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An at-home evaluation of a light intervention to mitigate sleep inertia symptoms

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ABSTRACT

Objectives: Under laboratory settings, light exposure upon waking at night improves sleep inertia symptoms. We investigated whether a field-deployable light source would mitigate sleep inertia in a real-world setting.

Methods: Thirty-six participants (18 female; 26.6 years \pm 6.1) completed an at-home, within-subject, randomized crossover study. Participants were awoken 45 minutes after bedtime and wore light-emitting glasses with the light either on (light condition) or off (control). A visual 5-minute psychomotor vigilance task, Karolinska sleepiness scale, alertness and mood scales, and a 3-minute auditory/verbal descending subtraction task were performed at 2, 12, 22, and 32 minutes after awakening. Participants then went back to sleep and were awoken after 45 minutes for the opposite condition. A series of mixed-effect models were performed with fixed effects of test bout, condition, test bout \times condition, a random effect of the participant, and relevant covariates.

Results: Participants rated themselves as more alert ($p = .01$) and energetic ($p = .001$) in the light condition compared to the control condition. There was no effect of condition for descending subtraction task outcomes when including all participants, but there was a significant improvement in descending subtraction task total responses in the light condition in the subset of participants waking from N3 ($p = .03$). There was a significant effect of condition for psychomotor vigilance task outcomes, with faster responses ($p < .001$) and fewer lapses ($p < .001$) in the control condition.

Conclusions: Our findings suggest that light modestly improves self-rated alertness and energy after waking at home regardless of sleep stage, with lower aggression and improvements to working memory only after waking from N3. Contrary to laboratory studies, we did not observe improved performance on the psychomotor vigilance task. Future studies should include measures of visual acuity and comfort to assess the feasibility of interventions in real-world settings.

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Introduction

Sleep inertia refers to the period of reduced alertness and impaired cognitive performance experienced immediately after waking from sleep. These symptoms can be experienced after any sleep-wake

transition but are more commonly observed following awakenings at night,¹ from deep sleep,² and under conditions of prior extended wakefulness² or chronic sleep loss.³ Therefore, on-call, extended operations, and night shift workers in the emergency services, health care, or military may be particularly at risk for severe sleep inertia symptoms when performing safety-critical tasks shortly after waking.⁴ To manage the risk of sleep inertia in these workers, there is a critical need for a reactive countermeasure to improve alertness and cognitive performance as soon as possible after waking.

In the laboratory, our group and others have trialed the use of light exposure after waking to reactively mitigate sleep inertia effects, with

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varying success. Studies using light during habitual daytime hours only reported improvements in subjective alertness but not in cognitive performance.^{5,6} However, polychromatic short wavelength-enriched light exposure following nighttime awakenings showed significant improvements in alertness, mood, and vigilant attention.⁷ The success of this nighttime intervention may be due to the increased effectiveness of light as an acute alerting intervention during the biological night compared to during the day.^{8,9}

Having demonstrated the potential of light as a countermeasure to sleep inertia at night in laboratory settings,⁷ we sought to extend this investigation to a real-world environment using a field-deployable light-emitting device. Furthermore, we aimed to explore the effects of light on another cognitive domain, working memory, which has been shown to be sensitive to sleep inertia.^{2,10} We hypothesized that bright, short wavelength-enriched light would improve alertness, mood, vigilant attention, and working memory after waking from nighttime sleep compared to a dim, red light control condition in an at-home setting.

Methods

Participants

Forty-five adults were recruited to participate in the study. Participants were included if they self-reported: (1) habitual nightly sleep of 6–9 hours, (2) habitual bedtime between 21:00 and 03:00, (3) habitual waketime between 06:00 and 12:00, and (4) absence of known medical or psychiatric conditions (as assessed by body mass index of 18–30 kg/m², General Health Screening Questionnaire, Beck Depression Inventory, State-Trait Anxiety Inventory, and Symptoms Checklist 90R). Participants were asked to abstain from illicit substances and alcohol during the study and were only allowed caffeine up until 2 hours after waking on the experimental day (allowing for at least 11 hours between the last consumption and testing). Inclusion criteria were deliberately less stringent than our usual in-laboratory criteria (eg, more flexible bedtimes and sleep duration) in order to reflect a more real-world population while still excluding factors known to directly influence results or put the participant at greater risk of harm.

Participants provided informed consent via video conferencing and electronic signature prior to participation in the study. The study protocol was approved by the NASA Institutional Review Board (STUDY00000335) under the Common Rule, which is based on the core principles of the Declaration of Helsinki.

Protocol

The within-subject, randomized crossover study was performed entirely at each participant's home with no laboratory visits. At enrollment into the study, participants were asked to follow their habitual routine for 5 nights and to select a bedtime between 21:00 and 03:00 with a waketime allowing for between 6 and 9 hours of time-in-bed to be followed for both the adaptation (night 6) and experimental night (night 7). Participants were contacted via a dedicated study cell phone and monitored remotely via a swivel-mounted, 1-way, infrared camera during all study procedures. Cameras were turned off and pointed away from participants during sleep opportunities. On the adaptation night (night 6), participants were guided through equipment setup, experimental procedures, and practice test bouts. At the participant's self-selected bedtime, lights were turned off, and the participant was instructed to try to sleep, not use their phone, and remain in bed attempting to sleep until a researcher called them at their habitual waketime the next day.

