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Tailored light intervention for sleep and cognition in World Trade Center (WTC) cohort

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ABSTRACT

World Trade Center rescue and recovery workers and volunteers (WTC RRWV) are vulnerable to circadian rhythm disruption due to stress and environmental exposures during the 9/11 operation, with high rates of cognitive impairment and poor sleep quality. This exploratory pilot study assessed the feasibility and preliminary effect of a 12-week light-based intervention targeting sleep and cognition. Twenty-three WTC RRWV aged ≥50 years with mild cognitive impairment and sleep disturbances completed the intervention. Sleep, cognition, and circadian-effective light exposures were measured pre-and post-intervention using actigraphy, Pittsburgh Sleep Quality Index, cognitive tasks (go/no-go, digit span, Stroop), and a Daysimeter. Results showed significant improvements in sleep quality and cognitive performance. Greater circadian-effective light exposure was positively associated with improved cognitive accuracy. These preliminary observations suggest that light-based interventions may enhance sleep and cognitive function in at-risk populations.

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Cognition; sleep; tailored light intervention; World Trade Center

Introduction

Circadian rhythms regulate diverse physiological and behavioral processes including sleep–wake timing, metabolism, and cognition.[1,2] These endogenous daily cycles are regulated by the master biological clock in the brain's suprachiasmatic nuclei, located in the hypothalamus.[1–3] Because their free-running period is on average slightly longer than the solar day, circadian rhythms must be synchronized to one's local time on Earth by environmental cues, of which the light-dark pattern incident on the retinas is the strongest.[4] Disruption to these cycles—often caused by insufficient daytime light or excessive nighttime light—can lead to circadian rhythm disruption (CRD), which is increasingly recognized as a contributing factor to neurodegenerative processes.[5] Disrupted sleep is not only a symptom but also a potential contributor to accelerated cognitive decline and neuroinflammation, particularly among aging adults and those with preclinical Alzheimer's disease (AD).[6–8] Multiple longitudinal studies have shown that poor sleep duration and quality are associated with lower memory performance and higher risk of developing mild cognitive impairment (MCI), highlighting the importance of interventions that can stabilize circadian rhythms and enhance both sleep and cognitive outcomes.

World Trade Center rescue and recovery workers and volunteers (WTC RRWV), who participated in the efforts at the World Trade Center site following the September 11, 2001, attacks, present a unique population at high risk for CRD and its consequences. These individuals were exposed to and continue to experience residual impacts from stress and environmental exposures during their work at Ground Zero, which have been implicated in neuroinflammation and cognitive dysfunction.[9–11] A recent longitudinal follow-up review of cognitive impairment and World Trade Center-related exposures found that 17.8% of WTC RRWV exhibited cognitive impairment

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by middle age, with an additional 14.2% developing MCI over 2.5 years after that initial assessment.[11] Their advancing age, combined with a high prevalence of poor sleep (e.g., insomnia, sleep-disordered breathing), emphasizes the importance of targeted interventions to mitigate cognitive decline in this population.[12,13]

Despite the promise of circadian-effective light therapy, its application in real-world, at-risk populations such as WTC RRWV remains underexplored. This cohort exhibits a high burden of stress-related and environmental risk factors linked to CRD, poor sleep, and cognitive dysfunction.[13] However, the insights gained may also inform interventions for other populations experiencing circadian misalignment, including shift workers, individuals with PTSD, and older adults with MCI.

By addressing modifiable environmental factors such as daily light exposure, this study offers preliminary evidence for the use and feasibility of non-pharmacological light-based strategies to improve sleep and cognitive function in vulnerable groups. We hypothesize that enhancing the light–dark signal through wearable light therapy will yield improvements in sleep quality and cognition among WTC RRWV with MCI and sleep disturbances.

Materials and methods

Participant selection

Twenty-three participants identified as WTC RRWV (mean age = 63.0 years, SD = 5.6; 10 females, 13 males) were enrolled in the study. Out of these, 16 completed intervention (mean age = 64.4 years, SD = 5.5; 9 females, 7 males) and 7 withdrew. Participant attrition ($n = 7$) was primarily due to non-study-related factors such as schedule conflicts and travel. Baseline characteristics for completers versus non-completers are summarized in Supplementary Table 1. Demographic data for the 16 participants who completed the intervention are summarized in Table 1. Participants were recruited through the Mount Sinai WTC Health Program Clinical Center beginning in March 2023, and the study concluded in September 2024. Informed consent was obtained from all participants in accordance with experimental protocols approved by the Institutional Review Board (IRB) of the Icahn School of Medicine at Mount Sinai, New York. Research was completed in accordance with the Helsinki Declaration. There was a minimal risk of harm to the participants, as no known threats to safety are associated with the devices used in the study and all comply with federal regulations regarding electromagnetic and radio interference.

Table 1. Demographics of the study participants.

Outcome	Quantity
Age (Mean [SD])	64.4 (5.6)
Sex (N)	
Male	7
Female	9
Race/Ethnicity (*N*)	
White	12
African American	2
Asian	1
White/Hispanic	1
Education level (*N*)	
12+ years	15
Not reported	1

Participants were added to the study if they had sleep disturbances based on Pittsburgh Sleep Quality Index (PSQI)[14] scores >5 and mild cognitive impairment as characterized by Montreal Cognitive Assessment (MoCA)[15] scores ranging from 17 to 25. Both the PSQI and MoCA have demonstrated strong internal consistency, each with a reported Cronbach's alpha of 0.83.[14,15] All participants and/or their caregivers were interviewed *via* phone to determine eligibility based on their medical history, current and previous treatment regimens, and current medication use. Excluded from the study were those with suicidal tendencies, recent psychotropic medication changes, major organ failure, uncontrolled disorders like hypertension or diabetes, obstructive vision conditions, prior cataract surgery with specific lenses, untreated sleep apnea, restless leg syndrome, or the presence of another brain disease accounting for their cognitive status. Those with histories of severe epilepsy, photosensitivity dermatitis, progressive retinal disease, or permanently dilated pupils were also excluded. Validated Spanish versions of the MoCA and PSQI were available. However, all participants in the final sample completed the English versions, as English was their primary language for communication. Consequently, language was not included as a covariate in subsequent analyses.

