Exposure to Short Wavelength-Enriched White Light and Exercise Improves Alertness and Performance in Operational NASA Flight Controllers Working Overnight Shifts

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Objective: We evaluated the efficacy of a combined short-wavelength-enriched white light and exercise fatigue countermeasure during breaks for flight controllers working overnight shifts. **Methods:** Twenty NASA flight controllers were studied for two blocks of nightshifts in ISS mission control, randomized to either the control or countermeasure condition. The countermeasure constituted passive exposure to blue-enriched polychromatic lighting for three 20-minute intervals, which included 10 minutes of exercise and occurred before and twice during their shifts. Alertness, performance, and mood were evaluated. **Results:** Flight controllers reported being significantly more alert ($P < 0.0001$) and happy ($P = 0.003$) and had faster reaction times (10% slowest responses; $P < 0.05$) during the countermeasure condition

Learning Objectives

- Discuss the physiologic challenges to sleep and circadian systems associated with nightshift work and the role of countermeasures to improve alertness.
- Summarize the design and implementation of a combined light and exercise countermeasure for NASA flight controllers working overnight shifts.
- Describe the countermeasure's effectiveness in terms of alertness, performance, and mood.

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Dr Lockley reports commercial interests from the last 3 years (2017–2020) unrelated to the study reported herein but are reported in the interests of full disclosure. SWL has received consulting fees from the BHP Billiton, Delos Living LLC, EyeJust Inc., Noble Insights, Pegasus Captital Advisors, The Rec Room, and Team C Racing; honoraria and/or paid travel from BHP Billiton, DIN, Emory University, IES, Ineos, MIT, Roxbury Latin School, SLTBR, Solemma and Teague; has current consulting contracts with Akili Interactive; Apex 2100 Ltd.; Consumer Sleep Solutions; Headwaters Inc.; Hintsa Performance AG; KBR Wyle Services LLC, Light Cognitive; Lighting Science Group Corporation; Look Optic, Mental Workout; PlanLED; Six Senses; Stantec View Inc.; has received unrestricted equipment gifts from Bionetics Corporation and F. Lux Software LLC; royalties from Oxford University Press; and has served as a paid expert in legal proceedings related to light, sleep and health. He is an unpaid Board Member of the Midwest Lighting Institute (non-profit) and was the Program Leader for "Safety and Productivity Improvements" in the CRC for Alertness, Safety and Productivity from 2015–2019. Dr Lockley's interests were reviewed and managed by Brigham and Women's Hospital and Partners HealthCare in accordance with their conflict of interest policies.

Dr Czeisler reports grants to BWH from FAA, NHLBI, NIA, NIOSH, NASA, and DOD; is/was a paid consultant to AARP (2018), American Academy of Dental Sleep Medicine (2017, 2018), Eisenhower Medical Center (2018), Emory University (2019), Ganésco, Inc. (2017), Inselspital Bern (2019), Institute of Digital Media and Child Development (2017, 2018, 2019), Klarman Family Foundation (2017, 2018, 2019), M. Davis and Co (2018), Physician's Seal (2019), Samsung (2016), Sleep Research Society Foundation (2019), State of Washington Board of Pilotage Commissioners (2018), Tencent Holdings Ltd (2019), Teva Pharma Australia (2019, 2020), UC San Diego (2018), University of Michigan (2017), University of Washington (2017, 2018), and Vanda Pharmaceuticals Inc (2017, 2018, 2019, 2020), in which Dr Czeisler also holds an equity interest; received travel support from Annenberg Center for Health Sciences at Eisenhower (2018), Aspen Brain Institute (2018), Bloomage International Investment Group, Inc. (2018, 2019), UK Biotechnology and Biological Sciences Research Council (2019), Bouley Botanical (2017, 2018, 2019), Dr Stanley Ho Medical Development Foundation (2019), European Biological Rhythms Society (2017, 2019), German National Academy of Sciences (Leopoldina) (2019), Illuminating Engineering Society (2018), National Safey Council (2017, 2018, 2019), National Sleep Foundation (2017, 2018, 2019), Society for Research on Biological Rhythms (2018), Sleep Research Society Foundation (2018), Stanford Medical School Alumni Association (2019), Tencent Holdings Ltd (2019), University of Zurich (2018), and Vanda Pharmaceuticals Inc (2017, 2018, 2019), Ludwig-Maximilians-Universität München (2018), National Highway Transportation Safety Administration (2018), Office of Naval Research (2018), Salk Institute for Biological Studies/ Fondation Ipsen (2018), The National Academy of Sciences, Engineering, and Medicine (2017), The Wonderful Company (2017), Department of Defense (2017); receives research/education support through BWH from Cephalon, Mary Ann & Stanley Snider via Combined Jewish Philanthropies, Jazz Pharmaceuticals PLC Inc (2017, 2018, 2019, 2020), Philips Respironics Inc (2017, 2018, 2019, 2020), Regeneron Pharmaceuticals (2018, 2019, 2020), Teva Pharmaceuticals Industries Ltd, Sanofi SA, Optum, ResMed, San Francisco Bar Pilots, Sanofi, Schneider, Simmons, Sysco, Philips, Vanda Pharmaceuticals; is/was an expert witness in legal cases, including those involving Advanced Power Technologies, Aegis Chemical Solutions LLC (2019), Amtrak (2019); Casper Sleep Inc (2019), C&J Energy Services (2019), Complete General Construction Co (2017), Dallas Police Association (2019), Enterprise Rent-A-Car (2019), Espinal Trucking/Eagle Transport Group LLC/Steel Warehouse Inc (2017, 2018, 2019), FedEx, Greyhound Lines Inc/Motor Coach Industries/FirstGroup America (2017, 2018, 2019), Pomerado Hospital/Palomar Health District (2017, 2018), PAR Electrical Contractors Inc (2019), Product & Logistics Services LLC/ Schlumberger Technology Corp/Gelco Fleet Trust (2019), Puckett Emergency Medical Services LLC (2019), South Carolina Central Railroad Company LLC (2017, 2018), Union Pacific Railroad (2019), United Parcel Service/UPS Ground Freight Inc (2017, 2018), and Vanda Pharmaceuticals (2019, 2020); serves as the incumbent of an endowed professorship provided to Harvard University by Cephalon, Inc.; and receives royalties from McGraw Hill, and Philips Respironics (2017, 2018, 2019) for the Actiwatch-2 and Actiwatch Spectrum devices. Dr Czeisler's interests were reviewed and are managed by the Brigham and Women's Hospital and Mass General Brigham in accordance with their conflict of interest policies.