On the morning of day 7, researchers phoned the participant at their preselected waketime, gave instructions on how to remove the

polysomnography equipment, and reminded participants to abstain from napping, consuming alcohol or illicit substances, drinking caffeine more than 2 hours after their waketime, and to be ready when the researcher called for the experimental night setup. Participants were otherwise free to engage in their usual activities on day 7, and light exposure was not limited or measured. For the 2 hours prior to bedtime (excluding baseline testing, see below), participants were in their usual bedroom lighting until the lights were out. Ambient lighting during the 2 hours before lights out and during each wake-up testing session was measured using light meters worn as a pendant, but the majority of the data from these sensors was lost due to device failure, and therefore, we are unable to report these levels.

On the experimental night (night 7), participants were contacted at 2 hours, and again at 1 hour, prior to their preselected bedtime to perform baseline testing. During baseline testing, bedroom lights were turned off, the red control light was turned on, and the Luninette glasses were worn in the off setting (ie, the setup was identical to the control condition). Participants were encouraged to close their window shades, but bedrooms differed as to the style of shades available. Following baseline testing, participants were instructed to check the setup of all equipment and were then remotely guided through the polysomnography equipment application before lights out at the preselected bedtime (same time as night 6). Participants were informed that they would receive at least 1 wake-up call during the night and to follow the researcher's instructions when they received a call. Participants were provided with a study cell phone, which was set to specific ringtone and screen settings. Researchers guided participants to set up their personal cell phones with similar settings as a backup.

Forty-five minutes after bedtime on night 7, participants received a phone call and were instructed to sit up on the side of their bed and turn on a dim, red light. Participants were then instructed to wear light-emitting glasses with the light either on (light condition) or off (control). Two minutes after the phone call, participants were instructed to perform an approximately 10-minute test bout. This test bout was repeated 4 times beginning at 2 (T1), 12 (T2), 22 (T3), and 32 (T4) minutes after the phone call. Participants were then instructed to go back to sleep and were called 45 minutes after the subsequent lights out to repeat the test bouts in the opposite condition (see Fig. 1).

Intervention

Luninette® Glasses 3 (Lucimed, Bierges, Belgium) set to the lowest setting (product specifications: approximately 500 lux; peak wavelength: 468 nm; bandwidth: 70 nm; and spectral irradiance: 21.8 μW/cm² ± 7%) were illuminated 1 minute after the phone call and remained illuminated for the duration of testing (approximately 40 minutes). Our measurements at approximate vertical eye level in a typical bedroom environment with blackout curtains confirmed the following values: illuminance: 431.15 lux; peak wavelength: 470 nm; irradiance: 1.28 W/m²; and α-opic equivalent daylight (D65) illuminance: 370.77 melanopic lux (Spectroradiometer ILT950, International Lighting Technologies; metrics calculated by the α-opic Toolbox v1.049). See [Supplemental material](#) for spectral power distribution (Fig. A.1). In the control condition, the glasses were worn but not switched on. In both conditions, a dim, red light was illuminated at a distance of approximately 18 in from the waist height of the participant (measurements at approximate vertical eye level in a typical bedroom environment with blackout curtains: illuminance: 0.66 lux; peak wavelength: 755 nm; irradiance: 0.00 W/m²; and α-opic equivalent daylight (D65) illuminance: 0.22 melanopic lux; see [Supplemental material](#) for spectral power distribution, Fig. A.1). Figueiro and colleagues^{11,12} have observed benefits of red light delivered close to the eye at > 50 lux. Our dim, red light control was

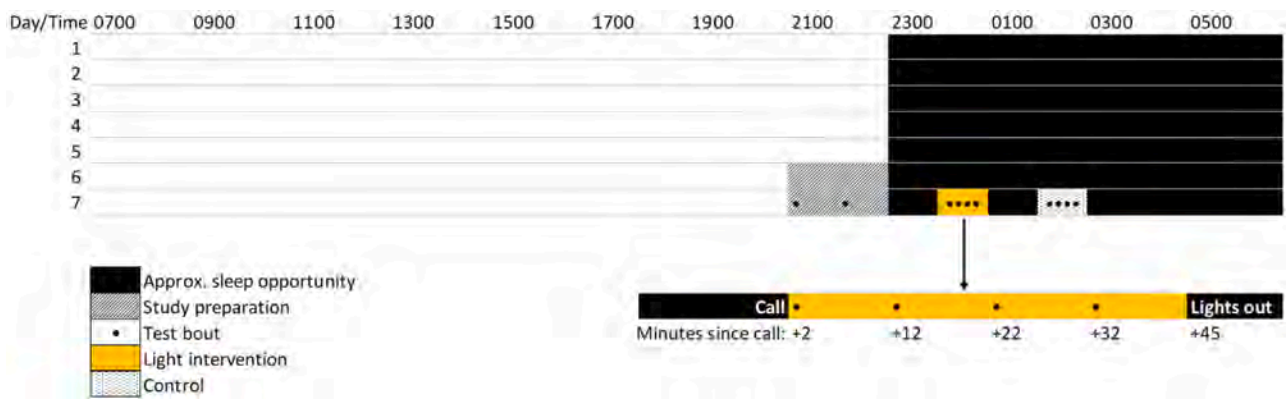


Fig. 1. Protocol schematic. Black shading indicates approximate sleep periods. Gray shading indicates study preparation activities including equipment setup, polysomnography application, and baseline testing. Black circles represent test bouts. The order of light intervention (yellow shading) and control (dotted shading) were randomized. Times shown are approximate and varied depending on habitual sleep-wake times.

deliberately designed to minimize any potential benefits with less than 1 lux of illuminance at eye level.

