Naval Submarine Medical Research Laboratory

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Personal Light Treatment Devices as a Viable Countermeasure for Submariner Fatigue

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Navy submariners experience circadian misalignment and fatigue that can lead to decreases in performance and negative health outcomes. This study investigates whether individualized lighting exposures, through the use of personal light treatment devices (PLTDs), can maintain circadian entrainment, improve sleep, and sustain performance in the crew of an active duty U.S. submarine. 42 active duty submariners were randomly assigned to a PLTD group or a control group. Participants in the PLTD group were provided with blue-light exposure glasses and blue-blocking glasses; participants in the control group did not use PLTDs. Over the 14-day experimental period, Sailors wearing PLTDs received a greater amount of sleep and more efficient sleep; Sailors wearing PLTDs also reported lower levels of sleepiness and presented with higher scores of projected performance effectiveness. Compliance with PLTD use was high, and Sailors did not report any major disruption to operational duties. These data provide preliminary evidence that PLTDs are a viable and effective countermeasure for fatigue onboard U.S. Navy submarines.

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submarine, sleep, fatigue, watchstanding, 24-hour day, circadian rhythms, countermeasure

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Abstract

Navy submariners stand rotating schedules of shift work (8-hour watches) that are discordant with the natural sleep/wake cycle, and they operate in an environment that lacks circadian-aligned lighting sources. As a result, Sailors experience circadian misalignment and fatigue that can lead to decreases in performance and negative health outcomes. This study investigates whether individualized lighting exposures, through the use of personal light treatment devices (PLTDs), can maintain circadian entrainment, improve sleep, and sustain performance in the crew of an active duty U.S. submarine. Forty-two active duty submariners were randomly assigned to a PLTD group or a control group. Participants in the PLTD group were provided with blue-light exposure glasses that provided light with a peak wavelength of 470 nm (worn for approximately 40 minutes upon waking) and with blue-blocking glasses that attenuated light exposure in the wavelength range of 400-510 nm (worn for approximately two hours before going to sleep); participants in the control group did not use PLTDs. Circadian phase (salivary dim light melatonin onset; DLMO), objective sleep (actigraphy), cognitive performance (Automated Neuropsychological Assessment Metrics; ANAM), and self-report mood and sleep measures were assessed before and after PLTD use. Over the 14-day experimental period, Sailors wearing PLTDs received a greater amount of sleep and more efficient sleep than Sailors in the control group; Sailors wearing PLTDs also reported lower levels of sleepiness and presented with higher scores of projected performance effectiveness, albeit no significant improvement in the ANAM was detected. Compliance with PLTD use was high, and Sailors did not report any major disruptions to operational duties. These data provide preliminary evidence that PLTDs are a viable and effective countermeasure for fatigue onboard U.S. Navy submarines. Considerations for PLTD use in the fleet are discussed.

Table of Contents

List of Abbreviations and Acronyms

ANAM	Automated Neuropsychological Assessment Metrics
ºC	Degrees Celsius
CA	California
CDD	Code substitution delayed
CDS	Code substitution simultaneous
CO	Commanding officer
CT	Connecticut
DLMO	Dim light melatonin onset
EAB	Emergency air breather
ESS	Epworth Sleepiness Scale
FAST	Fatigue Avoidance Scheduling Tool
GNG	Go/no-go
IL	Illinois
IQR	Interquartile range
ISI	Insomnia Severity Index
LED	Light emitting diode
LPS	Latency to persistent sleep
M	Mean
min	Minutes
mos	Months
nm	Nanometers
NSMRL	Naval Submarine Medical Research Laboratory
NY	New York
PED	Personal electronic device
PLTD	Personal light treatment device
POMS	Profile of Mood States
PRT	Procedural reaction time
PSQI	Pittsburgh Sleep Quality Index
SD	Standard deviation
SE	Sleep efficiency
SOL	Sleep onset latency
SRT	Simple reaction time
STN	Sternberg memory search
TIB	Time in bed
TMD	Total mood disturbance
TST	Total sleep time
U.S.	United States
WASO	Wakefulness after sleep onset
yrs	Years

List of Tables

List of Figures

Introduction

The U.S. Naval Submarine Force is dedicated to maintaining a ready and agile fleet (e.g., COMSUBFOR, 2020). A key tenant of upholding force readiness is ensuring that warfighters are prepared and healthy at all times. With a history of Naval incidents attributed to fatigued operators (e.g., Department of the Navy, 2017; National Transportation Safety Board, 2019), ensuring that Sailors are well-rested and at their peak is a crucial priority (e.g., U.S. Government Accountability Office, 2021). To that aim, the U.S. Navy has recently mandated that submarines operate on a 24-hour schedule (in contrast to the 18-hour day utilized in previous decades; COMSUBLANT/COMSUBPACINST 5400.49). This shift was expected to alleviate the "operational jetlag" associated with repeatedly-changing sleep times.

A recent Naval Submarine Medical Research Laboratory (NSMRL) study provided an in-depth look at the lifestyles and sleep habits of a fast-attack submarine crew operating on a straight-8s schedule (three-section rotation consisting of 8 hours on watch, 8 hours for training and other duties, and 8 hours of sleep; Chabal, Markwald, & Chinoy, 2021). These submariners received sleep quantities comparable to their peers in other military and civilian communities, and their projected performance metrics were better than those projected for submariners on the previously-employed 18-hour day. Nevertheless, potential areas for improved sleep and performance were highlighted. For example, 77.8% of the crew reported poor sleep quality, 56.1% reported high levels of daytime sleepiness, and 27.5% experienced levels of insomnia symptoms that would require clinical intervention. Therefore, in spite of an overall positive outcome associated with the circadian-aligned watchbill, Chabal et al.'s (2021) investigation highlighted that shifting to 24-hour days is a necessary but not sufficient countermeasure to submariner fatigue.