Clinical significance: In an operational, randomized, controlled trial, a combined fatigue countermeasure of shorter-wavelength light exposure and exercise was feasible to implement, acceptable night-shift workers and improved their alertness, performance and mood. These results have wide-spread implications in occupational environments where it is important for workers to perform optimally during overnight hours.

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compared to control. **Conclusions:** The combined light and exercise countermeasure improved alertness, performance, and mood in shift workers overnight. Further research is necessary to determine their relative contribution.

Keywords: circadian, light, performance, shift work, sleep

Nearly 15 million American employees work during the overnight hours.[1] Working the night shift presents a physiological challenge to the sleep and circadian systems. Not only does the night worker need to be awake when the brain is programmed to be asleep, but also needs to sleep when the brain is programmed to be awake. Full adaption to the shifted work and sleep–wake schedule is difficult and rare. Consequently, the most commonly reported symptoms of shift workers are sleep disturbance and excessive sleepiness.

Development of effective countermeasures to improve alertness at work is important, especially in safety sensitive professions such as first responders and healthcare workers. Appropriately timed light, the most powerful cue to the circadian clock, has been used to facilitate adaptation to night work.[2,3] In a laboratory study, exercise during simulated night shift has been shown to be an effective behavioral countermeasure to facilitate shifting circadian rhythms.[4]

In the mission control room at NASA's Johnson Space Center in Houston, flight controllers monitor and interact with the crewmembers on the International Space Station (ISS). For mission success and the well-being and safety of crewmembers, it is essential that they remain alert and have good communication. NASA was interested in the potential of the combination of exercise and light serving as a practical fatigue countermeasure for controllers working the night shift. Rodent studies have shown the complex relationship between light, exercise and the circadian system.[5–8] In humans, two studies have shown that exercise did not facilitate or inhibit bright light induced shifts in circadian timing.[9,10]

Although these circadian resetting properties of light and exercise may be useful when shift schedules permit adaptation, for example, on remote oil rigs with 14 night shifts in a row[11] and onsite facilities that enable sleep in darkness during the daytime, under ordinary circumstances most shiftwork schedules have either insufficient sequential nights or rotating schedules that preclude adaptation.[12] In these cases, countermeasures that improve alertness directly during the nightshift are needed. In addition to resetting the clock, light is an acute stimulant and improves alertness directly in the workplace.[13] In particular blue- and blue-enriched lighting has been shown to be an effective stimulant,[9,14] and has been shown to decrease sleepiness in night workers.[15,16] Intermittent exposure to blue-enriched lighting in operational night shift workers has not been studied. In more limited studies, exercise has also been shown to increase alertness acutely.[17,18] To our knowledge, the combined effect of these two countermeasures has not been evaluated in an operational setting during night shift work.

Therefore, we evaluated the acceptability and efficacy of a combined light and exercise countermeasure to maintain a high level of alertness and performance of ISS flight controllers while working the overnight shift.

METHODS

We recruited flight mission controllers who direct ISS operations at Johnson Space Center in Houston, TX. Twenty controllers who worked in flight control at NASA Johnson Space Center (9F, 33.3 ± 8.0 yrs [mean ± SD], range 25–50 yrs) enrolled in the study. Each participant was studied for two blocks of five consecutive overnight shifts (11 PM–8 AM on subsequent nights) during the study. The control and experimental conditions were counter-balanced. Each data collection block was scheduled to be preceded by 2 weeks of dayshifts.

Countermeasure Schedule

Under standard conditions, flight controllers only take breaks during a loss of signal/communication with the ISS. For this study, we coordinated with NASA management (Flight Directors) to ensure that flight controllers would be allowed to take two 20-minute breaks during each overnight shift in the experimental condition. Controllers were directed to take one break during the first half of their shift (11:00 PM–3:30 AM) and one during the second half of their shift (3:30 AM–8:00 AM). During the experimental condition, controllers went to the experimental break room before the shift to exercise and complete the questionnaire and performance testing and after the overnight shift to complete the questionnaire and performance testing in addition to the two breaks during the shift.

Combined Light/Exercise Countermeasure

We created an experimental break room that participants used during the experimental condition. The experimental break room provided participants with passive exposure to blue-enriched fluorescent lamps installed in existing ceiling fixtures (Correlated Color Temperature [CCT] 8000K, FO32/SKYWHITE/XP/ECO, Osram Sylvania, Westfield, IN). After installation of the new lamps in the experimental break room, the mean light levels were 179 ± 59 photopic lux when measured at 54″ in the vertical plane (4 measures 90° apart, approximate eye level), across 13 locations (IL1400 radiometer with an SEL-033/Y/W detector, International Light, Inc., Newburyport, MA). For comparison, light levels in Mission Control (4100 K fluorescent lamps) averaged 63 ± 17 lux at 54″ in the vertical plane across 23 locations.

Measures of the Spectral Power Distribution (SPD) of the lights (PR-650 SpectraScan Colorimeter with a CR-650 cosine receptor, PhotoResearch Inc., Chatsworth, CA) were used to calculate CIE standard international (SI) units calibrated for melanopsin sensitivity (see Footnote;[19]). The melanopic Equivalent Daylight (D65) Illuminance (EDI) was 31 melanopic lux for Mission Control, and 168 melanopic lux in the experimental break room. The melanopic Daylight Equivalent Ratios (DER), an overall indication of the relative melanopic strength of the spectra, were 0.50 and 0.94 for Mission Control and Experimental Breakrooms, respectively (Fig. 1).