Neurobehavioral measures

A 5-minute psychomotor vigilance task (PVT) measuring vigilant attention was performed on the NASA PVT+ application using an iPod (iPod 6th generation; iOS v.12.5.3; NASA PVT+ v.1.4.1 B.1999).¹³ Response speed (1/reaction time) and number of lapses (reaction time > 500 ms) were the predetermined outcome measures of interest based on effect sizes of this task¹⁴ and sensitivity to sleep inertia,¹⁵ and demonstrated improvements with light.⁷ Anticipatory trials (reaction time < 100 ms) were removed prior to the calculation of response speed. After the PVT, participants were prompted within the NASA PVT+ application to complete a Karolinska sleepiness scale (KSS)¹⁶ and 9 visual analog scales (VASs) of alertness and mood states (alert-sleepy, cheerful-miserable, calm-tense, depressed-elated, stressed-relaxed, peaceful-hostile, greedy-generous, aggressive-easygoing, and lethargic-energetic).^{7,17}

Once the tests on the iPod were complete, the participant was instructed to perform a 3-minute descending subtraction task (DST) as a measure of working memory and mental arithmetic. The researcher verbally provided the participant with a 3-digit starting number, from which the participant was required to subtract 9, say the remainder out loud, and then subtract 8 from the remainder and so forth until subtracting 2, after which they were to subtract 9 again and repeat the process.² If participants paused for 30 seconds, they were encouraged to continue. Responses were recorded live by 2 researchers and cross-checked for consensus. Trials in which the participant reached numbers below 3 digits were excluded. The outcome metrics of interest were the total number of responses (total responses), the total number of correct responses (total correct), and the percent correct responses (percent correct). Determination of correct and incorrect responses was consistent with rule sets employed in similar studies.^{10,18} In an effort to minimize practice effects, participants practiced the DST 9 times on the adaptation night (night 6).²

Sleep

Participants wore an activity monitor (Actiwatch Spectrum PRO, Philips Respironics, Murrysville, PA, USA) throughout the 1-week study. Rest intervals were defined by the rest start and end times provided by participants in a sleep diary. The Actiware algorithm (v6.0.9, Philips Respironics, Murrysville, PA, USA) was then used to estimate sleep duration within these rest periods. The software was set to the medium threshold (wake threshold 40) with sleep onset/

offset thresholds set at 10 minutes of immobility.¹⁹ Sleep on nights 6 and 7 was monitored polysomnographically using 8 electrodes: 2 prefrontal (positioned at approximately Fp1 and Fp2), 2 ocular (electrooculogram; positioned 1 cm outside and below the right canthus and above the left canthus), 1 chin (electromyogram; positioned on the right-hand side of the chin or right sternocleidomastoid muscle), 2 ground/bias (positioned at approximately Fp₂), and 1 reference (left mastoid; Prodigy Head Mount Unit, Cerebra Health Inc., Winnipeg, MB, Canada).²⁰ Sleep data were preprocessed using Prodigy default filters²¹ and scored by a single, blinded Registered Polysomnographic Technologist using the American Academy of Sleep Medicine rules.²² Sleep onset was defined as 3 consecutive epochs of N1 sleep or 1 epoch of any other sleep stage.

Analysis

Based on the results from our in-laboratory light intervention study,⁷ for a within-subject design, our power calculations estimated that we would need to study 30 participants in order to determine a difference with a 2-sided 5% type I error rate and 90% power.

Paired-sample *t*-tests and Wilcoxon signed-rank tests were used to assess demographic and sleep metrics between conditions. A mixed-effect multinomial logistic regression was used to evaluate differences in sleep stage at awakening between conditions. A series of mixed-effect models with Bonferroni-corrected post-hoc tests were performed with fixed effects of test bout (T1-T4), condition (control, light), test bout × condition, and a random effect of the participant. Baseline scores, randomization order, sex,²³ and actigraphically estimated sleep history across the prior 6 nights were included as covariates. One participant's sleep history was estimated based on sleep diaries due to an Actiwatch failure. Linear models were used in the analyses of KSS, alertness and mood scales, and PVT response speed. Due to overdispersion, a negative binomial model was specified for the analysis of the number of PVT lapses. A Poisson model was used for total responses and total correct on the DST, while the percent correct was arcsine-transformed and analyzed using a linear model. Data from trials in which participants were awake at lights on were excluded from our analyses. However, mixed-effect models are able to accommodate for missing data.²⁴ For all models, we computed marginal and conditional values for R^2 to reflect the variance explained by the fixed effects alone, as well as the combined impact of the fixed and random effects, respectively.²⁵ We also calculated Cohen's f^2 as a measure of standardized effect size for each of the fixed effects included in the models.²⁶ For this measure, Cohen (1992)²⁷ defined the magnitude of the effect as follows: $f^2 \geq 0.02$ (small), $f^2 \geq 0.15$ (medium), and $f^2 \geq 0.35$ (large). Significance was defined as $\alpha = 0.05$. All analyses were performed in R.