Light intervention

The light intervention employed in the study delivered a robust light–dark pattern specified for stimulating the human circadian system based on the mathematical model of circadian phototransduction proposed by Rea and colleagues.[16–18] According to the model, circadian stimulus (CS) is calculated from circadian-effective light (CL_A),[19] which is a biophysical construct relating the spectral sensitivity of the human retina to optical radiation for stimulation of the master biological clock in the suprachiasmatic nuclei.[16,20] Above the modeled threshold (CS = 0.1) of the circadian system, CL_A values are transformed into CS values until they reach a point of saturation (CS = 0.7), beyond which greater CL_A values do not incrementally affect CS. Previous research among people with Alzheimer's disease has shown that exposure to CS >0.3 during the day and <0.1 during the evening improved sleep, mood, and behavior in that population.[21–23] Although originally validated in Alzheimer's populations, the CS threshold of >0.3 was used here given the growing evidence of circadian disruption in MCI as a prodromal stage of neurodegeneration.[6] Additionally, prior studies conducted in office workers and other healthy adults have demonstrated that a CS threshold of >0.3 is appropriate for the general population.[24–26]

Although previous studies in Alzheimer's populations employed custom-built table and floor lamps designed for use in residential settings, the present study eased participant burden by providing a portable intervention using the commercially available light therapy glasses (Re-Timer, Londsdale SA, AU) shown in Figure 1. Participants wore the glasses during their usual morning routines (e.g., breakfast, reading, hygiene), and no significant disruptions to daily activities were reported. The light glasses' four light-emitting diodes (LEDs), positioned two on each side of the device frame's lower wings and directed up toward the eyes (see Figure 1), are specified by the manufacturer to provide 500-nm "green-blue" light at an "illuminance" level of 506 lx on the "high lux" setting, which was confirmed by readings directly facing the LED source taken by our laboratory. However, because CS is measured at the cornea and the device's nosepiece (and, therefore, the LEDs' position relative to the cornea) is adjustable by about 10 to 20 mm both vertically and horizontally, the experimenters conservatively evaluated its output at a standardized eye position to ensure the criterion CS value >0.3 would be achieved in the field. Measurements were taken 14 mm behind the LEDs (in the direction of the cornea) at the locations depicted in Figure 1 *via* spectrometer (Jaz, Ocean Optics, Dunedin, FL, USA) and CS was calculated using the Light and Health Research Center's CS Calculator (2.0).[27] According to the CS calculator, the glasses provided a CS of 0.36 (λ_{peak} = 501 nm, mean vertical illuminance = 179.5 lx) at each eye on the high lux setting, which comfortably exceeded the CS level specified in the experimental design. The light therapy glasses were worn 1 h per day, beginning within 1 h of the participants' habitual wake time, for a duration of 12 wks. Participants were instructed on the operation of the glasses and told to energize them on the high lux setting during use.

Study outcomes

Sleep quality

Pre- and post-intervention sleep quality was subjectively assessed using the PSQI questionnaire, which is a well-established instrument for evaluating sleep quality in clinical populations. The questionnaire consists of 19 self-rated items that generate seven component scores related to sleep quality, sleep latency, sleep duration, habitual sleep efficiency, sleep disturbances, use of sleep medication, and daytime dysfunction.[14] The sum of these component scores yields a global PSQI score ranging from 0 to 21. A global score >5 indicates poor sleep quality, while scores ≥10 place individuals in the worst tertile or quartile of the sleep quality distribution in most clinical studies.

Activity–rest

Wrist actigraphy has been validated in older adults and those with cognitive impairment, correlating strongly with polysomnography and sleep logs.[28,29] Participants were instructed to wear an actigraph (Actiwatch 2, Philips Respironics, Murraysville, PA, USA, or wGT3X-BT, ActiGraph, Pensacola,

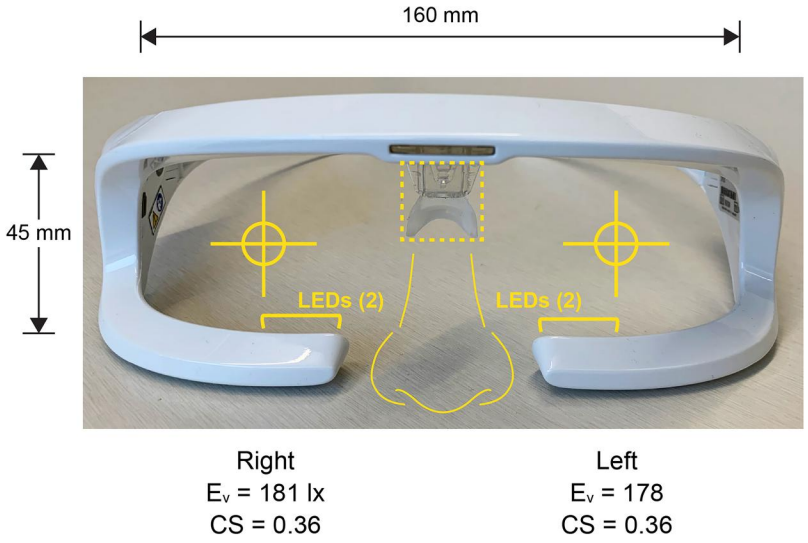

Figure 1. Front view of the light therapy glasses used in the experiment showing E_V and CS calculations for each eye and the locations of the LEDs, spectroradiometer measurement locations (indicated by crosshairs), and adjustable nosepiece (indicated by dashed line). The measurements were taken in the measured center of each side of the glasses, 14 mm behind (i.e., toward the cornea) the LEDs and facing directly forward. The measurement locations assume an exceptionally broad pupillary distance of 90 mm. The device measurements represent the inner dimensions of the frame. E_v: vertical illuminance.