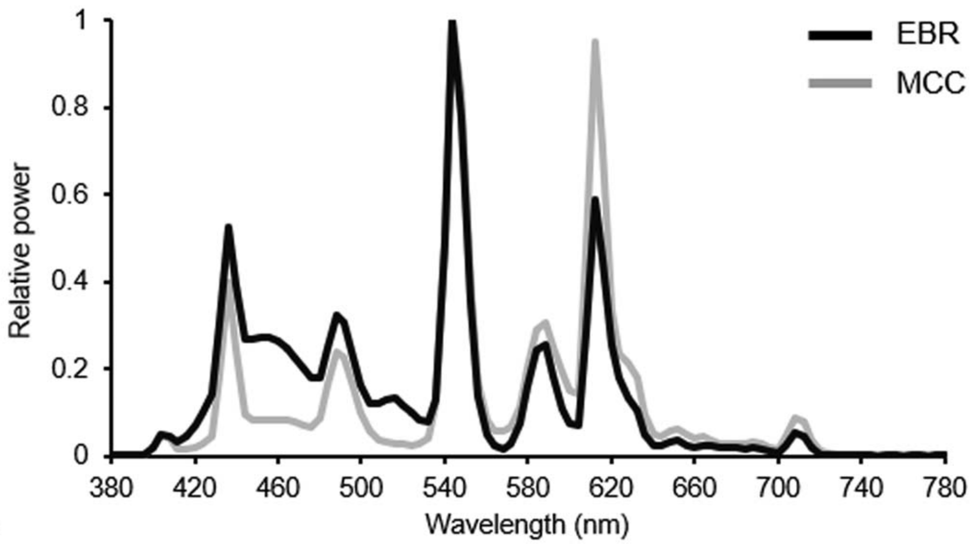
Participants were encouraged to exercise on treadmills or stationary bikes that were provided in the experimental break room (10 min bouts, not to exceed more than 65% maximum heart rate before their shift and during the two breaks. Maximum heart rate was based on the standard 220-age equation and feedback was provided as a function of the heart rate monitor as this limit was approached. Acceptance of the experimental break room with the short wavelength-enriched lighting and the use of exercise equipment was measured via compliance with the protocol. At the end of each shift, controllers reported whether they used the exercise equipment, for how long and whether they reached 65% of their maximum heart rate.

Outcomes

During the experimental condition, questionnaires and performance tests were completed during their time in the experimental break room. A location to complete the questionnaire and performance tests was not specified for those in the control condition, only that they should continue their normal routines during the control overnight shifts.

During each block of data collection, flight controllers continuously wore wrist Motionlogger actigraphs (Ambulatory Monitoring, Inc., Ardsley, NY) to collect rest/activity and light exposure patterns.

[1] As the 'non-visual' responses to light peak at approximately 480 nm, standard photopic illumination measures such as lux or footcandles, which are calibrated for the human color vision (photopic) system (which peaks at 555 nm), do not accurately express the 'strength' of the light stimulus for non-visual responses. While Correlated Color Temperature (CCT) has been used as a shorthand to predict the non-visual effects of light (as higher CCT light sources tend to have more short wavelength light), CCT is also not sufficiently accurate to quantify 'non-visual' light. New standard international (SI) units have therefore been provided by the CIE to define light for these purposes[19]) and these units are also provided herein.



A

B

	Photopic lux	S-cone-opic α-opic EDI (lux)	M-cone-opic α-opic EDI (lux)	L-cone-opic α-opic EDI (lux)	Rhodopic α-opic EDI (lux)	Melanopic α-opic EDI (lux)	Melanopic DER
EBR	179	191	178	176	172	168	0.94
MCC	63	29	53	63	37	31	0.50

FIGURE 1. (A) Spectral power distribution of the Experimental Break Room and Mission Control Center (MCC) lighting. (B) Photopic illuminance (lux) and the corresponding human retinal photoreceptor weighted α-opic equivalent daylight (D65) illuminances (α-opic EDI) and the melanopic Daylight Equivalent Ratio (DER) calculated according to CIE S 026/E:2018.[19]

The Motionlogger is a battery-operated device, the size of a watch, and is worn on the wrist of the non-dominant hand. Sleep was estimated for each day using the Action-W version 2.0 software (Ambulatory Monitoring, Inc., Ardsley, NY; UCSD algorithm with rescoring). To assist in the interpretation of the Motionlogger data, controllers completed daily sleep/wake logs as part of their morning routine. The logs also provided a subjective assessment of alertness and information regarding the use of fatigue countermeasures. The controllers also wore a heart rate monitor (Polar RS400 Heart Rate Monitor, Polar Electro Oy, Kempele, Finland) during each shift.

Mood, alertness, and performance were assessed before, twice during and following each shift. Controllers rated sleepiness using the Karolinska Sleepiness Scale (KSS).[20] Ratings ranged from 1 (very alert) to 9 (very sleepy, great effort to keep awake, fighting sleep). Visual analog scales (VAS) were competed to evaluate the mood, alertness, and physical well-being of the subjects. The scale consisted of a horizontal line drawn with each end of the line labeled with the extremes of a subjective continuum and the controller marked a position on the line between the two defined endpoints that best described how he or she felt at that moment. The dependent measure was the relative distance (mm) of the hash mark from the left end of the continuum. Word pairs included sleepy-alert, happy-sad, hostile-friendly, interested-bored, withdrawn-sociable, stressed-relaxed, physically exhausted-energetic, motivated-unmotivated, and sick-well.

Objective performance was evaluated using the Psychomotor Vigilance Task (PVT). The PVT is a measure of sustained attention performance[21] where the controller was required to maintain the fastest possible reaction time to a simple visual stimulus. Controllers completed a validated 5-minute version of the PVT[22–24] to accommodate the time-constrained operational environment on a handheld Palm Tungsten E2 Personal Digital Assistant (Palm, Inc., Sunnyvale, CA).

At the end of each work shift, controllers completed questions about subjective performance and productivity during the shifts, eye strain and the use of the caffeine and photic and exercise countermeasures. A post-study questionnaire was administered to assess the controllers' attitudes towards the fatigue countermeasure employed in the experimental break room.

Analysis

Data are reported as mean ± standard deviation. Mixed models were used to evaluate differences between conditions (overnight control and overnight experimental), across shift duration (pre-shift, first half of shift, second half of shift and post-shift), across consecutive shifts (1, 2, 3, 4, and 5) with ''participant'' as a random effect. Analysis was conducted using SAS 9.3 (SAS Institute, Cary, NC) and alpha level was set at 0.05.

