD = 1.5) on the MCTQ. Participants were kept on a fixed schedule starting one week prior to the first experimental session. To assure compliance with the schedule and to minimise practice effect on the performance tests (detailed below), participants came to the laboratory Monday through Thursday at 07:30 for the 54-minute performance test. They also wore wrist actigraphs; the actigraph data were used to confirm bedtimes. If on Friday, the day of testing, a participant deviated from the

schedule that week, then he/she was either removed from the study or asked to come the following week to make up the missing session. Participants were asked to refrain from alcohol and caffeine on the days of the experiment and were asked not to sleep after awakening for the day.

2.2. Lighting conditions

Subjects experienced four lighting conditions: (1) darkness/blue (DkB), where subjects remained in continuous darkness (dim ambient light <1 lux from red light emitting diodes (LEDs), $\lambda_{max} = 640 \pm 1$ nm, full-width-half-maximum (FWHM) $= 18 \pm 1$ nm) during the entire 26-hour session. In addition, subjects wore goggles with embedded LEDs that delivered narrow-band, blue light for 65 minutes every 4 hours starting at 08:00; (2) daylight/blue (DyB), where subjects were exposed to more than 500 lux at the cornea from natural daylight from a closed courtyard (i.e. no direct sunlight) from 07:00 to 17:00. Between 17:00 and 09:00 the following morning subjects experienced ambient darkness. In addition, subjects wore LED goggles that delivered narrow-band, blue light for 65 minutes every 4 hours starting at 08:00; (3) darkness/red (DkR), where subjects remained in continuous darkness (dim ambient light <1 lux from red ($\lambda_{max} = 640$ nm) LEDs) during the entire 26-hour session. In addition, subjects wore LED goggles that delivered narrow-band, red light for 65 minutes every 4 hours starting at 08:00; and (4) daylight/red (DyR), where subjects were exposed to more than 500 lux at the cornea from natural daylight from a closed courtyard (i.e. no direct sunlight) from 07:00 to 17:00. Between 17:00 and 09:00 the following morning subjects experienced ambient darkness. In addition, subjects wore LED goggles that delivered narrow-band, red light for 65 minutes every 4 hours starting at 08:00.

Special red and blue LED light goggles were constructed for the study. Sets of four red ($\lambda_{max} \approx 630$ nm, FWHM $= 20 \pm 1$ nm) or blue ($\lambda_{max} \approx 470$ nm, FWHM $= 20 \pm 1$ nm) LEDs were mounted on the lenses of transparent goggles. For both sets of spectra, one LED was mounted above and one was mounted below the centre of each goggle lens. To limit the luminance of the sources, and thus minimise the risk of blue light hazard,[36] a small diffuser was placed in front of each LED. Each light goggle was powered with a 9-V battery, and light output from each goggle was controlled with an electronic controller box.

The LED goggles were calibrated prior to each experimental session using a spectrometer (Oriel Multispec 77400 with an Oriel Instaspec IV CCD detector; Newport Corporation, Irvine, CA, USA). An opal diffuser was fixed over the fibre-optic input to the spectrometer to produce the needed spatial response for measuring irradiance. The spectrometer was first calibrated for wavelength accuracy using four visible spectrum mercury emission lines from a cool-white fluorescent lamp (GE F15T8 – CW; GE Lighting, East Cleveland, OH, USA) and the 632.8 nm emission line from a helium–neon laser (Melles Griot 05-LHP-141; CVI Melles Griot, Albuquerque, NM, USA). The output of the spectrometer was calibrated for spectral irradiance ($W/(m^2 \cdot nm)$) from readings taken at a prescribed distance (1.00 m) from a tungsten–halogen lamp standard (lamp #12, 75 W Q/CL) traceable to the National Institute of Standards and Technology. Each goggle lens was then placed in a measurement jig that held it approximately 2 cm from the spectrometer input diffuser – the typical distance between a participant's cornea and the lens.