FL, USA) on their non-dominant wrist to record pre- and post-intervention rest–activity data. Actigraphy outcomes for sleep included sleep duration (elapsed time from bedtime to waking at the end of the sleep period, in minutes); sleep efficiency (the percentage of sleep duration scored by the actigraphy software as asleep); sleep onset latency (the time required to transition from bedtime to the start of sleep, in minutes); and wake after sleep onset (WASO, the total time scored by the actigraphy software as awake during the sleep period, in minutes). The actigraphy data were also used to assess circadian rhythm regularity and stability[30,31] *via* the calculation of interdaily stability (IS), a measure of the consistency of the sleep-wake pattern across 24-h periods, and intradaily variability (IV), which quantifies the fragmentation of activity-rest cycles within a 24-h period. Both are unitless measures represented by decimal ratios ranging from zero to 1, with higher IS ratios indicating better interdaily stability and higher IV ratios indicating greater intradaily variability.

Cognition

Participants' pre- and post-intervention cognitive function was assessed using the MoCA, which evaluates various cognitive domains including short-term memory, visuospatial abilities, executive functions, attention, concentration, working memory, language, and orientation.[15,32] Although a validated Spanish-language version of the MoCA was available, it was not used in this study, as all participants had English as their primary language. Therefore, the English version of the MoCA was administered to the entire sample. Three cognitive performance tasks were also employed to evaluate pre- and post-intervention differences in specific cognitive domains, including sustained attention, short-term memory, and interference control with a high degree of sensitivity and specificity (67%–99%). Sustained attention and response inhibition were evaluated using the go/no-go (GNG) task, [33] in which participants responded to the word "go" by pressing a designated key within 2 s and refrained from responding when presented with "no go." Outcomes for the GNG task included accuracy (a decimal ratio representing the proportion of correct responses out of the total number of trials reported as a numeric value ranging from 0 to 1) and reaction time (RT, in milliseconds). The digit span task[34] was used to assess short-term memory capacity by presenting participants with a sequence of numbers that increased in length and were asked to repeat them in order. The longest correctly recalled sequence determined participants' digit span scores. The Stroop task[35] was used to measure interference control and cognitive flexibility by presenting participants with a series of color names (e.g., "red")

displayed in font colors that differed from the name's referent (e.g., "red" displayed in a blue font). Participants were asked to identify the color of the displayed word by pressing corresponding keys (e.g., "B" for "blue"). Outcomes for the Stroop task included total accuracy, as well as accuracy (a decimal ratio representing the proportion of correct responses out of the total number of trials reported as a numeric value ranging from 0 to 1) and RT (in milliseconds [ms]) for congruent (e.g., "red" displayed in a red font) and incongruent (e.g., "red" displayed in a blue font) stimuli, as well as the Stroop effect, calculated as the time difference (in milliseconds) between the mean RT to incongruent stimuli and the mean RT to congruent stimuli.

Circadian-effective light exposure

Participants' circadian-effective light exposures were measured using a personal light monitor called a Daysimeter[36] worn as a pendant (i.e., approximately at chest level) from waketime to bedtime during the pre- and post-intervention data collection periods. Calibrated in terms of photopic illuminance (lux) and the CS metric (see Light intervention), the Daysimeter when worn as a pendant yields light exposure measurements that closely correspond to those recorded at the eye.[37] In addition to CS exposures calculated from Daysimeter data for the entire day after waking, we also separately calculated participants' CS exposures during the 2-h period after waking combined with the 1-h CS dose delivered by the light glasses during that time. This latter calculation was performed because the Daysimeter worn as a pendant is incapable of capturing the localized stimulus provided by the intervention.

Protocol

The 14-week study employed a single-arm, pre-post design. The study began with a pre-intervention (or baseline) assessment period during which participants wore the actigraph and Daysimeter for 1 week. This period concluded with the completion of the questionnaires and cognitive performance tasks. The participants were then asked to wear the energized light therapy glasses for 1 h per day within the first 2 h of their habitual wake time for 12 wks. During the final week of the light intervention and the end of the study, the participants were once again instructed to wear the actigraph and Daysimeter. On the last day of that post-intervention assessment week, the participants once again completed the questionnaires and cognitive performance tasks.

The study devices (i.e., light therapy glasses, actigraph, Daysimeter) were either shipped or hand-delivered to the participants by a Mount Sinai clinical research coordinator, according to the individual participant's preference. Instructional manuals and personal guidance on the operation of all devices were provided in person or virtually *via* teleconferencing. If additional participant support was required, caregivers were instructed to work with the study's clinical research coordinators to ensure the protocol was followed and the devices were being used properly. The clinical research coordinators promptly addressed problems with the study devices and any deviations from the study's protocol.

Statistical analysis

The study's primary outcomes were the PSQI, MoCA, GNG task, digit span task, and Stroop task; the secondary outcomes were the sleep duration, sleep efficiency, sleep onset latency, WASO, IS and IV measures. To evaluate the effectiveness of the light intervention, pre- and post-intervention data for the primary and secondary outcomes were compared using one-tailed paired t-tests or Wilcoxon signed-rank tests, depending on the data distribution. Additionally, Spearman's correlation was used to assess the relationship between CS exposures and primary outcomes. Given the small sample size and single-arm design, additional estimation-based methods were used to enhance interpretability. These included: (1) histograms of individual change scores (post-pre) to visualize score distributions and identify variability (Supplementary Figure 1); (2) participant-level trajectory plots to illustrate within-subject pre-to-post changes across outcomes (Supplementary Figure 2); and (3) Cohen's *d* effect sizes to describe the magnitude of change without reliance on statistical significance testing (Supplementary Table 2). Cohen's *d* was calculated as the mean change