Table 1
Participant demographics.

	M	SD	Range
Age (years)	26.2	5.9	18-39
Average TST nights 1-6 (mins)*	460.6	33.3	398.5-524.3
PSQI	3.5	1.3	1-7
MEQ	51.8	8.4	35-70
ESS	5	2.4	2-10
	<i>n</i>	%	
Male	16	47.1	
Race/ethnicity**			
American Indian or Alaskan Native	0	0.0	
Asian	18	52.9	
Black or African American	0	0.0	
Native Hawaiian or other Pacific Islander	2	5.9	
White	18	52.9	

n = 34. M, mean; SD, standard deviation; TST, total sleep time; PSQI, Pittsburgh Sleep Quality Index; MEQ, morningness-eveningness questionnaire; ESS, Epworth sleepiness scale.

* As estimated by actigraphy.

** Participants could choose more than 1 race/ethnicity; therefore, totals may exceed the total sample size.

Results

Of the 45 participants recruited for the study, 36 (18 female, 17 male, 1 nonbinary; 26.6 years ± 6.1) completed the study. Six participants were excluded based on postconsent screening questionnaires. Two participants withdrew from the study before collecting any data. One participant withdrew on day 6 of the study. One participant's data were excluded due to noncompliance. As we included sex as a covariate in our models, 1 participant's data were excluded due to identifying as nonbinary. For thoroughness, we also repeated the analysis including the nonbinary participant and removing sex as a covariate. Those results are reported in Supplemental material (Tables A.1 and A.2). Table 1 displays the demographics for the 34 participants included in the main analyses (*n* = 17 with light intervention first).

Sleep

Table 2 displays the sleep architecture and sleep stage at awakening for the 45-minute sleep opportunities prior to each wake-up on night 7, as measured by polysomnography. The average total sleep time was 32.8 (± 10.8) minutes, and the majority (54%) of wake-ups were from N3 sleep. There were no significant differences in any

Table 2
Sleep architecture of the 45-min sleep opportunities preceding sleep inertia testing.

	Outcome	Overall	Light	Control	<i>p</i>	<i>ES</i>	
Night 7	W ^b	11.88 (10.94)	10.25 (11.13)	14.00 (12.63)	.30	-0.21	
	N1 ^a	6.41 (3.48)	6.40 (4.41)	6.43 (3.73)	.97	-0.01	
	N2 ^a	9.03 (4.70)	9.16 (6.01)	8.90 (4.90)	.79	0.05	
	N3 ^a	12.80 (7.77)	13.50 (9.71)	12.10 (10.29)	.52	0.11	
	REM ^b	0.00 (0.00)	0.00 (0.00)	0.00 (0.00)	.73	0.17	
	TST ^b	32.75 (10.81)	34.25 (10.38)	30.50 (14.25)	.36	0.18	
	SOL ^a	11.95 (9.13)	10.30 (9.03)	12.98 (10.04)	.15	-0.26	
	WASO ^b	0.75 (2.19)	0.00 (1.50)	0.50 (3.00)	.48	-0.17	
	Sleep Stage at Awakening (<i>n</i>) ^c	N1	10	6	4	.91	
		N2	16	7	9		
N3		37	19	18			
REM		2	1	1			
Awake		3	1	2			

ES, effect size; W, wake; N1, N2, N3, stage non-REM 1, 2, 3; REM, rapid eye movement; TST, total sleep time; SOL, sleep onset latency; WASO, wake after sleep onset.

^a Paired-samples *t*-test performed for group comparison with mean (standard deviation) and Cohen's *d* reported.

^b Due to the violation of the normality assumption, the Wilcoxon signed-rank test was performed for group comparison with median (interquartile range) and rank-biserial correlation reported.

^c Mixed-effect multinomial logistic regression was conducted to evaluate differences in sleep stage at awakening.

sleep metrics between sleep episodes prior to control versus light (intervention) wake-ups (all *p*-values > .05). Sleep architecture for Night 6 can be found in the Supplemental material (Table A.3).

Subjective measures

There were no significant main or interaction effects for KSS (all *p*-values > .05, all *f*² values ≤ 0.03; see Table 3 and Fig. 2). There was a significant, small effect of condition for VAS_{alert-sleepy} (*p* = .01, *f*² = 0.03) and VAS_{lethargic-energetic} (*p* = .001, *f*² = 0.05), with participants rating themselves as more alert and energetic in the light condition compared to the control condition (Table 4; Fig. 3). There was a significant, small effect of test bout for VAS_{cheerful-miserable} (*p* = .001, *f*² = 0.08), VAS_{calm-tense} (*p* < .001, *f*² = 0.08), VAS_{stressed-relaxed} (*p* = .02, *f*² = 0.04), and VAS_{peaceful-hostile} (*p* < .001, *f*² = 0.09), with participants rating themselves as more miserable, tense, stressed, and hostile as time since awakening increased.