In addition to rotating schedules of shift work, there are many aspects of submarine life that are likely to contribute to problematic sleep outcomes (see Chabal, Welles, Haran, & Markwald, 2018). Perhaps most salient is the unique lighting environment. In contrast to shore-based operations, Sailors stationed on a submarine are continually exposed to a dim lighting environment (Hunt & Kelly, 1995; Young et al., 2015) that lacks the full-spectrum lighting cues required to serve as a *zeitgeber* for the circadian system. In humans, exposure to light is the most significant time cue used by the body's circadian clock (Duffy & Wright, 2005); in fact, an individual's light exposure pattern may be an even more important determinant of circadian phase than their actual sleep schedule (Appleman, Figueiro, & Rea, 2013; Figueiro, Plitnick, & Rea, 2014). People who are not exposed to circadian-aligned lighting environments, such as night-shift workers, may present with adverse physiological changes including gastrointestinal and reproductive dysfunction, obesity, cardiovascular disease, and some cancers (for a review see Smith & Eastman, 2012); circadian misalignment has also been linked to deficits in performance outcomes (e.g., Whitmire et al., 2009). Regardless of the watch section to which submariners are assigned, they are not exposed to natural light (i.e., sun) cues that would provide the most potent signal to their bodies to become awake and alert at the beginning of their scheduled day.

Compounding the low-level light environment and lack of morning sun exposure onboard a submarine, Chabal et al.'s (2021) study highlighted a second source of potentially-mistimed lighting cues: the use of personal electronic devices (PEDs). PEDs include screen-based devices such as computers, tablets, e-readers, cell phones, televisions, and video game consoles. These devices have been found to emit sufficient quantities of short-wavelength (e.g., blue) light to affect the body's circadian system and disrupt sleep and alertness (Chang, Aeschbach, Duffy, &

Czeisler, 2015; Chinoy, Duffy, & Czeisler, 2018). Crucially, 91.4% of submariners reported the use of PEDs immediately prior to falling asleep while underway (Chabal et al., 2021). While this is not excessive compared to Americans in general (Gradisar et al., 2013), it means that submariners do not receive natural morning light exposure but *do* receive artificial evening light – a pattern of exposure opposite of what is biologically preferential. Correcting this lighting schedule may therefore provide a mechanism for improving sleep and performance outcomes of submariners.

Even low levels of light exposure can be sufficient to entrain (or hinder entrainment, depending on the timing of exposure) to a new sleep/wake schedule (Boivin & James, 2002). Such manipulation of light exposure and avoidance has been investigated extensively in both field and laboratory settings for its use in mitigating the effects of jet lag and shift work (Czeisler et al., 1990; Deacon & Arendt, 1996; Lahti, Terttunen, Lappamaki, Lonnqvist, & Partonen, 2007; Samel & Wegmann, 1997; Thompson et al., 2013). However, most previous research has used light boxes or light banks (e.g., Herljevic, Middleton, Thapan, & Skene, 2005; Jewett et al., 1997). These devices are not practical under the operational conditions present onboard a submarine, where the three-section watch rotation requires personnel to function on different sleep/wake schedules, and where the active nature of submarine duty limits the amount of time that personnel can sit in one location for an extended period of time. If light treatment is to be administered, it must be done individually and on a schedule that flexibly meets each submariner's unique operational requirements.

One way to administer individualized light treatment is through the use of glasses. Research has shown that battery-operated glasses providing blue light emitting diode (LED) light (peak wavelength 470 nm) can effectively impact the circadian schedule when used in both field and laboratory scenarios (Appleman et al., 2013; Figueiro, Bierman, Bullough, & Rea, 2009; Figueiro et al., 2014). Conversely, when light should be avoided to cue the onset of biological nighttime, blue-blocking glasses with orange-tinted lenses can be used to limit exposure to blue light (Sasseville, Paquet, Sevigny, & Hebert, 2006). Recent research at NSMRL has explored the use of such personal light treatment devices (PLTDs; blue-light glasses and blue-blocking glasses) and has confirmed their utility and practicality in a group of Special Forces Operators (Chabal, Couturier, et al., 2018). This study provided promising evidence that PLTDs can be effectively used to improve the sleep health of select military populations. Their utility onboard submarines is unknown.

This study explores the effectiveness of PLTDs in a submarine environment. Specifically, the study utilizes actigraphy, cognitive assessments, self-report measures, and salivary sampling to obtain both subjective and objective measures of sleep and cognitive performance. There are three primary aims: 1) Determine whether PLTDs can be used to improve Sailors' sleep. 2) Determine whether PLTDs impact Sailors' mood and performance. 3) Determine the operational feasibility of utilizing PLTDs onboard an operational Navy vessel.

Methods

Design

This study was conceptualized as a 2 x 2 mixed design. The independent variables were group (PLTD, control; between-subjects) and time of assessment (Assessment 1, Assessment 2; within-subjects). Dependent variables included subjective assessments of sleep (survey measures) and mood (Profile of Mood States; POMS), objective assessment of sleep (actigraphy), cognitive performance (Automated Neuropsychological Assessment Metrics;

ANAM), projected performance scores (Fatigue Avoidance Scheduling Tool; FAST), and circadian phase changes (dim light melatonin onset; DLMO).

Participants

Forty-two male participants (mean age 27.67 years, *SD* = 5.93 years) were recruited from a Virginia class fast-attack submarine stationed in Groton, CT. Immediately after recruitment, participants were assigned to either the experimental (i.e., PLTD) group or the control group, with every effort made to ensure equality among the groups in age, rank, and watchbill assignment. During the first day of the research study, it was discovered that two individuals assigned to the control group were utilizing PLTDs (borrowed from shipmates assigned to the PLTD condition); these individuals were moved to the PLTD group, resulting in 23 Sailors in the PLTD group and 19 Sailors in the control group. Demographic information for each of the groups is provided in Table 1.