divided by the standard deviation of the change scores—to describe the magnitude of change, with 0.2, 0.5, and 0.8 conventionally interpreted as small, medium, and large effects, respectively. All analyses were conducted using R v4.1.3 (R Foundation for Statistical Computing, Vienna, Austria). Apart from the seven participants who withdrew from the study, complete post-intervention data were not available for two participants in the subjective sleep (PSQI) analysis, three participants in the actigraphic sleep analyses (sleep duration, sleep efficiency, sleep onset latency, and WASO), two participants in the circadian rhythm regularity and stability (IS and IV) analyses, and two participants in the cognitive function (MoCA) analysis. Data from all 16 participants were available for cognitive performance (GNG, digit span, and Stroop task) analyses. Data was not available for two participants in the CS measure. The analyses for each outcome included only those participants for whom both pre- and post-intervention data were available. Statistical significance for comparisons was defined as $p < 0.05$. However, given the pilot nature of the study and small sample size, findings are interpreted as preliminary estimates rather than definitive tests of efficacy. The goal of these analyses was to explore potential signals of change and estimate effect sizes to inform future, adequately powered trials, rather than to draw definitive conclusions about efficacy.

Results

The results for the sleep quality, activity–rest, and cognition outcomes are summarized in Table 2 and described by outcome below.

Sleep quality

Participants showed a significant post-intervention improvement in subjective sleep quality, with a nearly 2-point reduction in mean PSQI score (Figure 2 and Table 2). While a change of more than 3 points is often cited as clinically meaningful,[38,39] our observed improvement—supported by a medium effect size ($d = -0.52$, Supplementary Table 2)—is notable given the relatively short 12-week intervention period. Downward pre-to-post trajectories for most participants further support this trend (Supplementary Figure 1 and Supplementary Figure 2).

Activity–rest

Although changes in activity–rest outcomes were not statistically significant, several post-intervention

Table 2. Results of the analyses conducted for the study's sleep quality, activity–rest, and cognition outcomes.

		Intervention			
Outcome	N[a]	Pre-(mean [SD])	Post-(mean [SD])	*p* value[b]	Trend
Sleep quality					
PSQI (score)	14	**10.21 (1.81)**	**8.29 (2.97)**	**0.036**	Better
Activity–rest					
Sleep duration (min)	13	424.05 (55.73)	395.99 (95.00)	0.183	Worse
Sleep efficiency (percentage)	13	83.89 (6.50)	85.55 (6.35)	0.068	Better
Sleep onset latency (min)	13	8.02 (7.19)	7.73 (8.10)	0.867	Better
Wake after sleep onset (min)	13	59.69 (23.80)	45.54 (21.71)	0.117	Better
Interdaily stability (decimal ratio)	14	0.45 (0.18)	0.42 (0.16)	0.615	Worse
Intradaily variability (decimal ratio)	14	0.83 (0.18)	0.81 (0.27)	0.729	Better
Cognition					
Cognitive function (MoCA)	16	23.29 (1.54)	24.06 (2.36)	0.119	Better
Go/no-go (GNG) task					
Accuracy (decimal ratio)	16	0.95 (0.08)	0.97 (0.04)	0.222	Better
Reaction time (ms)	16	**1050.10 (207.23)**	**934.52 (125.92)**	**0.015**	Better
Digit span task (score)	16	6.13 (1.15)	6.44 (1.36)	0.145	Better
Stroop task					
Total accuracy (decimal ratio)	16	0.87 (0.16)	0.90 (0.09)	0.366	Better
Accuracy, congruent (decimal ratio)	16	0.94 (0.20)	0.96 (0.11)	0.486	Better
Accuracy, incongruent (ms)	16	0.84 (0.17)	0.88 (0.10)	0.122	Better
Reaction time, congruent (ms)	16	1155.16 (190.09)	1129.81 (187.10)	0.299	Better
Reaction time, incongruent (ms)	16	**1334.46 (164.28)**	**1263.35 (155.53)**	**0.039**	Better
Stroop effect (ms)	16	179.30 (118.68)	133.54 (101.30)	0.125	Better

Notes: (a) Represents number of participants with available pre- and post-intervention data for each outcome. (b) Statistically significant ($p < 0.05$) values are shown in bold.

trends emerged, with notable individual variability in change scores (Supplementary Figure 1) and trajectories (Supplementary Figure 2). Participants exhibited slight decreases in mean sleep duration, sleep onset latency, and WASO, alongside a modest increase in sleep efficiency. Cohen's d effect sizes indicated small to medium effect sizes in sleep onset latency ($d = -0.05$), WASO ($d = -0.47$), sleep duration ($d = -0.39$), and efficiency ($d = 0.25$), suggesting a trend toward more consolidated and efficient sleep (Supplementary Table 2). In terms of circadian rhythm metrics, both IS and IV had small effect sizes ($d = -0.06$ and $d = -0.01$, respectively). These patterns provide useful estimates of variability that can inform the design of future controlled studies (see Table 2).

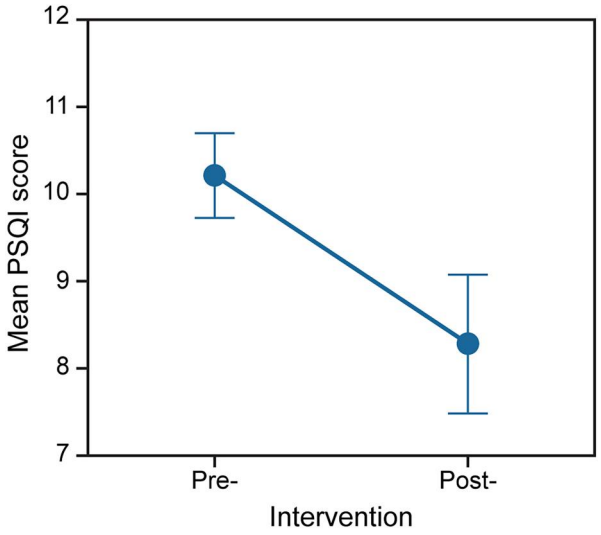

Figure 2. The significant post-intervention improvement in subjective sleep quality, indicated by lower PSQI scores. It should be noted that the post-intervention score still indicates sleep disturbance (i.e., PSQI >5).