A secondary analysis of subjective measures in a subset of participants waking from N3 (*n* = 14) revealed a significant, small effect of test bout for KSS (*p* = .03, *f*² = 0.10; Table A.4) with improved alertness over time. Several mood scales (VAS_{calm-tense}, VAS_{depressed-related}, and VAS_{stressed-relaxed}) trended towards improved mood in the light condition (all *p*-values < .09, all *f*² values > 0.02) with small, significant mood improvements for VAS_{aggressive-easygoing} (*p* = .004, *f*² = 0.10; Table A.5) and VAS_{lethargic-energetic} (*p* = .02, *f*² = 0.06). Results from an analysis of awakenings from N1 and N2 are presented as Supplemental material (Tables A.6 and A.7). There were no significant differences in condition for any of the subjective variables.

Objective measures

There was a significant, medium effect of condition for PVT response speed (*p* < .001, *f*² = 0.17) and a significant, small effect for PVT lapses (*p* < .001, *f*² = 0.08), with faster responses and fewer lapses in the control condition compared to the light condition (Table 3; Fig. 2). There was also a significant, small effect of test bout for PVT response speed (*p* = .003, *f*² = 0.06), with slowest responses immediately after waking. There was no significant condition × test bout effect for PVT outcomes.

There was a significant, medium effect of test bout for DST total responses (*p* < .001, *f*² = 0.16) and a significant, small effect for DST total correct (*p* < .001, *f*² = 0.12), with improved performance at T3 and T4 compared to T1 (Table 3; Fig. 2). There were no significant main effects of the condition, nor interaction effects for DST outcomes.

Table 3
Mixed-effect model results for Karolinska sleepiness scale (KSS), descending subtraction task (DST), and psychomotor vigilance task (PVT).

Variable	KSS		DST				PVT					
	<i>p</i>	<i>f</i> ²	<i>p</i>	<i>f</i> ²	<i>p</i>	<i>f</i> ²	<i>p</i>	<i>f</i> ²	<i>p</i>	<i>f</i> ²	<i>p</i>	<i>f</i> ²
Condition	.27	0.01	.69	<0.001	.76	<0.001	.18	0.01	<.001*	0.17	<.001*	0.08
Test bout	.11	0.03	<.001*	0.16	<.001*	0.12	.49	0.01	.003*	0.06	.08	0.03
Condition × Test bout	.14	0.03	.96	<0.001	1.00	<0.001	.87	<0.001	.31	0.02	.16	0.02
Covariates												
Baseline score	.08	0.02	<.001*	1.20	<.001*	0.89	<.001*	0.53	<.001*	0.38	.01*	0.04
Light order	.83	<.001	.43	0.02	.26	0.01	.49	<0.001	.40	<0.001	.92	<0.001
Sleep history	.04*	0.02	.05*	0.03	.16	0.01	.78	<0.001	.44	<0.001	.64	<0.001
Sex	<.001*	0.07	.17	0.02	.08	0.02	.75	<0.001	.14	0.01	.47	<0.001
Overall model												
<i>R</i> _M ² (<i>R</i> _C ²)	.28 (.64)		.68 (.80)		.72 (.84)		.61 (.73)		.63 (.82)		.21 (.65)	

* *p* < .05. *R*_M² = marginal *R*². *R*_C² = conditional *R*².