Table 1

Demographic Makeup of PLTD and Control Groups

	PLTD Group (*N* = 23)	Control Group (*N* = 19)	Statistical Comparison
Age	28.35 (6.13) yrs	26.84 (5.47) yrs	$t(40) = 0.82, p = 0.42$
Career Length	95.81 (83.13) mos	69.89 (56.00) mos	$t(38) = 1.14, p = 0.26$
Underway Time	18.60 (29.00) mos	13.82 (18.67) mos	$t(38) = 0.61, p = 0.54$
Watch Section	7 days 4 mids 9 swings 3 other	7 days 5 mids 5 swings 2 other	n/a
Rank	7 junior enlisted 10 senior enlisted 6 officer	7 junior enlisted 4 senior enlisted 8 officer	n/a

Note. PLTD = personal light treatment device. Unless otherwise notes, values represent means and those in parentheses represent standard deviations.

Materials

Personal light treatment devices. Participants in the PLTD group were issued blue-light exposure glasses and blue-blocking, orange-tinted glasses (see Figure 1). Both pairs of glasses were commercially-available and were able to be worn over existing prescription lenses to ensure compliance among all participants. Rechargeable blue-light glasses were purchased from AYO™ (Novalogy, Inc., Walnut, CA), who modified their product specifically for this study to ensure that it could function without Bluetooth connectivity. The glasses contained four LEDs that provided blue light exposure with a dominant wavelength of 470 nm ± 2 nm and an irradiance of approximately 250 $\mu W/cm^2$. Blue-blocking glasses were safety-style sunglasses purchased from UV Process Supply Inc. (Chicago, IL), that were used to attenuate blue-light between 400-510 nm.[1]

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[1] UV Process Supply reports that their orange glasses absorb "99% of UV radiation and visible light up to 510 nm."

Figure 1. Blue-light glasses (left) and blue-blocking glasses (right). Participants were instructed to wear the blue-light glasses for approximately 40 minutes after waking, and to wear the blue-blocking glasses for approximately two hours before bed.

Self-report measures. The following survey measures were collected from all participants during both Assessment 1 and Assessment 2:

- Demographic information (age, gender, rate/rank, time in service, time spent underway, status of submarine qualification) [collected during Assessment 1 only]
- Epworth Sleepiness Scale (ESS; Johns, 1991)
- Pittsburgh Sleep Quality Index (PSQI; Buysse, Reynolds, Monk, Berman, & Kupfer, 1989)
- Insomnia Severity Index (ISI; Bastien, Vallieres, & Morin, 2001)
- Profile of Mood States, Abbreviated (POMS; Grove & Prapavessis, 1992)
- Blue-Light Exposure Questionnaire: Open-ended questions inquiring about sources of blue light exposure (e.g., TV, laptops, cell phones) [collected during Assessment 2 only]
- PLTD Use Questionnaire: Open-ended questions inquiring about compliance with PLTD use, satisfaction with PLTDs, and suggestions/recommendations for future implementation of PLTDs; this survey was only completed by the PLTD group [collected during Assessment 2 only]

Cognitive measures. Participants completed a 15-minute version of the Automated Neuropsychological Assessment Metrics (ANAM; Vista Life Sciences., Parker, CO) during both Assessment 1 and Assessment 2 using Samsung Tab A tablets. Sub-tests included all of the cognitive tests from the ANAM UltraMobile test battery: simple reaction time (SRT), procedural reaction time (PRT), go/no-go (GNG), spatial processing, code substitution simultaneous (CDS), code substitution delayed (CDD), and Sternberg memory search (STN). A composite score was calculated by averaging ANAM-provided throughput *z*-scores (which account for both speed and accuracy) from all subtests (see Rasmussen et al., 2001).

Actigraphy. Participants were issued a research-grade, water-resistant wrist actigraphy watch (Ambulatory Monitoring, Inc. Motionlogger Micro Watch) on the first day of the underway and wore the watches continuously until they were collected during Assessment 2. Watches were initialized using Motionlogger WatchWare (Ambulatory Monitoring Inc., Ardsley, NY; version 1.99.17.4) with the following settings enabled: zero-crossing, light sensor, case temperature, and 60 second epochs.

ActionW (Ambulatory Monitoring Inc., Ardsley NY; version 2.7.3045) was used to mark periods of unusable data (e.g., during periods when the watch was not being worn) and to apply the Cole-Kripke algorithm with recommended rescoring rules (Cole, Kripke, Gruen, Mullaney,

& Gillin, 1992; Webster, Kripke, Messin, Mullaney, & Wyborney, 1982). In-bed periods were determined automatically by in-house software previously validated by an experienced sleep researcher (Chabal et al., 2021).

Data from the watches were used to calculate the following measures:

- Total sleep time (TST; number of minutes spent asleep while in bed, averaged over each 24 hour day)
- Time in bed (TIB; number of minutes in bed, averaged over each 24 hour day)
- Sleep efficiency (SE; the percentage of time asleep while in bed; averaged over each 24 hour day).
- Sleep onset latency (SOL; number of minutes between first going to bed and first falling asleep, averaged over all in-bed periods)
- Wakefulness after sleep onset (WASO; number of minutes awake during each sleep attempt, averaged over all in-bed periods)
- Latency to persistent sleep (LPS; number of minutes between first going to bed and at least ten consecutive minutes of sleep, averaged over all in-bed periods).

Additionally, sleep/wake periods determined from the actigraphy watches were used to compute projected performance scores using the Fatigue Avoidance Scheduling Tool, (FAST; Eddy & Hursh, 2006; Hursh, Balkin, Miller, & Eddy, 2004).

Sleep logs. Participants filled out sleep logs for each day of the study by marking an “X” in a box for each half hour interval that they were asleep and leaving the box blank if they were awake. Participants in the PLTD group also used their sleep logs to indicate the times that they wore their blue-light or orange-tinted glasses. Participants marked an “O” in a box for each half hour interval that they were wearing orange-tinted glasses and a “B” in a box for each half hour interval that they were wearing the blue-light glasses.