Partners Healthcare Research Committee approved the protocol.

RESULTS

Participants

Flight controllers reported 6.9 ± 1.1 hours of sleep in the control condition and 7.0 ± 0.8 hours of sleep in the experimental condition. Actigraphic estimates of sleep were similar: 6.7 ± 1.1 hours of sleep in the control condition and 6.9 ± 0.9 hours hours of sleep in the experimental condition. There was no significant difference in sleep duration between conditions, or modality of data collection (ie, actigraphy vs sleep diary).

Compliance

To assess protocol feasibility, we evaluated the ability for controllers to take breaks as this was a critical step in the fatigue countermeasure. On the end-of-shift questionnaires, controllers reported taking 1.96 ± 0.93 breaks during overnight control shifts and 2.73 ± 1.07 breaks during overnight experimental shifts ($P = 0.03$)

One flight controller reported never using the exercise equipment. The other 19 controllers reported using the exercise equipment during their breaks in the experimental overnight shift condition. Overall, 89% ± 24% of prescribed exercise sessions were completed; of the 19 who exercised, 94% ± 13% of sessions were

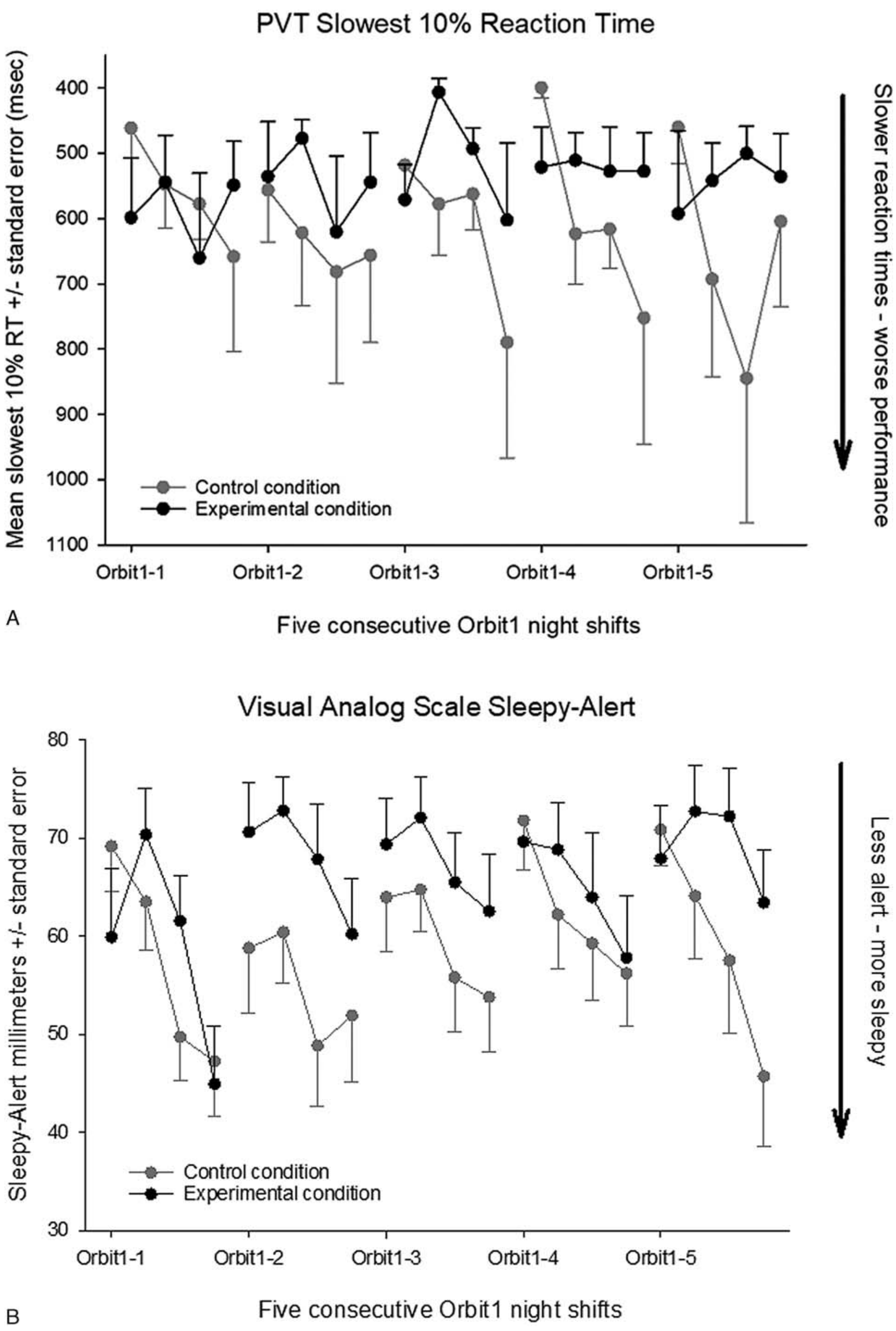


FIGURE 2. (A) Reaction time (slowest 10%) was significantly faster during the overnight experimental condition as compared to the overnight control condition ($P < 0.05$). Reaction time significantly declined throughout the duration of the shift ($P < 0.05$). (B) Similarly, controllers reported being significantly more alert in the overnight experimental as compared to the overnight control condition ($P < 0.001$). Alertness significantly declined throughout the duration of the shift ($P < 0.001$).

completed. The mean duration of exercise when undertaken was 9.9 ± 0.8 minutes. Controllers were instructed not to exceed 65% maximum heart rate (MHR). By self-report on the end-of-shift surveys, controllers reported reaching 65% MHR during $69\% \pm 40\%$ of the exercise sessions.

Caffeine

Caffeine use was reported by 80% of the participants in the experimental condition and 75% of the participants in the control condition. There was no difference in caffeine use between the control (reported 62% of nights) and the experimental conditions (reported 61% of nights).

Eye Strain, Fatigue, and Task Load

There were no differences in the ratings of eye strain, eye discomfort, mental, physical or temporal demand, performance, effort or frustration between the experimental and control conditions.