Spectral irradiance levels were iteratively measured to reach 40 lux (0.401 W/m^2 for 470 nm and 0.182 W/m^2 for 630 nm). Previous studies showed that 40 lux of both red and blue lights increased nocturnal alertness after a 45-minute exposure and that the blue light

was predicted to be above threshold and below saturation for melatonin suppression.[19] It has already been established that the acute alerting effect of light is not simply a melanopsin response, which is insensitive to red light. Therefore, we equated the stimuli according to the orthodox photopic luminous efficiency function (lux), which has sensitivity at long wavelengths. This does not imply, however, that the spectral sensitivity of the acute alerting effect of light is accurately characterised by this spectral weighting function.

The light levels for the daylight (Dy) and darkness (Dk) sessions at each work station were continuously monitored with a calibrated light meter[37] permanently mounted at eye level on the desktop with its photosensor directed toward the window. The average daylight illuminance measured at eye level on the desktop during the weeks that participants were exposed to daylight was 836 ± 387 lux; the average corneal illuminance level was 0.3 lux during the nighttime and dark conditions.

2.3. Outcome measures

Performance was measured using the 54-minute, Multi-Attribute Task (MAT) Battery for Human Operator Workload and Strategic Behavior Research software program (NASA COSMIC collection, Open Channel Foundation). The MAT battery is comprised of (i) a monitoring task, (ii) a tracking task, (iii) a communication task, and (iv) a resource management task. Only data from the tracking task are presented here because it has previously been shown to be the most sensitive of the MAT battery tasks to performance decrements at night. For the tracking task, the highly practiced subjects used a joystick to maintain a moving circle on a fixed target presented at the centre of a computer-generated display. Average deviation distances of the circle from the target for 1 minute were recorded. The root mean square (RMS) data from a subject represent the 1-minute average pixel deviations from the central target over six 9-minute epochs (i.e. over 54 minutes); higher values of the RMS deviations indicate poorer performance. Tracking periods took up 70% of each test session.

Prior to and just after performing the MAT battery, subjects completed the KSS, a nine-point scale used to assess their subjective sleepiness; higher values of KSS indicate that subjects felt sleepier.

2.4. Procedures

Participants were continuously awake for 26 hours from 07:00 Friday morning to 09:00 Saturday morning during all four experimental sessions. Each session was separated by at least one week. The study was conducted at the Lighting Research Center in Troy, NY, USA from mid-January 2010 to mid-March 2010. For the DyR session, participants were exposed to approximately 65 minutes of red light every 4 hours from the custom-made LED goggles. These red-light exposures were presented against a background of daylight during the day and of darkness at night. Performance on the 54-minute tracking task was measured every 4 hours during the red-light exposures; the KSS questionnaire was administered just before and just after performing the tracking task. The same session protocol was followed for the DkR session, the DyB session, and the DkB session; the blue-light LED goggles delivered the light during the DyB and the DkB sessions. For each session, either the blue or the red lights were always energised at 08:00 on Friday morning and again every 4 hours, at 12:00, 16:00, and 20:00, through Saturday morning at 00:00, 04:00, and 08:00. Energised LED goggles were continuously worn 10 minutes prior to the start of and throughout the performance test. Performance tests were completed at 09:05, 13:05, 17:05, and 21:05

on Friday and 01:05, 05:05, and 09:05 on Saturday morning.

Upon arrival at the laboratory, each participant was assigned to a desk space to be shared with one other participant. Desks were positioned in front of west-facing windows that overlooked a courtyard. Windows were covered with black curtains at 17:00 in every Dy session and for the entire day during every Dk session. Participants used these desks to work on their computers, watch movies, play computer games, or read. Personal laptops were dimmed down and covered with orange filters with a transmittance of less than 2% from 380 nm to 550 nm (Roscolux Filter, #21 Golden Amber: Rosco Laboratories, Inc., Stamford, CT, USA) to prevent additional light from contributing to circadian stimulation. Participants were asked to remain seated at their desk and to get up only to use the restroom, which was nearby and illuminated with red (<1 lux from LEDs, $\lambda_{max} = 640 \pm 1$ nm, FWHM $= 18 \pm 1$ nm) traffic lights.