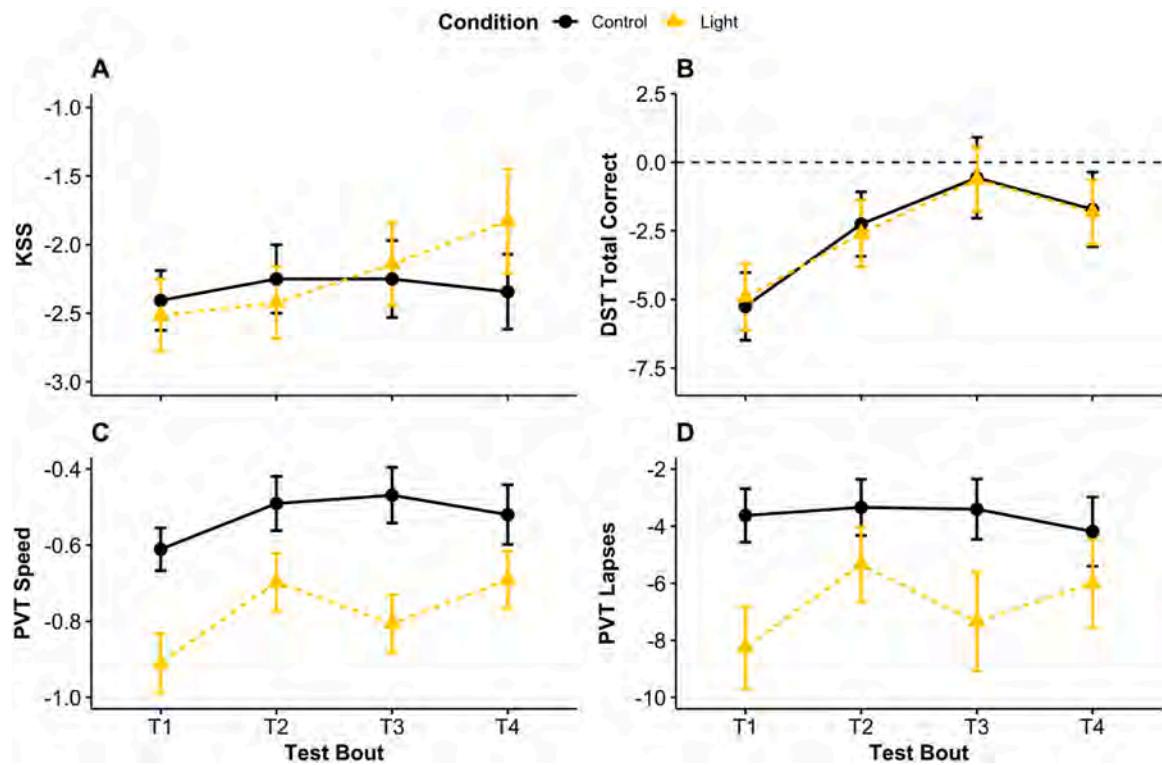


Fig. 2. Effect of intervention on primary outcome metrics. Mean (\pm standard error) change from baseline for (A) Karolinska sleepiness scale (KSS), (B) descending subtraction task (DST) total responses correct, (C) psychomotor vigilance task (PVT) response speed (1000/reaction time [ms]), and (D) PVT lapses across the sleep inertia testing period by condition (yellow triangles, dashed line = light intervention; black circles, solid line = control). Upward indicates better outcomes for all variables.

A secondary analysis of objective measures in a subset of participants waking from N3 ($n = 14$) revealed a small, significant improvement in DST total responses in the light condition ($p = .03$, $f^2 = 0.08$; Table A.4) and a trend toward improvement for DST total correct ($p = .07$, $f^2 = 0.04$). Results for PVT outcomes following awakening from N3 were similar to the whole cohort (all p -values < .001, all f^2 values > 0.15). Results from an analysis of awakenings from N1 and N2 are presented as Supplementary material (Table A.6). There were no significant differences in condition for any of the objective variables, except PVT speed, which continued to be significant in the same direction as N3 and whole group analyses.

Discussion

This study was designed as a real-world translation of our in-laboratory study,⁷ which demonstrated the potential of polychromatic short wavelength-enriched light as a countermeasure to sleep inertia following nighttime awakenings. The results from this at-home study partially replicated our in-laboratory findings. Similar to our in-laboratory study, we observed a modest improvement in subjective alertness and mood with a light intervention, as well as improved working memory, but only when waking from slow wave sleep. However, contrary to our in-laboratory study, we did not see an improvement in vigilant attention in the light condition. There are several possible

Table 4
Mixed-effect model results for alertness and mood scales.

Variable	Alert-sleepy		Cheerful-miserable		Calm-tense		Depressed-elated		Stressed-relaxed		Peaceful-hostile		Greedy-generous		Aggressive-easygoing		Lethargic-energetic	
	p	f ²	p	f ²	p	f ²	p	f ²	p	f ²	p	f ²	p	f ²	p	f ²	p	f ²
Condition	.01*	0.03	.12	0.01	.89	<0.001	.32	<0.001	.52	<0.001	.98	<0.001	.94	<0.001	.31	<0.001	.001*	0.05
Test bout	.78	0.01	.001*	0.08	<.001*	0.08	.06	0.03	.02*	0.04	<.001*	0.09	.28	0.02	.17	0.02	.81	<0.001
Condition × test bout	.55	0.01	.73	0.01	.70	<0.001	.80	<0.001	.81	<0.001	.94	<0.001	.72	0.01	.46	0.01	.44	0.01
Covariates																		
Baseline Score	.01*	0.04	.21	0.01	.09	0.01	.003*	0.05	.13	0.01	<.001*	0.11	<.001*	<.001*	<.001*	<.001*	<.001*	0.10
Light order	.67	<0.001	.32	<0.001	.19	0.01	.20	0.01	.04*	0.02	.02*	0.03	.47	<0.001	.01*	0.03	.72	<0.001
Sleep History	.25	0.01	.94	<0.001	.44	<0.001	1.00	0.00	.64	<0.001	.03*	0.03	.92	<0.001	.24	0.01	.83	<0.001
Sex	.01*	0.04	.39	<0.001	.45	<0.001	.54	<0.001	.94	<0.001	.23	0.01	.16	0.01	.39	<0.001	.04*	0.02
Overall model																		
R _M ² (R _C ²)	.25 (.58)		.10 (.74)		.12 (.64)		.26 (.68)		.12 (.72)		.38 (.72)		.44 (.72)		.41 (.75)		.41 (.75)	

* p < .05. R_M² = marginal R². R_C² = conditional R².

explanations for our findings, which underscore important challenges in translating laboratory-based findings to real-world settings.

In our laboratory study, vigilant attention, alertness, and mood were improved with light exposure during the sleep inertia period following awakenings specifically from slow wave sleep.⁷ In this translated at-home study, alertness and mood were also improved in the light exposure condition, especially following an awakening from slow wave sleep. Furthermore, the light intervention improved performance on a nonvisual working memory task following awakenings from slow wave sleep. This significant improvement in working memory was not observed when including all participants, nor in a subset of those waking from lighter stages, suggesting that this countermeasure may be most effective following deep sleep or in cases of severe sleep inertia.² In this study, we extended our findings of the effect of sex on subjective alertness, with females rating themselves as sleepier than males, even under light intervention conditions.²³ Lastly, we were unable to replicate our finding of significant improvements on a visual vigilant attention task. Previous light intervention studies have shown mixed results for cognitive performance depending on the task²⁸ and light exposure timing (eg, daytime versus nighttime²⁸⁻³¹ and time into the night).³² Our observed effect sizes were small to medium, suggesting that this light intervention only modestly influenced the outcome measures. It is unlikely that these effect sizes were due to a lack of power, given that our analyzed sample (n = 34) was still larger than our pre-determined power calculations (n = 30). Future studies are needed to determine whether our observed effects are specific to the task, the light source, and/or the sleep inertia conditions, such as sleep stage upon waking.