Performance

The slowest 10% reaction times on the PVT averaged 543.7 ± 311.4 ms in the experimental condition, significantly faster than the control (611.0 ± 476.9 ms) condition ($P = 0.031$). (Fig. 2A) There were no significant differences between the experimental and control conditions in PVT mean reaction time ($P = 0.11$) or number

TABLE 1. Statistical Comparison of Outcome Variables

Outcome	Condition	Consecutive Shift	Shift Duration	Interaction
Slowest 10% response time	0.0308	ns	0.0449	ns
KSS	0.0176	ns	<0.0001	ns
Sleepy/Alert	<0.0001	ns	<0.0001	ns
Happy/Sad	0.0031	ns	ns	ns
Hostile/Friendly	0.0040	ns	ns	ns
Interested/Bored	<0.0001	0.0255	<0.0001	ns
Withdrawn/Sociable	0.0001	ns	0.0253	ns
Stress/Relaxed	ns	ns	ns	ns
Physically exhausted/Energized	<0.0001	ns	<0.0001	ns
Motivated/Unmotivated	<0.0001	ns	<0.0001	ns
Sick/Well	ns	ns	0.0297	ns

P values or ns (non-significant) is indicated for comparison of condition (experimental vs control), consecutive shifts (1st, 2nd, 3rd, 4th, and 5th successive shift), and shift duration (pre-shift, first half of shift, second half of shift, and end of shift).

KSS, Karolinska Sleepiness Scale.

of lapses (reaction time >500 ms) ($P = 0.19$). There were no significant differences in performance among consecutive shifts (overnight shift 1 to overnight shift 5).

Across the duration of a shift (pre-shift, first half of shift, second half of shift, end-of-shift), mean 10% slowest reaction times ($P = 0.045$) slowed. In post hoc analysis, mean 10% slowest reaction times during the first break, second break and at the end of the shift were all slower than pre-shift on the control condition ($P = 0.018$, $P = 0.002$, and $P = 0.0001$, respectively) while there were no significant changes during the experimental condition. There were no other significant differences found in other PVT measures of reaction time or lapses of attention (Table 1).

Alertness and Mood

In the experimental condition, controllers rated themselves significantly more alert ($P < 0.0001$) (Fig. 2B), happier ($P = 0.0031$), more friendly ($P = 0.004$), more interested ($P < 0.0001$), more sociable ($P = 0.0001$), more energetic ($P < 0.0001$), and more motivated ($P < 0.0001$) as compared to the control condition. There was no significant difference between conditions on the stressed/relaxed scale. On the KSS, controllers in rated themselves sleepier in the control condition as compared to the experimental condition ($P = 0.018$). Across the five night shifts, only the interested/bored scale showed significant results ($P = 0.026$), but no consistent pattern was apparent in post hoc analysis (Table 1).

Across the duration of the shifts, controllers had higher scores on the KSS ($P < 0.0001$), reported being less alert ($P < 0.0001$; Fig. 2B), less interested ($P < 0.0001$), less sociable ($P = 0.025$), less energetic ($P < 0.0001$), less motivated ($P < 0.0001$) and less well ($P = 0.030$) compared to the pre-shift score. In post hoc analysis, all scales showed degraded reports of mood on the second break and post-shift compared to pre-shift ($P < 0.011$), except for sick/well where only the post-shift–pre-shift ratings were significantly different ($P = 0.033$). There were no other significant differences found in alertness and mood (Table 1).

Table 2 lists the means and standard deviations of all outcomes by condition, across the duration of shifts and across the five night shifts.

Subjective Rating of Combined Countermeasure

Controllers rated the impact of the fatigue countermeasure for improving alertness as 5.7 ± 1.0 on a 7-point Likert scale, anchored with by 1, "Not helpful at all" and 7, "Extremely helpful."

DISCUSSION

Using a counter-balanced design, we showed that it was feasible and acceptable to implement a combined fatigue countermeasure for flight mission controllers at NASA JSC Mission Control in an operational setting. The countermeasure consisted of short work breaks with intermittent exposure to blue-enriched white light and exercise, before and during the night shift. This combination was effective in significantly improving alertness, mood and objective measures of performance during overnight shifts.

In this study, those working overnight shifts averaged more than 6.5 hours of nightly sleep, similar to NASA mission flight controllers in a 1992 study.[25] The lack of difference in sleep duration between the control and experimental conditions suggests that the differences we observed in alertness, performance or mood cannot be ascribed to differences in sleep. Likewise, there was no difference in the use of caffeine between the experimental and control conditions, again suggesting that the difference we observed in alertness, performance or mood cannot be attributed to differences in caffeine use.

The combined fatigue countermeasure of intermittent exposure to blue-enriched light and exercise improved objective performance and measures of alertness and mood and blunted the decline in those measures that is typical across the duration of overnight shifts. The intermittent lighting countermeasure may have contributed to a shift in the circadian phase, more appropriately aligning the controllers to the night shift.[2] For example, in one lab-base study, intermittent exposure to 15-minute bouts of 9500 lux bright light was effective in circadian resetting.[26] Moreover, intermittent exercise on a simulated night shift has also been shown to facilitate phase delays[4] and may have contributed to any phase shifting that may have occurred in this study. Because we did not have a measure of circadian timing in this study, the extent that the light and/or exercise facilitated circadian alignment to the night shift is unknown. Future work using a combined countermeasure of blue-enriched white lighting and exercise should evaluate this aspect of the combined countermeasure's effectiveness.