Cognition

Statistically significant improvements were observed in some cognitive outcomes following the intervention. Mean reaction time (RT) on the go/no-go (GNG) task significantly decreased post-intervention ($p < 0.05$), indicating faster response times (Figure 3A, Table 2). Similarly, Stroop incongruent RT showed a significant reduction ($p < 0.05$), suggesting improved cognitive control and processing speed (Figure 3B, Table 2). Medium effect sizes were observed for GNG RT ($d = -0.60$), Stroop incongruent RT ($d = -0.47$) (Supplementary Table 2). Other cognitive outcomes showed non-significant trends in cognitive improvement, with small effect sizes observed. MoCA ($d = 0.33$), GNG accuracy ($d = 0.25$), Stroop incongruent accuracy ($d = 0.30$), Stroop congruent accuracy ($d = 0.09$), and digit span ($d = 0.27$) all increased with small effect sizes. Similarly, Stroop congruent RT ($d = -0.13$), and Stroop effect ($d = -0.30$) decreased with small effect sizes. Visual inspection of participant trajectories and histograms in Supplementary Figures 1 and 2 highlight heterogeneity in cognitive responses.

Circadian-effective light exposure

During the intervention period, participants received an average circadian stimulus (CS) of 0.44 (SD = 0.17) within the first two hours of waking, and 0.31 (SD = 0.11) throughout the day. A significant positive correlation was observed between CS exposure—both in the 2-h post-wake window ($\rho = 0.55$, $\boldsymbol{p} = 0.043$) and across the day ($\rho = 0.59$, $\boldsymbol{p} = 0.024$)—and Stroop

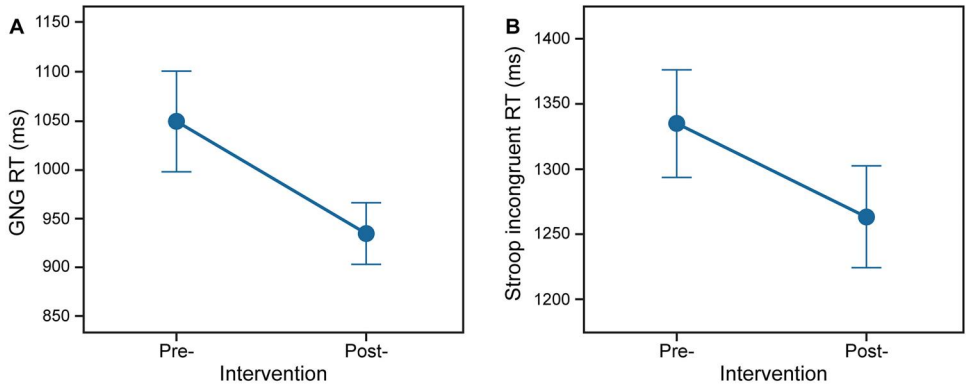

Figure 3. The significant post-intervention improvement in the GNG task (A) and Stroop incongruent task (B), as indicated by a reduction in RT (ms).

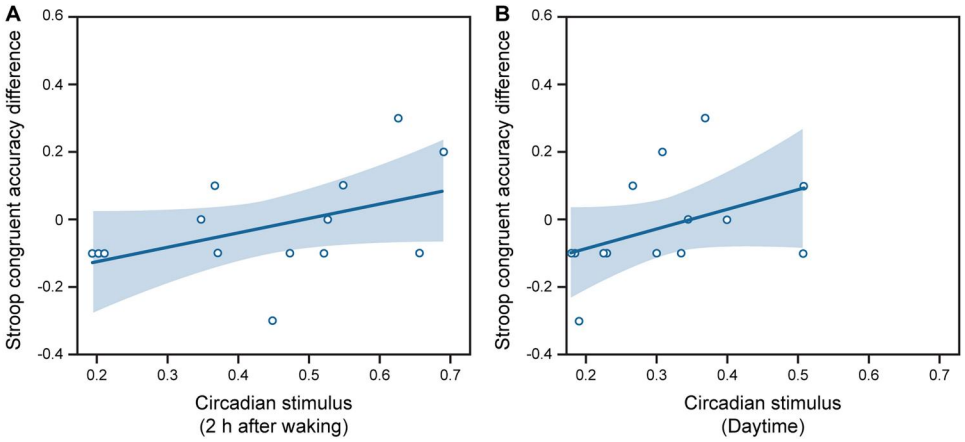

Figure 4. Association between CS values and Stroop congruent accuracy 2 h after waking, including the intervention, (A) and during the daytime (B). The shaded area in each panel represents the 95% confidence interval of the linear regression line. Stroop congruent accuracy is reported as a decimal ratio.

congruent task accuracy. These associations suggest that higher daytime light exposure may be related to better cognitive performance on selective attention tasks (Figure 4).

Discussion

This pilot study explored the feasibility and preliminary effects of a wearable, circadian-effective light therapy intervention in a cohort of WTC RRWV with MCI and comorbid sleep disturbances. Preliminary signals suggest that morning light exposure *via* portable light therapy glasses may be a practical and acceptable intervention in this high-risk population, with participants reporting modest improvements in subjective sleep quality and select cognitive outcomes. These findings align with prior studies showing that light interventions can improve sleep-related symptoms in PTSD and aging populations,[23,40] and enhance attention and executive function in both clinical and healthy cohorts.[41,42]

Significant pre–post improvements were observed in PSQI scores and in reaction time performance on go/no-go and Stroop tasks, though the use of simple change scores as the primary analytic approach warrants caution. It is well-established that change scores can have reduced reliability due to the additive nature of measurement error from pre- and post-intervention assessments.[43,44] In small samples, this compounded error variance can obscure genuine treatment effects and inflate Type II error rates. To mitigate this, we supplemented our analyses with effect size estimates (Cohen's *d*) and visualized participant-level changes to better characterize variability in response.