2.5. Data analyses

The tracking task scores were determined for each participant, as were the grand average scores from all individuals. Normalisation factors were then determined for each participant based upon the ratio of that individual's mean value to the grand mean value. Scores were then multiplied by the reciprocal of the associated participant's normalisation factor; these normalised values were then used in the subsequent statistical analyses. These data normalizations minimise inherent individual differences in the performance capabilities; without this normalisation the data from one participant could systematically affect the inferences drawn from the study.[38]

Some performance data were lost due to computer malfunctions or complications with starting the MAT battery program. One participant did not have data from test periods 17:05, 21:05, and 09:05 (Saturday morning) during the DkR session. Data from 12 participants who had complete sets were included in the analyses and are reported here. The 2 (daylight: daylight vs. darkness) $\times$ 2 (coloured light: red vs. blue) $\times$ 7 (time: 7 sampling times) repeated measures analysis of variance (ANOVA) was performed using the normalised tracking scores. *Post hoc*, two-tailed paired Student's *t*-tests were performed to further investigate the main effects and interactions. Data from 13 subjects were used in the 2 (daylight: daylight vs. darkness) $\times$ 2 (coloured light: red vs. blue) $\times$ 7 (time: 7 sampling times) ANOVA that was performed for the normalised KSS scores. Although KSS responses were obtained prior to (first period) and just after (second period) the participants completed the tracking task, only the second-period data were used in the ANOVA for the normalised KSS data.

3. Results – Experiment 1

The repeated measures ANOVA using the normalised performance data revealed a significant main effect of daylight ($F_{1,11} = 13.2$; $p = 0.004$) and of time ($F_{6,66} = 29.4$; $p < 0.0001$) and a significant daylight by time interaction ($F_{6,66} = 2.9$; $p = 0.01$). Participants performed significantly better in sessions when they were exposed to daylight than in sessions when they remained in the dark. The mean $\pm$ standard error of the mean normalised tracking scores (RMS) was 25.3 ± 0.5 during sessions when daylight was available and 28.9 ± 0.5 when it was not. The main effect of coloured light was not statistically significant ($F_{1,11} = 2.9$; $p = 0.12$) nor was the daylight by coloured light interaction ($F_{1,11} = 2.1$; $p = 0.17$). *Post hoc* two-tailed paired Student's *t* tests revealed that performance was significantly worse at night (05:00) in the dark sessions than in the Dy sessions ($t_{23} = -3.6$, $p = 0.002$). There was also a significant difference in tracking scores between the daylight and