Given that shifting the endogenous rhythm in sleepiness through photic circadian phase resetting, however, can be limited in rotating shiftworkers,[12,27] the alerting effects of light, either directly or via melatonin suppression are likely important mechanisms of action for the observed improvements in performance. Both monochromatic[14,28] and polychromatic light[29–32] have acute stimulant properties during both the night and during the day, when melatonin is not present. In a laboratory study, intermittent bright light exposure (three 30-min bouts at 1000 lux) at night improved both alertness and objective performance.[33] Outside of the laboratory, the alertness of college students was improved when exposed to bright light during evening classes.[34] and Viola and colleagues reported that even during daytime hours, exposure to blue-enriched light improved alertness, mood and subjective performance and reduced daytime sleepiness in office workers.[13]

TABLE 2. Mean ± Standard Deviation of Outcome Variables

		Control				Experimental			
Outcome		Pre-Shift	1st Half of Shift	2nd Half of Shift	Post-Shift	Pre-Shift	1st Half of Shift	2nd Half of Shift	Post-Shift
Slowest 10% response time	Shift 1	461.6 ± 182.2	547.9 ± 274.9	577.7 ± 222.3	658.2 ± 598.4	598.5 ± 353.5	544.1 ± 286.6	660.2 ± 535.2	548.7 ± 275.6
	Shift 2	556.1 ± 327.5	621.9 ± 461.4	681.5 ± 703.3	656.1 ± 553.4	535.4 ± 347.5	477.7 ± 118.9	620.2 ± 478.2	544.2 ± 310.8
	Shift 3	518.3 ± 213.9	577.6 ± 312.3	562.4 ± 225.5	789.8 ± 707.2	571.2 ± 210.9	406.5 ± 83.2	493.2 ± 117.7	602.4 ± 457.9
	Shift 4	399.7 ± 62.8	623.4 ± 314.7	616.3 ± 241.4	752.2 ± 799.6	521.4 ± 254.8	510.8 ± 169.6	527.6 ± 272.3	527.8 ± 246.9
	Shift 5	460.3 ± 222.3	692.9 ± 598.2	845.1 ± 885.5	604.2 ± 505.1	592.4 ± 525.2	542 ± 233.6	500.5 ± 170.9	535.6 ± 268.4
KSS	Shift 1	4.1 ± 1.3	4.2 ± 1.8	5.9 ± 1.5	6.1 ± 1.7	4.1 ± 1.9	3.8 ± 1.8	5.4 ± 2.1	5.9 ± 2.3
	Shift 2	4.7 ± 2.2	4.7 ± 2.0	5.9 ± 2.1	5.8 ± 2.3	3.6 ± 1.7	4.1 ± 1.7	4.7 ± 2.1	5.2 ± 2.4
	Shift 3	4.2 ± 2.0	4.4 ± 1.7	4.6 ± 1.7	5.3 ± 1.7	4.1 ± 1.7	3.8 ± 1.9	4.4 ± 1.8	5.0 ± 2.1
	Shift 4	3.6 ± 1.8	4.2 ± 1.9	4.7 ± 1.8	5.6 ± 1.5	4.5 ± 2.0	4.6 ± 2.2	4.7 ± 2.1	5.0 ± 2.3
	Shift 5	4.0 ± 1.7	4.6 ± 2.0	4.8 ± 2.3	5.9 ± 2.0	4.0 ± 1.5	4.3 ± 1.8	4.1 ± 2.0	4.7 ± 1.9
Sleepy/Alert	Shift 1	69.1 ± 18.8	63.5 ± 19.7	49.7 ± 18.5	47.2 ± 23.0	59.9 ± 29.0	70.4 ± 19.4	61.5 ± 18.8	44.9 ± 24.2
	Shift 2	58.8 ± 27.2	60.4 ± 20.7	48.8 ± 25.5	51.9 ± 27.9	70.6 ± 20.9	72.8 ± 14.2	67.8 ± 23.2	60.2 ± 23.5
	Shift 3	63.9 ± 22.5	64.7 ± 17.5	55.8 ± 22.5	53.8 ± 23.0	69.3 ± 18.0	72.1 ± 15.8	65.5 ± 18.4	62.5 ± 22.2
	Shift 4	71.8 ± 19.8	62.2 ± 22.8	59.3 ± 23.2	56.2 ± 22.1	69.6 ± 19.5	68.8 ± 26.4	63.9 ± 25.1	57.8 ± 24.0
	Shift 5	70.8 ± 15.2	64.1 ± 25.9	57.5 ± 29.3	45.7 ± 28.8	67.9 ± 22.2	72.7 ± 18.8	72.2 ± 20.2	63.4 ± 22.2
Happy/Sad	Shift 1	24.0 ± 12.1	27.4 ± 16.3	32.6 ± 16.4	28.5 ± 16.0	30.6 ± 21.5	22.3 ± 14.7	27.2 ± 15.8	28.6 ± 15.0
	Shift 2	33.4 ± 15.5	34.6 ± 19.8	34.8 ± 20.7	32.3 ± 22.7	26.7 ± 18.7	20.2 ± 11.0	24.1 ± 18.0	21.9 ± 14.6
	Shift 3	24.9 ± 15.5	26.6 ± 16.5	26.6 ± 12.3	26.8 ± 17.5	26.4 ± 12.3	25.5 ± 17.0	25.5 ± 13.1	26.9 ± 19.1
	Shift 4	23.9 ± 18.5	26.2 ± 19.2	29.1 ± 19.9	28.9 ± 20.5	25.1 ± 20.4	24.3 ± 19.5	27.7 ± 19.9	27.8 ± 19.8
	Shift 5	23.6 ± 14.7	30.0 ± 19.7	27.5 ± 18.9	32.7 ± 25.9	28.2 ± 22.3	25.9 ± 17.8	20.2 ± 14.4	19.4 ± 11.9
Hostile/Friendly	Shift 1	79.8 ± 17.6	77.3 ± 20.5	70.8 ± 20.6	76.5 ± 16.3	75.9 ± 19.5	75.2 ± 14.2	74.4 ± 19.2	74.4 ± 16.1
	Shift 2	66.5 ± 20.5	71.9 ± 18.8	69.3 ± 21.8	72.4 ± 22.3	77.9 ± 16.0	79.9 ± 14.2	74.5 ± 22.7	76.3 ± 19.5