Salivary sampling. Salivary samples were collected from all participants during Assessment 1 and Assessment 2. Saliva was obtained via the passive drool method, using sampling kits from Salimetrics, Inc. (Carlsbad, CA). During both assessments, participants provided 8-12 samples of approximately 0.5 ml each. The samples were collected every hour while the participants were on watch and were placed in the freezer within 15 minutes of collection. At the time of each sample, participants filled out a short questionnaire about their dietary intake and behavior leading up to each saliva collection; these questions were used to explain potential discolorations in the saliva samples.

Procedure

The present study occurred in three phases: a one-day assessment of performance conducted on either the first or second day of the underway (Assessment 1), a lighting manipulation of 12-14 days (number of days varied depending on when participants were able to report for the first and second assessments), and a one-day post-manipulation performance check (Assessment 2). A research rider was present during the entire duration of the underway to administer all assessments and to maximize compliance with all participants’ use of the actigraphy watches and sleep logs.

On the first day of the underway, all participants were given an actigraphy watch and a sleep log. Participants were instructed to wear the watch as soon as they received it and to keep it on continuously throughout the duration of the study. Participants were also provided instructions for how to properly log their sleep using the sleep log.

Assessment 1. At the time of the first assessment, all participants completed the ANAM, the survey measures, and provided salivary samples for use in a dim light melatonin onset (DLMO) analysis. Participants in the PLTD group were provided with their PLTDs and were given instructions for proper use.

Lighting manipulation. During the lighting manipulation phase of this study, participants assigned to the PLTD group were instructed to wear the blue-light glasses for approximately 40 minutes after waking, prior to reporting to their watch station, and to wear the blue-blocking glasses for approximately two hours prior to sleep, after coming off watch. Participants wore the PLTDs during recreation time, meals, report writing, and other activities conducted aside from watch. If a participant's sleep schedule did not permit the PLTDs to be worn for the recommended amount of time, they were directed to wear the PLTDs for as long as possible.

Assessment 2. Collection of the second set of assessments occurred 12-14 days after Assessment 1. All participants completed the ANAM, the survey measures, and provided salivary samples for use in the DLMO analysis. Participants also returned all research equipment (actigraphy watches, PLTDs) and sleep logs. Every effort was made to collect performance data metrics at the clock-time consistent with Assessment 1.

DLMO collection. All saliva samples were collected on the submarine with oversight from the military research rider. Eight to twelve saliva samples were collected from each participant during each assessment, for a total of 16-24 samples per participant. Saliva sample collection began before the start of each watch shift and proceeded every hour while the participants were standing their dedicated watches. The research rider split each watch section (i.e., days, swings, mids) into forward and aft stations, and collected data from each station sequentially. All forward samples were placed into long term frozen storage prior to proceeding to the aft section of the boat for collection. Samples were placed into the freezer within 15 minutes of collection. If any off-watch participants were available for saliva collection, their samples were obtained after the aft samples were properly stored. At the time of each saliva sample, participants were asked questions regarding their recent food/beverage/medication consumption, PLTD use, and activities. If a sample appeared to be discolored or contaminated, the participant was asked to rinse their mouth and redo the sample. Although participants were encouraged to wear blue-blocking glasses during all saliva collections to prevent light contamination, this was not always feasible due to operational constraints (e.g., watchstanders utilizing computerized displays).

The research rider (with assistance from the corpsman on the submarine) was responsible for administering, documenting, and storing the saliva samples. Documentation included important information about the saliva sample and the participant's behavior that is needed for data analysis and interpretation (e.g., denoting the exact timing of the saliva sample, whether the participant reported having any food or drink prior to the sample, whether the participant was wearing their blue-blocking glasses, etc.). Saliva samples were contained in labeled sample tubes, organized in boxes, and stored in a freezer for the duration of the underway. Once the boat returned to Groton, samples were placed in a cooler with ice packs and were immediately transported to a -40°C freezer at NSMRL. Frozen samples were shipped on dry ice to the Salimetrics' SalivaLab (Carlsbad, CA) for melatonin analysis.

Circadian phase of the DLMO was estimated from the hourly saliva samples. The first three consecutive and consistently low "daytime" samples were used as the baseline for each circadian phase assessment. DLMO was calculated as the linearly interpolated time at which melatonin levels reached a threshold of two times the baseline mean. Only the melatonin curves that showed the required pattern of a baseline followed by a rise above the calculated DLMO threshold for more than one consecutive sample were used for analysis.

Results

PLTD Compliance and Subjective Assessment

According to sleep log entries,[2] Sailors in the PLTD group wore their blue-light glasses for an average of 44.32 min (*SD* = 17.10 min) at a time, and their blue-blocking glasses for an average of 79.81 min (*SD* = 34.34 min) at a time. Compliance ratings of PLTD use ("How would you rate your compliance with wearing the blue-light glasses and blue-blocking glasses (i.e., how often did you wear the devices when you were supposed to?)") were high overall (*M* = 5.26, *SD* = 1.01; 7-point scale with 1 = "Never," 4 = "About half the time," 7 = "Always"), with 19/23 Sailors reporting that they wore their PLTDs as instructed greater than half of the time (see Figure 2).

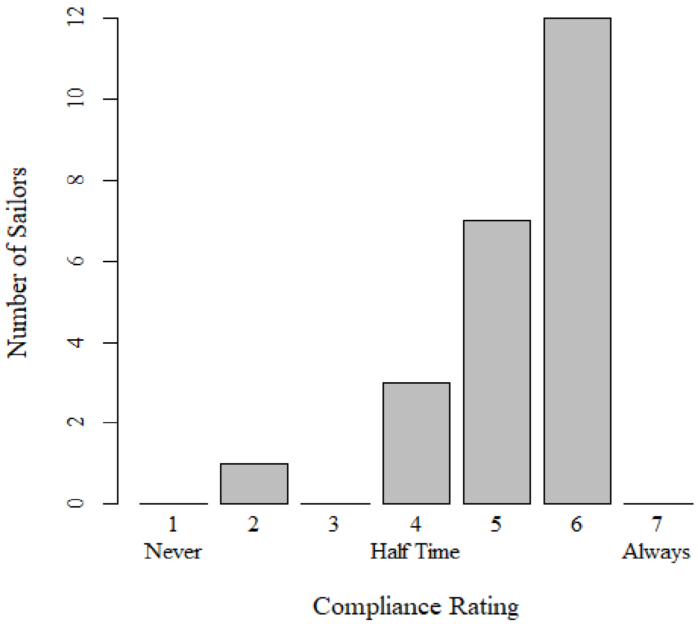

Figure 2. Compliance ratings of personal light treatment device (PLTD) use.