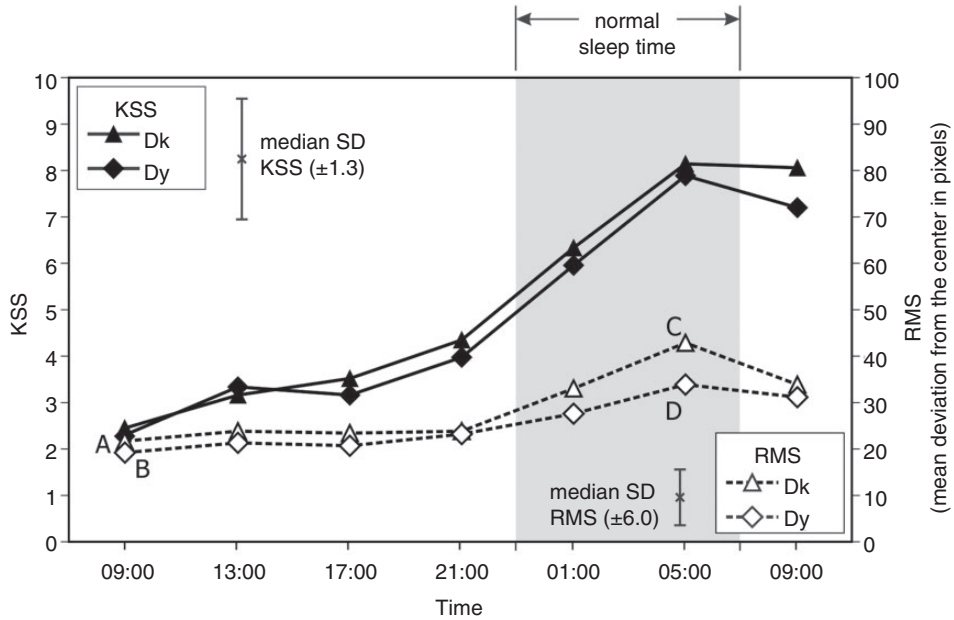

Figure 1. Self-reports of sleepiness using the KSS questionnaire (solid symbols) and normalised scores for the 54-minute MAT tracking task performance scores (open symbols) for different sampling times during continuous wakefulness for the two daylight (Dy) and the two darkness (Dk) sessions. Better performance and less feelings of sleepiness are represented by lower values on each ordinate. Performance was significantly better ($p<0.05$) at the first sampling time (09:00) in the Dy session (B) than in the Dk session (A). Also, performance was significantly better ($p<0.01$) at the sixth sampling time (05:00) in the Dy session (D) than in the Dk session (C). KSS responses were not statistically different for any sampling time

dark sessions at the first sampling time (09:00; $t_{23}=-2.5$, $p=0.02$). Using the KSS data, only the main effect of time was statistically significant ($F_{13,156}=40.1$; $p<0.0001$). These effects are shown in Figure 1.

4. Method – Experiment 2

4.1. Subjects

Eight subjects (mean ± SD 37.1 ± 14.3 years of age; two females), who participated in experiment 1 were available to participate in the follow-up, two-session study; Rensselear's institutional review board approved the study. The mean ± SD MCTQ score was 2.8 ± 1.6. Participants were kept on a fixed schedule starting one week prior to the first experimental session. To assure compliance with the schedule and to minimise practice effect on the performance tests, participants came to the laboratory Monday through Thursday at 07:30 for the 54-minute performance test. They also wore wrist actigraphs; the actigraph data were used to confirm bedtimes. Participants were asked to refrain from alcohol and caffeine on the days of the experiment and were asked not to sleep after awakening for the day.

4.2. Lighting conditions

Subjects experienced two lighting conditions: (1) total darkness (DkT), where subjects remained in continuous dim ambient light (<1 lux from red LEDs, same as experiment 1) during the entire 26-hour session and (2) daylight/blue (DyB-2), where subjects

experienced the same condition as described in experiment 1.

4.3. Procedures

A within-subject, two-session laboratory study was performed where subjects were continuously awake for 26 hours from 07:00 Friday morning to 09:00 Saturday morning. Experiment 2 was conducted in October 2010 and separated by one week. The study was conducted at the Lighting Research Center in Troy, NY, USA. For the DyB-2 session, participants were exposed to the same exact conditions as in Experiment 1, namely, the custom-made LED goggles delivered blue light for 1 hour every 4 hours against a background of daylight during the day and of darkness at night. Performance on the 54-minute tracking task was measured starting 10 minutes after the blue light goggles were energised; the KSS questionnaire was administered at the start and end of each performance test. For the DkT session, subjects remained in dim light for the duration of the session; the KSS questionnaire and the tracking task were administered at the same times as in the DyB-2 session.

4.4. Data analyses

Data obtained during the daylight/blue session from the eight subjects who participated in the first experiment (DyB-1) were used in the statistical analyses for the second experiment. Mean tracking task scores from each of the eight participants were determined using the data from the DyB-1 as well as those obtained in the second experiment (DkT and DyB-2), as was the grand average scores from all eight participants. Normalisation factors were then determined for each participant based upon the ratio of that participant's mean value to the grand mean value. These data normalisation process were the same as used in the first experiment using only those data obtained from the eight participants during the DyB-1, DyB-2, and DkT sessions. Again, this normalisation procedure minimises inherent individual differences in the performance capabilities of subjects; without this normalisation the data from one subject could systematically affect the inferences drawn from the study.[38,41]

For the normalised tracking task scores, a 3 (daylight: DyB-1, DyB-2, and darkness: DkT) by 7 (time: seven sampling times) repeated measures ANOVA was performed. One subject experienced equipment failure for one sampling time (05:00) during DyB-2, so performance data from that subject were not obtained at that sampling time. To perform the ANOVA, the tracking task score from DyB-1 at 05:00 was used as the tracking task score for DyB-2 at 05:00. Statistically significant effects from the ANOVA were examined using *post hoc*, two-tailed paired Student's *t*-tests. For the KSS data, one ANOVA utilised the same variables as those used in the tracking task score data. KSS responses were obtained prior to (first period) and just after (second period) the participants completed the tracking task; only the second-period data were used in the ANOVA for the normalised KSS data that was conducted using data from the eight participants.