	Shift 3	74.1 ± 21.4	73.5 ± 15.1	76.8 ± 12.5	75.3 ± 19.2	75.4 ± 14.0	80.9 ± 11.4	78.5 ± 10.6	77.5 ± 15.4
	Shift 4	80.9 ± 16.3	74.2 ± 20.0	77.1 ± 12.4	72.7 ± 19.9	79.5 ± 14.5	76.5 ± 20.8	76.1 ± 17.2	70.0 ± 18.9
	Shift 5	78.8 ± 11.8	74.3 ± 18.5	71.6 ± 22.4	65.9 ± 25.4	74.8 ± 18.7	77.6 ± 18.7	81.8 ± 14.7	83.2 ± 12.8
Interested/Bored	Shift 1	30.2 ± 18.3	26.9 ± 16.5	41.8 ± 15.9	41.6 ± 17.2	27.6 ± 18.3	26.2 ± 16.4	33.9 ± 17.8	36.0 ± 20.1
	Shift 2	38.3 ± 17.5	42.8 ± 23.0	43.9 ± 24.5	37.9 ± 19.8	33.3 ± 22.6	27.4 ± 13.7	29.1 ± 19.2	33.4 ± 22.4
	Shift 3	30.4 ± 17.2	35.4 ± 20.1	36.3 ± 17.1	37.4 ± 19.6	29.1 ± 13.3	27.3 ± 13.7	29.5 ± 11.4	33.8 ± 13.9
	Shift 4	33.6 ± 19.3	36.1 ± 21.8	43.6 ± 22.1	47.5 ± 17.5	30.3 ± 21.1	36.4 ± 22.6	35.6 ± 18.5	36.6 ± 21.8
	Shift 5	29.5 ± 18.6	41.1 ± 23.7	43.6 ± 29.9	46.8 ± 21.9	35.4 ± 19.5	30.8 ± 14.7	30.3 ± 17.6	30.5 ± 20.6
Withdrawn/Sociable	Shift 1	72.5 ± 19.6	70.4 ± 17.1	61.5 ± 19.8	67.1 ± 22.3	72.2 ± 20.6	75.4 ± 16.3	70.1 ± 19.9	65.8 ± 23.4
	Shift 2	61.3 ± 23.6	62.6 ± 22.9	62.7 ± 25.6	63.2 ± 25.6	75.6 ± 20.1	77.5 ± 15.8	71.2 ± 22.9	73.4 ± 18.1
	Shift 3	71.8 ± 19.1	68.9 ± 21.5	68.7 ± 20.6	69.0 ± 19.3	76.9 ± 13.2	76.1 ± 12.6	70.9 ± 19.3	71.3 ± 15.9
	Shift 4	75.7 ± 18.2	73.6 ± 19.4	70.9 ± 22.7	69.3 ± 21.5	74.3 ± 21.3	74.8 ± 21.3	69.9 ± 24.9	70.4 ± 24.5
	Shift 5	75.2 ± 17.7	68.6 ± 24.7	66.3 ± 28.1	65.0 ± 27.5	75.9 ± 17.2	72.6 ± 20.8	75.6 ± 19.9	78.4 ± 15.8
Stress/Relaxed	Shift 1	62.7 ± 16.1	62.6 ± 19.3	63.7 ± 17.9	60.7 ± 20.5	55.9 ± 25.2	59.2 ± 16.3	56.2 ± 22.0	58.2 ± 22.5
	Shift 2	58.1 ± 16.1	59.6 ± 19.5	54.8 ± 21.2	57.6 ± 25.5	60.2 ± 24.4	69.7 ± 15.7	63.4 ± 19.6	67.4 ± 20.3
	Shift 3	63.1 ± 22.6	62.8 ± 19.4	58.9 ± 18.7	63.8 ± 19.4	60.0 ± 20.2	58.2 ± 21.1	62.5 ± 17.8	66.0 ± 20.7
	Shift 4	67.8 ± 18.8	66.6 ± 22.8	65.3 ± 17.6	61.6 ± 26.2	62.5 ± 21.5	66.2 ± 17.3	66.4 ± 16.3	61.5 ± 23.3
	Shift 5	59.5 ± 23.6	61.5 ± 25.3	61.1 ± 26.8	59.6 ± 29.1	57.2 ± 22.3	63.4 ± 17.0	68.2 ± 17.0	72.6 ± 19.5
Physically exhausted/ Energized	Shift 1	63.4 ± 18.9	54.1 ± 21.4	49.4 ± 16.0	40.8 ± 18.2	65.3 ± 21.5	64.8 ± 18.7	51.5 ± 20.8	45.4 ± 22.4
	Shift 2	53.6 ± 24.5	55.5 ± 22.1	47.1 ± 20.8	42.4 ± 19.8	66.5 ± 21.0	66.5 ± 16.9	58.9 ± 21.1	57.0 ± 18.6
	Shift 3	56.0 ± 24.2	58.6 ± 18.5	53.9 ± 22.4	46.7 ± 18.5	63.7 ± 18.0	64.5 ± 15.6	57.5 ± 20.2	55.5 ± 15.7
	Shift 4	67.6 ± 16.6	54.0 ± 21.9	54.3 ± 16.9	44.9 ± 17.2	59.0 ± 21.9	56.7 ± 20.6	54.6 ± 20.8	48.4 ± 17.5
	Shift 5	60.4 ± 22.3	56.5 ± 26.5	52.3 ± 29.6	40.9 ± 25.5	57.7 ± 20.6	54.1 ± 18.6	55.5 ± 17.8	56.7 ± 21.4
Motivated/ Unmotivated	Shift 1	32.6 ± 19.4	32.3 ± 18.2	44.2 ± 17.2	56.4 ± 15.6	34.1 ± 21.2	31.4 ± 20.5	40.9 ± 18.2	50.1 ± 23.3
	Shift 2	46.9 ± 22.1	45.9 ± 24.7	48.3 ± 26.8	51.0 ± 24.6	35.4 ± 22.1	34.6 ± 20.6	38.7 ± 19.6	42.8 ± 24.2
	Shift 3	39.9 ± 22.9	39.9 ± 21.4	38.7 ± 21.8	47.6 ± 21.6	36.4 ± 16.2	37.1 ± 14.5	33.6 ± 15.4	41.1 ± 15.8
	Shift 4	35.4 ± 19.3	42.4 ± 24.6	46.1 ± 22.5	53.4 ± 19.7	35.2 ± 21.7	39.6 ± 21.5	44.8 ± 20.7	47.4 ± 25.3
	Shift 5	38.0 ± 22.7	48.3 ± 24.8	43.6 ± 25.3	52.6 ± 28.1	40.6 ± 21.3	33.6 ± 16.9	34.5 ± 17.3	35.5 ± 22.5
Sick/Well	Shift 1	86.4 ± 14.8	85.7 ± 12.1	82.7 ± 15.0	82.4 ± 14.2	79.8 ± 19.0	78.9 ± 18.6	75.8 ± 19.3	71.3 ± 19.5
	Shift 2	80.4 ± 16.0	82.3 ± 16.2	77.0 ± 14.9	74.1 ± 21.9	79.0 ± 20.1	83.4 ± 14.5	83.1 ± 18.4	84.8 ± 14.3
	Shift 3	82.1 ± 16.1	82.0 ± 13.5	80.4 ± 15.5	81.8 ± 13.5	82.1 ± 15.1	86.4 ± 15.6	83.7 ± 14.0	82.0 ± 15.4
	Shift 4	84.7 ± 13.6	83.5 ± 13.8	82.8 ± 14.2	86.5 ± 8.8	81.2 ± 19.7	83.8 ± 17.1	84.0 ± 15.2	77.6 ± 16.0
	Shift 5	83.9 ± 13.4	81.1 ± 15.0	79.6 ± 20.2	78.1 ± 22.8	85.4 ± 14.3	88.9 ± 10.1	86.0 ± 12.9	87.6 ± 9.9