Overall, PLTD use did not interfere with submarine life. Only 5/23 Sailors reported that PLTD use interfered with their operational duties. For two of those Sailors, the reported interference was with emergency air breather (EAB) use; however, in the event of an emergency

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[2] Sleep logs were not available from 3 participants.

scenario in which EABs are required, submariners would not be expected to continue with PLTD use. One Sailor reported that the orange-tinted glasses fogged while wearing a mask to mitigate the spread of COVID-19; however, mask use is unlikely to be required once the COVID-19 pandemic is under control, so this interference is unlikely to cause problems if PLTDs are deployed to the fleet. One Sailor reported interference with "watchstanding," though the exact nature of this interference was not reported; as PLTDs are not intended for use while on watch, this concern should be mitigated. Finally, one Sailor reported that the "intense blue light made it difficult to focus on tasks." This complaint is valid, and should be considered in further end-user testing.

Eight Sailors reported that PLTD use interfered with personal activities including getting dressed (2/23 participants), eating meals (1/23 participants; this Sailor reported that the orange-tinted glasses made food seem less flavorful due to muted colors), viewing personal electronic devices (2/23 participants), or "seeing" (3/23 participants).

In order to gauge submariners' overall subjective assessment of the PLTDs, they were asked to provide open-ended responses about the perceived pros and cons of each of the two types of PLTDs. Responses (edited for grammar, spelling, punctuation, and clarity) are provided in Tables 2 and 3. As shown, 11/23 Sailors provided comments indicating that the blue-light glasses helped them feel alert and/or awake, and 9/23 made comments about how the blue-blocking glasses were relaxing, induced tiredness, or helped with sleep.

At the conclusion of the research study, the Commanding Officer (CO) of the participating submarine provided NSMRL with a formal letter of support for the use of PLTDs. In his letter, he reports, "I felt that wearing the PLTDs after waking allowed me to feel more awake after use; and I felt that I fell asleep faster and remained asleep more effectively. The PLTDs positively impacted my mood and performance and were unobtrusive, with no negative ramifications on operational responsibilities" (C.W. Phillips III, personal communication, December 17, 2020).[3] The CO's support, coupled with reports from the research rider that Sailors requested to continue with PLTD use after the completion of the study, provide an overall positive evaluation for the use of PLTDs as an effective fatigue countermeasure.

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[3] The submarine CO was not a participant in the present study; however, he was provided with a set of PLTDs for his situational awareness. The study team does not have any formal documentation about how the CO utilized the PLTDs or about how any of his sleep/ performance metrics were impacted.

Table 2

Positive and Negative Experiences with Blue-Light Glasses

Participant	Positives	Negatives
1	look cool	didn’t charge very well
2	seemed to help with waking up	uncomfortable visually after ~30 min
3	felt refreshed	couldn't see
4	ease of use, storage, and charging; fit moderately well	required constant nose piece adjustment
5	could hardly feel them when I was wearing them	how bright they were when I first woke up; when walking in a slightly dark p-way it was even harder to see
6	[no response provided]	case was round and difficult to stow on submarine
7	they did seem to work	intensity of light
8	wearing them was calming before watch	too bright in dark berthing areas
9	they wake me up in the morning	they make it difficult to see
10	seemed to work for a few hours	block a lot of up vision
11	helped me feel awake	blocks some vision
12	neutral	blocked upper field of view, which made walking difficult at 6'3" tall on sub
13	they made me feel awake	could not see in dim places
14	easy to carry	difficult to see in unlit passageways
15	felt like it helped me wake up	while walking in darker areas they almost blinded me
16	right after getting out of the rack, when I wore the glasses I felt more alert	it was very hard to navigate in the dark while wearing them
17	they wake me up rapidly	light is sometimes bright
18	very comfy on the face, easy to use	I couldn't see in dark places and very bright on the eyes
19	[no response provided]	look funny
20	the nosepiece was easy to alter/an easy fit	it's mildly inconvenient to keep them charged
21	seemed to make me feel alert sooner after waking up and more alert after removing	interfered with peripheral vision; difficult to see in low levels of light
22	made me feel more awake	as soon as I took them off I felt tired again
23	they actually made me feel more alert when waking up	[no response provided]

Table 3

Positive and Negative Experiences with Blue-Blocking Glasses

Participant	Positives	Negatives
1	filtered blue light, very stylish	nothing
2	same function as blue light filter on electronic screens	color-shifts everything
3	made me feel tired	n/a
4	n/a	did not fit; caused physical discomfort on the bridge of the nose and squeezed tight to sides of head; cause headaches almost daily; food was less enjoyable and muted taste
5	I felt like they actually helped me fall asleep	made it difficult to study or watch movies to relax
6	[no response provided]	didn't fit well with a hat; fogged with a mask on
7	functioned as intended	n/a
8	helps me relax before bed	nothing
9	they make lights seem brighter	they did not interfere with my activities
10	[no response provided]	uncomfortable; distortion in colors
11	relaxing	makes things look weird
12	felt like I fell asleep faster	squeezing the temples; very tight; some rough edges
13	quickly made me feel tired	made coloration different when watching movies/TV
14	sturdy, remain in place during workouts	uncomfortable after 2 hours
15	relaxing	hard to watch TV
16	no comment	very uncomfortable, otherwise they were fine
17	comfortable	didn't really feel like they worked
18	they made me feel sleepy a lot faster than without them	too big and very stiff
19	[no response provided]	look funny
20	nothing to add	it was difficult to see certain colors on dry-erase board (specifically orange)
21	seemed to make me feel drowsy sooner	very tight
22	nothing to add	it's hard to watch a movie or play a game due to blocking out blue light
23	[no response provided]	[no response provided]

Objective Assessment of PLTDs

The high compliance ratings and low levels of reported interference provide preliminary evidence that PLTDs might be a viable countermeasure for sleep and fatigue-related issues onboard submarines. In order to empirically evaluate this assumption, below we provide an analysis of objective and self-reported sleep, mood, cognitive performance, and circadian rhythms of Sailors who utilized PLTDs. In all cases, the PLTD users are compared to control group participants, who did not use any study-prescribed countermeasures for sleep.