5. Results – Experiment 2

Figure 2 shows the tracking task scores over 26 hours of wakefulness during the DkT session and during the two DyB sessions. The tracking task score ANOVA revealed a significant main effect of sampling time ($F_{6,42} = 15.03$; $p < 0.0001$) and a significant sampling time by daylight interaction ($F_{12,84} = 2.08$; $p = 0.026$); the main effect of daylight was not significant ($F_{2,12} = 1.05$; $p > 0.05$). *Post hoc* two-tailed paired Student's *t*-tests showed that tracking task scores obtained in the DkT session were significantly worse (higher RMS) than those obtained in both DyB sessions at the 05:00

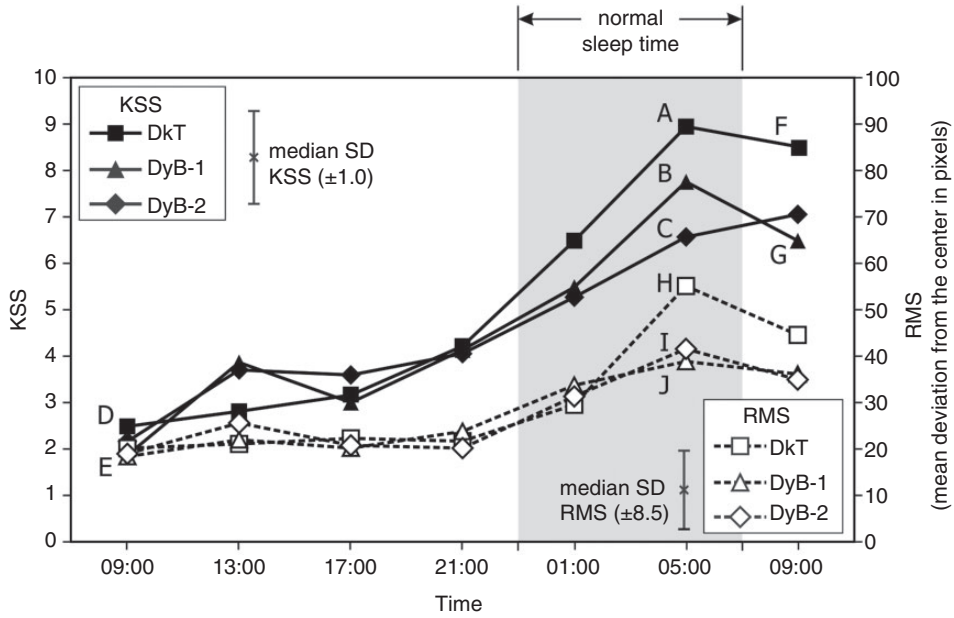

Figure 2. Self-reports of sleepiness using the KSS questionnaire (solid symbols) and normalised scores for the 54-minute MAT tracking task performance scores (open symbols) for different sampling times during continuous wakefulness for two daylight/blue sessions, one from experiment 1 (DyB-1) and one from experiment 2 (DyB-2), and for the total darkness session from experiment 2 (DkT). Better performance and less feelings of sleepiness are represented by lower values on each ordinate. Subjects reported feeling significantly sleepier at 05:00 in the DkT session (A) than in both the DyB-1 (B) and DyB-2 (C) sessions ($p<0.05$). Subjects also reported feeling significantly sleepier in the DkT session at 09:00 Friday (D) and at 09:00 Saturday (F) than at the same times (E and G) in the DyB-1 session ($p<0.05$). Performance was significantly worse at 05:00 in the DkT session (H) than at the same time in the DyB-1 (J) and the DyB-2 (I) sessions

sampling time (DyB-1: $t_7=2.35$, $p=0.05$; DyB-2: $t_7=3.22$, $p=0.015$).