This study offers valuable feasibility data. Participants demonstrated high protocol adherence, with wearable device readings confirming that participants consistently wore the monitoring sensors during the required times. Although the light therapy glasses did not have embedded adherence tracking, self-reported data indicated high compliance, with participants reporting use on intervention days. Additionally, no adverse effects were reported, and individual-level outcomes showed heterogeneity—suggesting that certain subgroups may benefit more than others, possibly due to variation in baseline circadian disruption, PTSD severity, or other comorbidities.[11,45]

The improvement in PSQI scores shown in this study is consistent with our previous research demonstrating that high circadian-effective light exposures (CS $\geq$ 0.3) during the day improved subjective sleep (i.e., PSQI and Sleep Disorder Inventory scores) in people living with Alzheimer's disease and related dementias. Also, like our previous work, improvements in objective sleep measures were observed, but not all of them reached statistical significance. There were no significant changes in objective measures of circadian robustness (i.e., interdaily stability and intradaily variability). Interdaily stability decreased slightly post-intervention (mean IS = 0.42 to 0.39), though this was a non-significant

change that does not support improved circadian regularity (see Table 2). This lack of statistical significance may be due to the study's small sample size as well as to the short intervention duration. Our previous work shows that a longer intervention period will result in stronger improvement in sleep outcomes. [22] These preliminary findings suggest that a circadian-effective light intervention may be used as a viable non-pharmacological treatment for mitigating circadian misalignment and improving sleep quality—thereby possibly avoiding well-documented health risks associated with CRD—in the WTC RRWV cohort.

Similarly, statistically significant post-intervention improvements (i.e., decreases) in cognitive performance were observed in RTs for the GNG task and Stroop incongruent outcomes, which may be a feasible reflection of an improvement in response inhibition, selective attention, and executive control. These results are consistent with studies linking light exposure to enhancements in higher-order cognitive processes such as attention, memory, and decision-making.[46,47] The positive correlations between higher daytime CS exposures and Stroop congruent accuracy (see Figure 4) warrant further studies on the role of light in modulating cognitive performance, perhaps through better sleep. Considered together, the study's sleep and cognitive performance outcomes are consistent with previous studies showing the link between better sleep and better cognition.[11,48–50]

These preliminary findings highlight the feasibility and potential utility of circadian-effective light interventions for addressing sleep and cognitive disturbances in WTC RRWV with MCI. Given the high prevalence of disrupted sleep–wake cycles and executive dysfunction in this population, light-based strategies may represent a practical, non-pharmacological approach worth further investigation. While current results do not establish clinical efficacy, they offer direction for future research aimed at optimizing light therapy protocols—including parameters such as dose, timing, and spectral composition—and evaluating their integration with other behavioral interventions like cognitive behavioral therapy. Longitudinal and controlled studies will be essential to determine whether such interventions yield sustained improvements in sleep and cognitive function and whether they can be adapted for broader use in occupational or training settings.

Despite encouraging findings, this study has several limitations. The absence of a control group leaves opens the possibility that observed changes could be attributed to nonspecific effects such as regression to the mean,[51] practice effects, and expectancy bias, precluding causal inference. Indeed, cognitive reaction-time tasks like GNG and Stroop are susceptible to practice effects that can produce modest gains with repeated exposure, independent of intervention.[52] External variables, including seasonal increases in ambient morning light (particularly in spring/summer months), may have also contributed to increased circadian-effective light exposure, thereby confounding the effects attributed to the intervention. Additionally, adherence was self-reported, and the Daysimeter could not capture the localized stimulus from the glasses, introducing uncertainty in actual dose delivery. Although adherence was monitored through self-report logs, the possibility of reporting inaccuracies or overestimation cannot be fully excluded, which may have introduced bias in estimating the actual exposure to the light intervention. Additionally, these results are specific to individuals with mild cognitive impairment and should not be generalized to those with Alzheimer's disease or other dementias. Attrition (∼30%) and missing data further constrain internal and external validity. Future studies should incorporate control conditions and consider mixed-effects or time-series models to better account for individual variability over time.

Nevertheless, these preliminary findings offer qualified support for the feasibility and acceptability of circadian-effective light interventions in the WTC RRWV population. Additional research, including follow-up on shorter-duration interventions such as those used by Zalta et al, may help determine whether light therapy can improve sleep outcomes in WTC RRWV specifically with PTSD.[40]

Conclusion

In summary, this pilot study demonstrates that delivering a tailored, circadian-effective light dose

via wearable glasses is feasible and well tolerated in WTC RRWV with MCI and sleep disturbances. Participants reported modest improvements in subjective sleep and cognitive processing speed. However, given the study's uncontrolled design, small sample size, and potential for confounding, these findings should be interpreted as preliminary signals of promise, not evidence of efficacy. Rather than establishing effectiveness, this study provides important insights into protocol adherence, intervention tolerability, and outcome variability. These findings lay the groundwork for larger, randomized trials aimed at determining whether circadian-based light interventions can reliably improve sleep and cognitive health in aging and occupationally exposed populations.

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Data availability statement

All data presented in this study will be made available by the corresponding author upon reasonable request.