KSS, Karolinska Sleepiness Scale.

The mechanism by which light improves alertness is not clear—light has both direct stimulating properties and suppresses melatonin, which may in turn increase alertness. In the current study, we cannot differentiate between the potential mechanisms of action of light on alertness and it is likely that the benefits are driven by multiple factors. Moreover, we cannot rule out that the control lighting also improved alertness (as compared to darkness) especially given the large inter-individual variation and high sensitivity to light at night.[29,35,36] We were able to show, however, that the blue-enriched light and exercise was able to improve alertness and performance over and above any impact of the control condition.

Exercise alone increases physiological arousal and can help promote alertness in the short-term.[37] By counteracting the circadian temperature nadir that normally occurs during the night shift, exercise may have contributed to the reduction in sleepiness and improvement in alertness and objective performance that we observed.[38] Previous studies of intermittent and continuous exercise have been shown to improve workplace alertness and performance. Engaging in 10 minutes of moderate exercise every 2 hours throughout a 40-hour sleep deprivation protocol increased alertness in aviators for up to 50 minutes post-exercise.[18] Recent studies have focused on continuous exercise in the workplace, such as sitting on exercise balls at one's desk or using a walking treadmill desk station.[39,40] A one-year study of volunteers walking 1–2 miles per hour on a treadmill desk showed improvements in performance and interactions with co-workers.[41] However, a 2018 review of active workstations evaluated seven studies and found little evidence for changes in worker productivity or performance, perhaps due to small sample sizes.[39] Both intermittent and continuous exercise and the time course of associated improved alertness should continue to be explored in order to develop the most appropriate fatigue countermeasures for safety-sensitive workers. Furthermore, because the lighting and exercise countermeasure were tested in combination, it is not possible to determine from these data the extent to which each of these countermeasures contributed to the observed improvements in performance, alertness and mood. It has been hypothesized that a high arousal level is necessary for shorter wavelength light to effectively increase alertness.[42,43]

As with all fatigue countermeasures that move from the laboratory to an operational setting, it was important to demonstrate the feasibility of the combined countermeasure. In this case, we needed to find appropriate near-by space in the mission control building for an experimental break room to house the combined fatigue countermeasure. The blue-enriched white lights were installed in existing fixtures, which was simple and cost-effective. We chose blue-enriched white light exposure, as it has been shown to produce greater alerting responses than exposure to standard polychromatic sources of similar illuminance[13,15,32,34,44] while permitting normal visual function (that would be precluded with narrowband light). Our study also involved an increase in light illuminance which, when combined with the change in spectrum, resulted in a greater than 5-fold increase in melanopic EDI (melanopic lux), the primary photoreceptor mediating the non-visual effects of light (Fig. 1B).[19] Given the translational nature of the study, and its critical setting, we were unable to test the effects of changing illuminance and spectrum separately, but both likely contribute to the overall improvement in performance observed. Further studies should attempt to optimize the illuminance/spectrum balance to achieve maximum benefits with minimum energy expenditure, to investigate pragmatic intermittent schedules and to explore the use of the enhanced lighting during all shifts (eg, not just the night shift).

Another critical component was management's support of the combined fatigue countermeasure and support for controllers taking breaks during their overnight shifts, even when the ISS was in satellite communication. A system to monitor the control room from the experimental break room and an emergency recall system alleviated the controllers' concern about missing communication with the crewmembers or important events while on break. The high compliance of the participants with all aspects of this project (ie, number of breaks taken, number of exercise sessions completed) demonstrates the willingness of the controllers to participate in countermeasures that have the potential to alleviate fatigue. The combined countermeasure was well-tolerated and was rated as helpful in improving alertness. The task load questionnaire did not show any increases in demand, effort or frustration in the experimental condition compared to the control condition. Additionally, the blue-enriched white light installed in the experimental break room was well tolerated, as evidenced by lack of symptoms on the eye strain questionnaire. We thus conclude that the combined protocol was feasible and acceptable in this operational setting.

This study has a few limitations. The increased number of breaks taken in the experimental condition as compared to the control condition could have contributed to our results, as breaks alone have been shown to acutely increase alertness.[45] Although the control condition allowed for breaks as was the usual practice in the operational flight mission control facility, it was not an identical active control with identical breaks taken without the lights and exercise. Further research is needed to determine the contribution of breaks, exercise and light on the improvement of performance, alertness and mood in operational situations. Additionally, as with any operational study of this nature, we cannot account for the expectancy effect of the experimental condition.

A combined non-pharmacological fatigue countermeasure of short-wavelength light exposure and exercise was feasible to implement, acceptable to flight mission controllers and successful in improving the alertness, performance and mood of controllers working overnight shifts. This countermeasure should be considered in environments where it is important for workers to remain alert and perform optimally overnight. Future research should explore the timing, duration and intensity of the lighting/exercise countermeasure to determine optimal effectiveness.

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