Sleep. As in Chabal et al. (2021), all objective sleep outcome data were modeled using the *lmer* function from the *lme4* package in R; these models were then evaluated using the *Anova* function (type II) from the *car* package. For each variable of interest, the constructed model included a fixed effect of group (PLTD vs. control), with a maximally-converging random effects structure for subject and date.[4]

Actigraphy data were available from 41/42 participants; missing data are the result of a lost actigraphy watch. During data cleaning, a few days of "excessive" sleep were noted in the actigraphy data (e.g., a day with >14 hours of sleep); these data points likely reflect problems with the actigraph rather than actual sleep, as the lengthy sleep periods were not reflected in the participants' sleep logs. In order to account for these potentially-aberrant data, 16 outliers (of 603 total observations) in total sleep time were identified at ±1.5 interquartile range (IQR). These data points were removed from all actigraphy analyses.

Sleep outcomes are shown in Table 4. Although groups did not differ in the number of down periods or TIB, the PLTD group trended toward receiving a greater TST per 24 hours than did the control group. Accordingly, SE of the PLTD group was marginally higher.

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[4] Only the model for WASO converged at the full random slopes structure. Models for number of down periods, TIB, TST, SE, and SOL included random intercepts of subject and date; the model for LPS included only a random intercept of subject.

Table 4

Objective Sleep Outcomes

Variable	Overall Mean (SD); $N = 41$	PLTD Mean (SD), $N = 22$	Control Mean (SD), $N = 19$	Statistical Comparison
# Down Periods	1.50 (0.82)	1.40 (0.69)	1.62 (0.94)	$X^2(1) = 2.28$, $p = 0.13$
TIB (min)	470.83 (98.61)	480.07 (99.01)	459.37 (97.13)	$X^2(1) = 1.67$, $p = 0.20$
TST (min)	419.67 (88.91)	431.31 (87.21)	405.25 (89.10)	$X^2(1) = 3.57$, $p = 0.06$
SE (%)	88.05 (7.34)	89.15 (6.72)	86.69 (7.94)	$X^2(1) = 3.18$, $p = 0.07$
SOL (min)	8.51 (4.70)	8.73 (5.15)	8.28 (4.16)	$X^2(1) = 0.43$, $p = 0.51$
LPS (min)	16.54 (21.04)	17.34 (23.48)	15.70 (18.08)	$X^2(1) = 0.22$, $p = 0.64$
WASO (min)	29.50 (28.08)	29.31 (27.77)	29.69 (28.45)	$X^2(1) = 0.18$, $p = 0.68$

Note. PLTD = personal light treatment device; TIB = time in bed; TST = total sleep time; SE = sleep efficiency; SOL = sleep onset latency; LPS = latency to persistent sleep; WASO = wake after sleep onset. SOL, LPS, and WASO values are computed based on each down period. All other variables are computed over each 24-hour period. Standard effect size estimates cannot be calculated for individual model terms due to the way that variance is partitioned in multilevel models (Rights & Sterba, 2019).

Clinical subjective sleep outcomes. Each of the assessed clinical sleep measures results in a composite score; this composite score is used as a numerical cut-off to determine candidates for clinical intervention. For all analyses of sleep survey data, we considered the binary outcome of "clinically significant" / "not clinically significant" as the dependent variable of interest. This variable was modeled using the *glmer* function from the *lme4* package in R. All models contained interactive terms of group (PLTD vs. control) and assessment time (pre vs. post) as fixed effects, with a maximally-converging random effects structure of subject. Models were evaluated using the *Anova* function (type III) from the *car* package. For all clinical sleep models, data were available for 40/42 participants.[5]

ESS. Overall, submariners in the current study reported mean ESS scores of 7.99 (*SD* = 3.90), which is consistent with civilian adult populations (Sander et al., 2016) and is lower (better) than the sleepiness levels reported in a past study of underway submariners (Chabal et al., 2021). A significant effect of assessment time revealed that more submariners presented with clinically-relevant sleepiness (ESS >10) at the time of the second assessment ($N = 12$) than at the time of the first assessment ($N = 7$; $X^2(1) = 7.39$, $p = 0.007$); however, a significant interaction also emerged between assessment time and group ($X^2(1) = 5.92$, $p = 0.01$). To follow up on this

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[5] Data from one PLTD-group participant are missing from assessment 1; data from one control-group participant are missing from assessment 2. Though survey data are available from 40 participants, a number of participants skipped questions on some of the questionnaires, which prevented the calculation of a composite score. 28 full pairs of data are available for ISI and 38 full pairs of data are available for PSQI.

significant interaction, separate models were constructed for each of the two groups (containing a fixed effect of assessment time and a random intercept of subject) and were evaluated using type II Anovas. Results revealed a non-significant trend of assessment time only for the control group ($X^2(1) = 3.32$, $p = 0.07$; PLTD group: $X^2(1) = 0.51$, $p = 0.48$). This suggests that, for the experimental group, PLTDs may have reduced the sleepiness effects brought about by submarine life.