References

1. Refinetti R. Circadian rhythmicity of body temperature and metabolism. *Temperature*. 2020;7(4):321–362. doi:10.1080/23328940.2020.1743605.
2. Valdez P. Circadian rhythms in attention. *Yale J Biol Med*. 2019;92(1):81–92.
3. Huang W, Ramsey KM, Marcheva B, Bass J. Circadian rhythms, sleep, and metabolism. *J Clin Invest*. 2011;121(6):2133–2141. doi:10.1172/jci46043.
4. Roenneberg T, Kantermann T, Juda M, Vetter C, Allebrandt KV. Light and the human circadian clock. In: Kramer A, Merrow M, eds. *Circadian Clocks*. chap 1. *Handbook of Experimental Pharmacology* Springer; 2013:311–331.
5. Chellappa SL, Vujovic N, Williams JS, Scheer FAJL. Impact of circadian disruption on cardiovascular function and disease. *Trends Endocrinol Metab*. 2019;30(10):767–779. doi:10.1016/j.tem.2019.07.008.
6. Leng Y, Musiek ES, Hu K, Cappuccio FP, Yaffe K. Association between circadian rhythms and neurodegenerative diseases. *Lancet Neurol*. 2019;18(3):307–318. doi:10.1016/S1474-4422(18)30461-7.
7. Yaffe K, Falvey CM, Hoang T. Connections between sleep and cognition in older adults. *Lancet Neurol*. 2014;13(10):1017–1028. Oct doi:10.1016/S1474-4422(14)70172-3.
8. Mattis J, Sehgal A. Circadian rhythms, sleep, and disorders of aging. *Trends Endocrinol Metab*. 2016;27(4):192–203. doi:10.1016/j.tem.2016.02.003.
9. Deri Y, Clouston SAP, DeLorenzo C, et al. Neuroinflammation in World Trade Center responders at midlife: a pilot study using [18F]-FEPPA PET imaging. *Brain Behav Immun Health*. 2021;16:100287. doi:10.1016/j.bbih.2021.100287.
10. Singh A, Zeig-Owens R, Rabin L, et al. PTSD and depressive symptoms as potential mediators of the association between World Trade Center exposure and subjective cognitive concerns in rescue/recovery workers. *Int J Environ Res Public Health*. 2020;17(16):5683. doi:10.3390/ijerph17165683.
11. Clouston SAP, Hall CB, Kritikos M, et al. Cognitive impairment and World Trade Centre-related exposures. *Nat Rev Neurol*. 2022;18(2):103–116. doi:10.1038/s41582-021-00576-8.
12. Clouston SAP, Diminich ED, Kotov R, et al. Incidence of mild cognitive impairment in World Trade Center responders: long-term consequences of re-experiencing the events on 9/11/2001. *Alzheimers Dement*. 2019;11(1):628–636. doi:10.1016/j.dadm.2019.07.006.
13. Dietch JR, Ruggero CJ, Schuler K, Taylor DJ, Luft BJ, Kotov R. Posttraumatic stress disorder symptoms and sleep in the daily lives of World Trade Center responders. *J Occup Health Psychol*. 2019;24(6):689–702. doi:10.1037/ocp0000158.
14. Buysse DJ, Reynolds CF, Monk TH, Berman SR, Kupfer DJ. The Pittsburgh Sleep Quality Index: a new

instrument for psychiatric practice and research. *Psychiatry Res*. 1989;28(2):193–213. doi:10.1016/0165-1781(89)90047-4.
15. Nasreddine ZS, Phillips NA, Bédirian V, et al. The Montreal Cognitive Assessment, MoCA: a brief screening tool for mild cognitive impairment. *J Am Geriatr Soc*. 2005;53(4):695–699. doi:10.1111/j.1532-5415.2005.53221.x.
16. Rea MS, Figueiro MG, Bullough JD, Bierman A. A model of phototransduction by the human circadian system. *Brain Res Brain Res Rev*. 2005;50(2):213–228. doi:10.1016/j.brainresrev.2005.07.002.
17. Rea MS, Nagare R, Figueiro MG. Modeling circadian phototransduction: quantitative predictions of psychophysical data. *Front Neurosci*. 2021;15:615322. doi:10.3389/fnins.2021.615322.
18. Rea MS, Nagare R, Figueiro MG. Modeling circadian phototransduction: retinal neurophysiology and neuroanatomy. *Front Neurosci*. 2021;14:615305. doi:10.3389/fnins.2020.615305.
19. Rea MS, Figueiro MG, Bierman A, Bullough JD. Circadian light. *J Circadian Rhythms*. 2010;8(1):2. doi:10.1186/1740-3391-8-2.
20. Rea MS, Figueiro MG, Bierman A, Hamner R. Modelling the spectral sensitivity of the human circadian system. *Lighting Res Technol*. 2012;44(4):386–396. doi:10.1177/1477153511430474.
21. Figueiro MG, Plitnick B, Roohan C, Sahin L, Kalsher M, Rea MS. Effects of a tailored lighting intervention on sleep quality, rest–activity, mood, and behavior in older adults with Alzheimer's disease and related dementias: a randomized clinical trial. *J Clin Sleep Med*. 2019;15(12):1757–1767. doi:10.5664/jcsm.8078.
22. Figueiro MG, Sahin L, Kalsher M, Plitnick B, Rea MS. Long-term, all-day exposure to circadian-effective light improves sleep, mood, and behavior in persons with dementia. *J Alzheimers Dis Rep*. 2020;4(1):297–312. doi:10.3233/ADR-200212.
23. Figueiro MG, Plitnick BA, Lok A, et al. Tailored lighting intervention improves measures of sleep, depression, and agitation in persons with Alzheimer's disease and related dementia living in long-term care facilities. *Clin Interv Aging*. 2014;9:1527–1537. doi:10.2147/CIA.S68557.
24. Nagare R, Woo M, MacNaughton P, Plitnick B, Tinianov B, Figueiro M. Access to daylight at home improves circadian alignment, sleep, and mental health in healthy adults: a crossover study. *Int J Environ Res Public Health*. 2021;18(19):9980. doi:10.3390/ijerph18199980.
25. Figueiro MG, Kalsher M, Steverson BC, Heerwagen J, Kampschroer K, Rea MS. Circadian-effective light and its impact on alertness in office workers. *Lighting Res Technol*. 2019;51(2):171–183. doi:10.1177/1477153517750006.
26. Figueiro MG, Steverson B, Heerwagen J, et al. Light, entrainment and alertness: a case study in offices. *Lighting Res Technol*. 2020;52(6):736–750. doi:10.1177/1477153519885157.
27. Light and Health Research Center. CS Calculator (2.0). Icahn School of Medicine at Mount Sinai. Updated July 16, 2021. Accessed 1 September, 2024. https://cscalc.light-health.org/.
28. Kushida CA, Chang A, Gadkary C, Guilleminault C, Carrillo O, Dement WC. Comparison of actigraphic, polysomnographic, and subjective assessment of sleep parameters in sleep-disordered patients. *Sleep Med*. 2001;2(5):389–396. doi:10.1016/S1389-9457(00)00098-8.
29. Kosmadopoulos A, Sargent C, Darwent D, Zhou X, Roach GD. Alternatives to polysomnography (PSG): a validation of wrist actigraphy and a partial-PSG system. *Behav Res Methods*. 2014;46(4):1032–1041. doi:10.3758/s13428-013-0438-7.
30. Witting W, Kwa IH, Eikelenboom P, Mirmiran M, Swaab DF. Alterations in the circadian rest-activity rhythm in aging and Alzheimer's disease. *Biol Psychiatry*. 1990;27(6):563–572. doi:10.1016/0006-3223(90)90523-5.
31. Fekedulegn D, Andrew ME, Shi M, Violanti JM, Knox S, Innes KE. Actigraphy-based assessment of sleep parameters. *Ann Work Expo Health*. 2020;64(4):350–367. doi:10.1093/annweh/wxaa007.
32. Zadikoff C, Fox SH, Tang-Wai DF, et al. A comparison of the mini mental state exam to the Montreal cognitive assessment in identifying cognitive deficits in Parkinson's disease. *Mov Disord*. 2008;23(2):297–299. doi:10.1002/mds.21837.
33. Gomez P, Ratcliff R, Perea M. A model of the go/no-go task. *J Exp Psychol Gen*. 2007;136(3):389–413. doi:10.1037/0096-3445.136.3.389.
34. Woods DL, Kishiyamaa MM, Lund EW, et al. Improving digit span assessment of short-term verbal memory. *J Clin Exp Neuropsychol*. 2011;33(1):101–111. doi:10.1080/13803395.2010.493149.
35. Scarpina F, Tagini S. The Stroop color and word test. *Front Psychol*. 2017;8:557. doi:10.3389/fpsyg.2017.00557.
36. Bierman A, Klein TR, Rea MS. The Daysimeter: a device for measuring optical radiation as a stimulus for the human circadian system. *Meas Sci Technol*. 2005;16(11):2292–2299. doi:10.1088/0957-0233/16/11/023.
37. Figueiro MG, Hamner R, Bierman A, Rea MS. Comparisons of three practical field devices used to measure personal light exposures and activity levels. *Light Res Technol*. 2013;45(4):421–434. doi:10.1177/1477153512450453.
38. Qin Z, Zhu Y, Shi DD, Chen R, Li S, Wu J. The gap between statistical and clinical significance: time to pay attention to clinical relevance in patient-reported outcome measures of insomnia. *BMC Med Res Methodol*. 2024;24(1):177. doi:10.1186/s12874-024-02297-0.
39. Costandi S, Kapural L, Mekhail NA, et al. Impact of long-term evoked compound action potential controlled closed-loop spinal cord stimulation on sleep quality in patients with chronic pain: an EVOKE randomized controlled trial study subanalysis. *Neuromodulation*. 2023;26(5):1030–1038. doi:10.1016/j.neurom.2022.10.050.