Our study design allowed for the measurement of alertness, mood, and cognitive performance under conditions of sleep inertia in a nonlaboratory setting. This was evidenced by an impairment in all outcomes relative to presleep baseline immediately after waking, which gradually returned toward baseline levels across successive test bouts. Based on our in-laboratory study, we allowed a 45-minute sleep opportunity in order to increase the likelihood of waking participants from stage N3 sleep. Waking from N3 is known to exacerbate sleep inertia symptoms.² This approach was moderately successful, with over half of all wake-ups occurring from N3 sleep, and only 4% already awake at the time of the wake-up call. Moreover, in allowing habitual sleep in the week prior to the experimental night (ie, not satiating sleep, as is common in laboratory studies), a degree of naturalistic chronic sleep restriction may have contributed to the severity of sleep inertia measured. Overall, our study design captured impairments following naturalistic sleep conditions with wake-up calls scheduled to reflect peak night call times for emergency service workers.³³

We endeavored to replicate the conditions of our laboratory study as best as possible; however, it was also our intention to adapt some elements to the field setting. For example, we changed the light intervention equipment from a light canvas on a large apparatus to commercially available light-emitting glasses designed for personal, at-home use. Although the average intensity and spectral components of the light sources were similar, the delivery differed substantially. The laboratory light source was at least 1 foot from the participant and diffused within the room, whereas the glasses emitted light within an inch of the eyes and, thus, the comfort level of the light delivery may have differed. Future studies should include subjective scales of comfort, tolerance, and visual acuity when assessing field-deployable light sources to determine the likelihood of use in real-world settings as discomfort or visual impairment may be a barrier to implementation.³⁴⁻³⁷

It is important to evaluate the relative effectiveness of personalized light-emitting devices in real-world settings. Although not commercially marketed as a tool to improve alertness during the sleep inertia period, the glasses we used are typically marketed for