ISI. ISI scores ($M = 8.55$, $SD = 4.46$) were within the range of those observed by Chabal et al. (2021). Overall rates of probable clinical insomnia (ISI > 14; Bastien et al., 2001) were low, with only 5 submariner participants presenting with insomnia at the first assessment and 2 presenting with insomnia at the second assessment. The specified model failed to converge with an included interaction effect, so ISI effects were re-modeled using fixed effects of group and assessment time and a random intercept of subject; the model was evaluated using a type II Anova. No significant effects were detected (group: $X^2(1) = 1.51$, $p = 0.22$; assessment time: $X^2(1) = 0.89$, $p = 0.35$), indicating that the use of PLTDs did not impact the prevalence of insomnia as determined by the ISI.

PSQI. Submariners averaged PSQI scores of 6.61 ($SD = 3.40$). Clinically-relevant sleep quality (PSQI > 5; Buysse et al., 1989) was not significantly different across time ($X^2(1) = 0.52$, $p = 0.47$) or group ($X^2(1) = 0.37$, $p = 0.54$), and no interaction emerged ($X^2(1) = 0.01$, $p = 0.92$). PLTDs did not impact clinically-relevant sleep quality as determined by the PSQI.

Mood and cognitive performance. Mood (POMS) and cognitive performance (ANAM) outcome data were modeled using the *lmer* function from the *lme4* package in R. For each variable of interest, the constructed model included interactive terms of group (PLTD vs. control) and assessment time (pre vs. post) as fixed effects, with a random intercept of subject (models failed to converge with random slopes). Models were evaluated using the *Anova* function (type III) from the *car* package.

POMS. POMS data were available from 40/42 participants. As found in Chabal et al. (2021), submariners experienced a greater total mood disturbance (TMD) at the second assessment point ($M = 102.13$, $SD = 20.82$) when compared to the first assessment point ($M = 96.85$, $SD = 20.09$; $X^2(1) = 4.79$, $p = 0.03$), but no effects of group ($X^2(1) = 2.42$, $p = 0.12$) or interactions between assessment time and group ($X^2(1) = 1.20$, $p = 0.27$) were observed. This suggests that PLTD use does not meaningfully impact submariners' mood.

ANAM. ANAM data were available from 39/42 participants. ANAM composite performance was not significantly affected by group ($X^2(1) = 0.51$, $p = 0.48$) or time ($X^2(1) = 1.27$, $p = 0.26$), and no significant interaction emerged ($X^2(1) = 2.85$, $p = 0.09$). This implies that cognitive performance was not meaningfully impacted by PLTD use.

Projected performance. Although the present study did not have the means to assess real-time performance of submariners, it can be estimated using outputs from the Fatigue Avoidance Scheduling Tool (FAST), which projects the predicted effectiveness and fatigue of an individual over time, based upon recent sleep history (e.g., hours of sleep, hours of wakefulness, current sleep debt) and circadian cycles (Eddy & Hursh, 2006; Hursh et al., 2004). As in Chabal et al. (2021), projected performance scores were derived for each one-minute interval of the study period by inputting all raw actigraphy data[6] into the FAST program (See Chabal et al., 2021 for detailed information about the assumptions of the FAST model). FAST scores were analyzed only during each participant's wake periods, as projected performance is not meaningful during times of sleep.

FAST scores were available from 40/42 participants. One participant in the PLTD group had missing data due to a lost actigraphy watch, and one in the control group had consecutive days of missing data (due to removing his watch) that could not be accommodated by the FAST program. The remaining 485,970 data points were modeled using the *lmer* function with interactive effects of group (PLTD vs. control) and time, with maximally-converging random intercept of subject; this model was evaluated using the *Anova* function (type III) from the *car* package. Time was included in the statistical model because it is expected that projected performance scores will change over time as a submarine underway progresses (Chabal et al., 2021). Considering only group level differences (without accounting for the statistical variability created by fluctuations over time) may mask effects by inflating error rates when data are binned or collapsed.

A significant interaction between group and time ($X^2(1) = 398.60$, $p < 0.001$), as visualized in Figure 3, reflects that FAST scores of the PLTD group were more stable over time and were not as vulnerable to steep projected performance dips (main effect of time: $X^2(1) = 8072.86$, $p < 0.001$). Participants in the PLTD group also had higher overall projected performance scores ($M = 87.35\%$, $SD = 9.54\%$) than participants in the control group ($M = 83.21\%$, $SD = 10.83\%$; $X^2(1) = 5.18$, $p = 0.02$).[7] Critically, the association between projected performance and PLTD use holds while submariners are on watch. While on watch, participants in the PLTD group reached performance scores of nearly 90% (PLTD: $M = 89.04\%$, $SD = 8.24\%$; Control: $M = 85.19\%$, $SD = 8.83\%$; $X^2(1) = 4.02$, $p = 0.04$).

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[6] Outliers that were removed from actigraphy analyses were not included in FAST modeling.

[7] Importantly, in spite of a main effect of group, the PLTD and control groups did not differ in FAST scores on day one ($X^2(1) = 1.37$, $p = 0.24$), which supports the assumption that differences in FAST scores are attributed to the PLTD intervention.