40. Zalta AK, Bravo K, Valdespino-Hayden Z, Pollack MH, Burgess HJ. A placebo-controlled pilot study of a wearable morning bright light treatment for probable PTSD. *Depress Anxiety*. 2019;36(7):617–624. doi:10.1002/da.22897.
41. Blume C, Garbazza C, Spitschan M. Effects of light on human circadian rhythms, sleep and mood. *Somnologie*. 2019;23(3):147–156. doi:10.1007/s11818-019-00215-x.
42. Vandewalle G, Maquet P, Dijk D-J. Light as a modulator of cognitive brain function. *Trends Cogn Sci*. 2009;13(10):429–438. doi:10.1016/j.tics.2009.07.004.
43. Cronbach L, Furby L. How we should measure "change": Or should we? *Psychol Bull*. 1970;74(1):68–80. doi:10.1037/h0029382.
44. Lord FM. A paradox in the interpretation of group comparisons. *Psychol Bull*. 1967;68(5):304–305. doi:10.1037/h0025105.
45. Abbott SM, Malkani RG, Zee PC. Circadian disruption and human health: a bidirectional relationship. *Eur J Neurosci*. 2020;51(1):567–583. doi:10.1111/ejn.14298.
46. Iaccarino HF, Singer AC, Martorell AJ, et al. Author correction: gamma frequency entrainment attenuates amyloid load and modifies microglia. *Nature*. 2018;562(7725):E1. doi:10.1038/s41586-018-0351-4.
47. Iaccarino HF, Singer AC, Martorell AJ, et al. Gamma frequency entrainment attenuates amyloid load and modifies microglia. *Nature*. 2016;540(7632):230–235. doi:10.1038/nature20587.
48. Deak MC, Stickgold R. Sleep and cognition. *Wiley Interdiscip Rev Cogn Sci*. 2010;1(4):491–500. doi:10.1002/wcs.52.
49. Diekelmann S. Sleep for cognitive enhancement. *Front Syst Neurosci*. 2014;8:46. doi:10.3389/fnsys.2014.00046.
50. Schouten DI, Pereira SIR, Tops M, Louzada FM. State of the art on targeted memory reactivation: sleep your way to enhanced cognition. *Sleep Med Rev*. 2017;32:123–131. doi:10.1016/j.smrv.2016.04.002.
51. Barnett AG, van der Pols JC, Dobson AJ. Regression to the mean: What it is and how to deal with it. *Int J Epidemiol*. 2005;34(1):215–220. doi:10.1093/ije/dyh299.
52. Calamia M, Markon K, Tranel D. Scoring higher the second time around: meta-analyses of practice effects in neuropsychological assessment. *Clin Neuropsychol*. 2012;26(4):543–570. doi:10.1080/13854046.2012.680913.