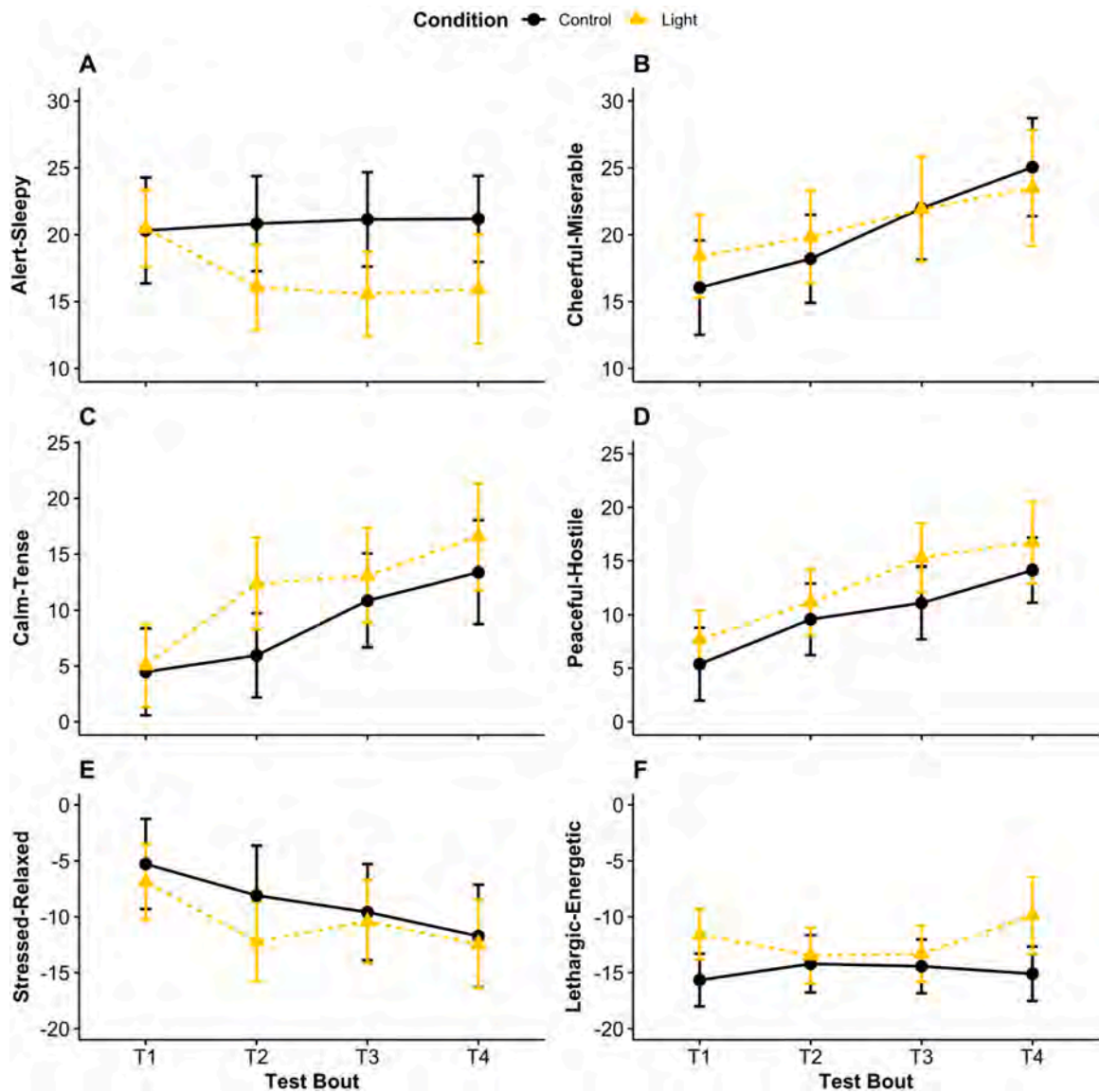


Fig. 3. Effect of intervention on visual analog scales of alertness and mood. Mean (\pm standard error) change from baseline for (A) alert-sleepy, (B) cheerful-miserable, (C) calm-tense, (D) peaceful-hostile, (E) stressed-relaxed, and (F) lethargic-energetic across the sleep inertia testing period by condition (yellow triangles, dashed line = light intervention; black circles, solid line = control).

circadian phase-shifting and recommended to be used in well-lit settings.³⁸ From an operational point of view, personalized light-emitting devices can be beneficial when there is a need for individuals to receive light without disturbing others. However, given that our results suggest that individual use in a dimly lit room may not improve performance on visual tasks, the use of such devices in similar operational settings may not be suitable. These glasses may still be beneficial for improving alertness in well-lit rooms where outfitting the room with the appropriate light specifications is cost-prohibitive, but the glasses are an affordable option. Another benefit to personalized light devices is that they allow the wearer to move about freely rather than be tethered to a static light source. This may be a critical need in many operational scenarios.³⁶ Further research is needed to validate the use of such devices for specific occupational settings and outcomes.

Limitations

Our translational, crossover study assessing the efficacy of a light intervention in an at-home setting under supervised conditions is

not without limitation. Our approach allowed for the control of many factors that would otherwise obscure the interpretation of results while allowing for a degree of variance to reflect a more ecologically valid population and setting. Although perhaps a limitation from a study design perspective, these real-world variations highlight the challenges of translational science more broadly and stress the importance of testing interventions in a range of operational environments to determine feasibility. Similarly, these translational methods could be responsible for our antithetical vigilant attention results. It is possible that the light from the glasses introduced screen glare or difficulty seeing the device screen. However, we included a nonvisual working memory task in order to capture cognitive performance without the use of a screen-based device. These insights are critical to understanding and reassessing implementation strategies.

Given the emphasis on real-world applications, exposure to light was not controlled during the day before the experimental night. All participants were, however, in indoor lighting for the 2 hours prior to bedtime on nights 6 and 7. All wake-up testing was performed at night (between the phases of astronomical twilight) with no lighting

other than the study devices. We did attempt to document actual light levels but, due to device failure, we were unable to do so. Scheuermaier and colleagues³⁹ observed that polychromatic blue-enriched light exposure prior to bed in elderly participants improved alertness upon awakening the next morning compared to polychromatic white light. While it is possible that differing prebed light exposures influenced our sleep inertia measurements, it is unlikely to have had a large effect, given that the bedroom light levels were not experimentally enhanced in our younger population.

Conclusions

Our study of light-emitting glasses as a countermeasure to sleep inertia in an at-home setting following awakenings at night demonstrated the challenges in translating a laboratory-demonstrated intervention into the real world. When awoken from slow wave sleep, the light intervention modestly improved alertness, some aspects of mood, and working memory. However, wearing light-emitting glasses immediately after waking in a dimly lit room at night appeared to worsen performance on a visual attention task. Future studies of light interventions should include measures of visual acuity and comfort, as well as a variety of visual and nonvisual performance tasks. Feasibility and efficacy studies of interventions in real-world environments are critical steps in the translation of basic science to operational settings.

Dr. Czeisler's contribution to this work

Dr. Czeisler and colleagues' work demonstrating the acute alerting effects of light provided the foundation for our exploration of this intervention during the sleep inertia period. Performance and alertness immediately after waking have also been explored by Dr. Czeisler's group, describing the time course of dissipation and revealing critical influencing factors, such as the circadian phase and homeostatic drive. We humbly extend this work in the spirit of developing countermeasures to help improve alertness in real-world settings with the view to supporting shift workers, a population that has been the focus of much of Dr. Czeisler's groundbreaking research.

Public health relevance statement

This research is of particular relevance to nearly half the working population who are exposed to unscheduled or irregular working hours including on-call and shift work populations, such as the emergency services, health care, and military. By providing an evaluation of a potential countermeasure to sleep inertia in a real-world environment, this work can help to tailor fatigue management guidance and raises applied questions for future evaluation.

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Declaration of conflicts of interest

Dr. Flynn-Evans report others from Baby Sleep Science, outside the submitted work. The other authors have declared no conflicts of interest.

Appendix A. Supporting information

Supplementary data associated with this article can be found in the online version at [doi:10.1016/j.sleh.2023.07.015](https://doi.org/10.1016/j.sleh.2023.07.015).

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