Figure 2 also shows the second-period (after completing the tracking task) KSS results. As with the RMS tracking task ANOVA, there was a significant main effect of sampling time ($F_{6,42}=22.64$; $p<0.0001$) and a significant sampling time by daylight interaction ($F_{12,84}=2.84$; $p=0.003$), but the main effect of daylight was not significant ($F_{2,14}=1.97$; $p>0.05$). As with the tracking task scores, the *post hoc*, two-tailed paired Student's *t*-test showed that subjects reported feeling sleepier at 05:00 in the DkT session than in both of the DyB sessions (DyB-1: $t_7=2.38$, $p=0.049$; DyB-2: $t_7=2.63$, $p=0.03$). Subjects also reported feeling sleepier at 09:00 (Friday) and at 09:00 (Saturday) in the DkT session than in the DyB-1 session ($t_7=3.24$, $p=0.01$ and $t_7=3.41$, $p=0.01$, respectively).

6. Discussion

Based upon observations in the laboratory of subject behaviour during sessions of prolonged wakefulness (e.g. no sleep for more than 24 hours), we hypothesised that performance at night would be worse if subjects stayed in a dark room during the day than if they stayed in a brightly illuminated room during the day. Experiment 1 was designed to statistically compare performance at night

after exposure to daylight and to darkness during the day. The results supported our hypothesis showing that performance on a 54-minute tracking task was significantly better at night (05:00) following daylight exposure than it was following darkness during the day. Performance scores over one 26-hour session in experiment 1 were replicated in experiment 2 using a subset of participants. Also, the general findings from experiment 1 were supported and extended by including a session where performance was measured during a 26-hour session in total darkness. Performance scores were worse at night during the DkT session than during any other experimental session in either experiment.

For comparison, the present results were compared to those of Turner,[39] who also used the MAT battery with subjects that were kept continuously awake overnight. In her study, Turner compared performance with and without various amounts of caffeine intake. Nonaka compared the present results to 300 mg caffeine intake, which is equivalent to about 2–4 cups of coffee.[40] The comparisons showed that at 05:05 tracking for the DyB condition, for example, was lower (i.e. better performance) than for tracking by those who took 300 mg of caffeine. Future research should investigate the additive effects of daylight exposure and caffeine on nighttime performance.

Although the present set of studies shows evidence for a daylight carryover effect, the relative magnitude of the daylight exposure carryover effect into the night cannot be unambiguously determined from either of our two studies. By balancing the two intermittent coloured light (red and blue) exposures in both the Dk sessions and the Dy sessions in experiment 1, it was possible to demonstrate that exposure to daylight during the day had a carryover effect into the night during prolonged wakefulness. It can be reasonably assumed from earlier work[22] that the coloured lights increased performance and decreased sleepiness at night (i.e. at 05:00), but the magnitude of their effects cannot be isolated. The balanced design employed in experiment 1 only enabled us to infer that the coloured light exposures had no differential effects on performance and sleepiness. Additional research will be required to assess the magnitudes of the contributing effects from coloured light exposures as they might affect performance and subjective sleepiness at night during prolonged wakefulness.

We also hypothesised that daylight would have only a modest impact on performance during the day. Figure 1 showed slightly better performance throughout the three daytime sampling times for the Dy sessions than for the Dk sessions, but the only statistically significant difference between daylight and darkness occurred at the first sampling time (09:05) in experiment 1. An examination of the data revealed that the difference in the mean values of the Dy sessions and the Dk sessions was essentially the same throughout the daytime sampling times (09:05, 13:05, and 17:05); this can be readily seen in Figure 1. However, the variance in the *post hoc* paired Student's *t*-tests increased steadily from the first, to the second, to the third daytime sampling times, although this cannot be seen in Figure 1. Thus, the increased variance in the paired Student's *t*-tests across the daytime hours compromised statistical significance even though the differences in the mean values for daylight and dark sessions were essentially the same. Regardless, the impact of light on performance at the tracking task was smaller during the day than at night, as hypothesised. The hypothesised modest effect of daytime light on performance and sleepiness was more strongly supported by results from experiment 2. For all of the daytime sampling times, exposure to light in the two Dy sessions (DyB-1 and DyB-2) did not enhance performance relative to the Dk session (DkT; Figure 2).

Lafrance *et al.*[41] also showed that light had little effect on performance during the day.

In that study, participants were exposed to 9000–13 000 lux at eye level from late morning to early afternoon (between 09:00 and 13:00) after two consecutive nights of 4-hour sleep restriction. There were no significant effects on subjective alertness and global performance. Badia *et al.*[29] also showed that bright light exposure (2500 lux at the eye level) increased performance and alertness at night, but not during the daytime hours. Smolders *et al.*[42] did show, however, that 1000 lux at the eye level of a 4000 K light source improved performance in an auditory psychomotor vigilance task compared to lower light levels (200 lux at the eye level). They did not run a dark control condition, so it is not known whether the 200 lux condition would still be significantly better than darkness during the day. Figueiro and Rea[22] also showed that blue-light exposure (40 lux at eye level) improved short-term reaction time throughput (Tput) at 12:00 and matching to sample Tput in the late afternoon, but this effect was smaller during the day than at night. It should be noted, however, that the 54-minute tracking task employed in the present study was different than the short-term performance tests (i.e. 6–7 minutes) used by Figueiro and Rea.[22] It may be that the alerting effect of light could not be fully sustained for the entire duration of the tracking task. In fact, daytime light exposures have also been associated with an increase in subjective and objective markers of alertness, such as fMRI and KSS.[26,27] As suggested by Lafrance *et al.*[41] an increase in alertness by light exposure may induce a change in strategy adopted by individuals who, in their studies, increased speed at the expense of more errors. Therefore, light may result in an acute increase in alertness during the day that may not be translated into improved, sustained performance. Further studies need to be carried out to investigate the relationship between the light-induced alertness and both short-term and long-term performance.

More generally, as shown in both Figures 1 and 2, performance and self-reports of sleepiness are better during the day than later during the night after prolonged wakefulness. As day turns into night, performance decreases and sleepiness increases, exhibiting peak detrimental effects at 04:00–05:00. The deterioration over the course of the 26-hour sessions probably reflects the physiological transition between the circadian time for daytime wakefulness to the time for nighttime sleep in diurnal humans.[22] Of note, the present findings are consistent with those from Monk *et al.*[43] showing that performance is usually worse between 03:00 and 05:00. Also, consistent with this postulate and with previous literature concerning the impact of circadian time on human physiology,[44,45] performance increased and self-reports of sleepiness decreased during the last sampling time (09:05) even though subjects had been continuously awake for more than 24 hours.

Finally, the present results have implications for the design of buildings because prolonged absence from daylight exposure in buildings, such as that which may occur during winter months at higher latitudes, may be associated with poor performance during the day as well as during the night. The present results may also have implications for shift workers, who have to maintain performance at night, when the levels of alertness decline. Future studies could investigate whether a personal lighting scheme that might include daylight exposure upon awakening in the afternoon and, when awake at night, exposure to intermittent red light can improve performance in the field. Of note, the use of red light at night instead of blue light should help maintain alertness without suppressing the hormone melatonin. The hormone melatonin is produced by the pineal gland at night and in darkness. Suppression of nocturnal melatonin by light at night exposure resulting in circadian disruption has been associated with increased risk for sleep disorders and even cancer.[46]

Munch *et al.*[47] showed that a 6-hour exposure to daylight (approximately 985 lux at eye level) starting 4 hours after waking for two consecutive days improved evening performance in the second day of the experiment when compared with exposure to 176 lux at the cornea of a 3700 K light source. Combined with the present results, it is reasonable to hypothesise that prolonged absence from daylight exposures, such as may occur during winter months at extreme latitudes, may ultimately lead to poor performance during the day as well as during the night. These speculations are important to test experimentally because those results might support the widely held, but heretofore unsubstantiated, belief that daylight improves productivity.

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