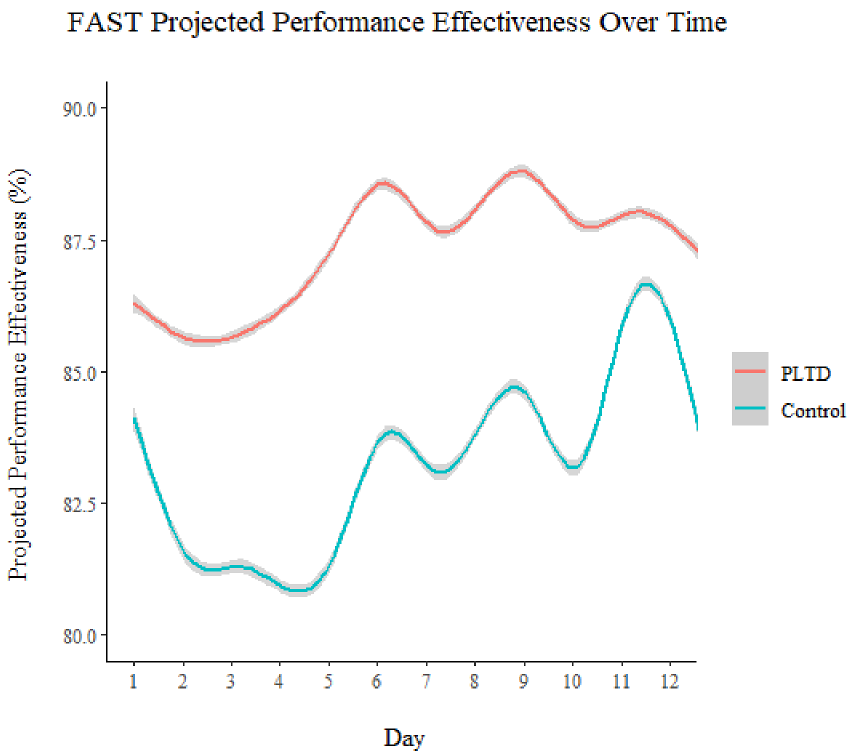

Figure 3. *Mean projected performance effectiveness (both on and off watch), derived from the Fatigue Avoidance Scheduling Tool (FAST), plotted by underway time. Colored lines represent the smoothed conditional means for the personal light treatment device (PLTD) group (orange) and the Control group (blue), as visualized using the geom_smooth modifier of R's ggplot function; shaded regions represent the 95% confidence interval of the predictive model. The observed fluctuations in FAST scores over time underscore the need to consider time as a factor when evaluating differences between groups, as collapsing across days may mask effects by increasing statistical variability.*

DLMO. Saliva samples were successfully collected during both assessments from all 42 participants. 6-11 samples were collected from each participant during the first assessment (*M* = 8.0, *SD* = 0.8) and 5-11 samples were collected from each participant during the second assessment (*M* = 9.2, *SD* = 1.3). However, in spite of successful saliva collection, only 10/84 salivary collections resulted in usable DLMO values; moreover, only one submariner had a usable DLMO from both assessment periods. DLMO values could not be computed for the following reasons: most melatonin samples did not reach the threshold of detection (12 calculations), no detectable baseline values (9 calculations), samples missing collection times (3 calculations), patterns that were not physiologically possible (29 calculations, including 1 with a false rise, 1 with a flat curve, and 2 with no clear pattern), and patterns that likely represented dim light melatonin offset rather than DLMO (21 calculations). DLMO times, therefore, do not represent a meaningful dependent variable for this study. As observed in Chabal et al. (2021) and Young et al. (2015), without employing more extensive dim lighting and behavioral controls, the submarine environment is not conducive to the collection of accurate salivary melatonin values.

Discussion

Data collected onboard an active U.S. Navy submarine provide initial support for the use of PLTDs as a countermeasure for fatigue and circadian misalignment. Not only were PLTDs shown to be feasible (causing no interference to non-watch submarine operations) and usable (Sailors reported minimal complaints with the PLTD design), but they also provided submarine crews with objectively better sleep and fatigue outcomes. The most striking finding is the increase in FAST projected performance scores demonstrated by Sailors who utilized the PLTDs. Compared to their peers (who completed the same submarine mission on the same schedule, but without the use of PLTDs[8]), submariners who wore PLTDs displayed projected performance scores that were approximately five percentage points higher; on watch, the PLTD group reached projected performance of nearly 90%. Though these projected performance scores did not correspond to detectable differences in ANAM cognitive performance, this is likely because ANAM only captured performance at two single instances rather than throughout the course of the underway. Future work should evaluate cognitive performance during every scheduled watch period in order to determine whether PLTD use meaningfully impacts cognition.

Although direct changes in melatonin levels could not be confirmed in the present study, it is likely that the PLTDs worked by suppressing morning melatonin levels (via blue-light exposure) and allowing melatonin levels to rise before bed (by blocking the blue-light that would interfere with melatonin production). Although this light cycle (greater exposure to light in the mornings than in the evenings) happens naturally for most people in most contexts, it is notably missing onboard a submarine, where a lack of windows prevents sunlight exposure and a rotating schedule of shift work necessitates the round-the-clock use of artificial light sources.

The potential circadian misalignment brought about by a submarine’s lighting environment is compounded by Sailors’ nighttime use of personal electronic devices (see Chabal et al., 2021). During the present experiment, participants were asked to track the daily amount of time that they spent watching TV, using a computer (for personal use, not including for operational duties), and using a handheld device (e.g., tablet, e-reader, cell phone). Nearly every participant (39/41; data were missing from one participant) reported PED usage in their personal (off-watch) time. On average, those Sailors used blue-light emitting PEDs for 3.63 hours per day (*SD* = 2.91 hours; *range* = 0.5-13 hours). At least some of that PED usage occurred immediately before sleep; 18/39 reported regularly watching TV before sleep, 10/39 reported regularly using a computer before sleep, and 30/39 reported regularly using a handheld device before sleep. This underscores the importance of using blue-blocking PLTDs to prevent unwanted and mistimed blue light exposure that is likely to disrupt sleep and circadian rhythms.

Considerations for Integrating PLTDs to the Fleet

Based on the preliminary data presented here, the Submarine Force should consider taking the next steps to integrate PLTDs to the fleet. The next phase of research should include investigations into optimal device usage and device sourcing.

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[8] Although every effort was made to match participants on age, rank, and watchbill assignment across the PLTD and control groups, it was not possible to achieve a one-to-one match in all cases. While the submarine mission was the same for all participants, it is possible that their daily lighting environments and opportunities for sleep were not identical.

Device usage. In the present experiment, Sailors were instructed to wear the blue-light glasses for approximately 40 minutes after waking and to wear the blue-blocking glasses for approximately two hours before bed. Though these exposure periods were shorter than what has been previously reported in the literature (e.g., Appleman et al., 2013; Chabal, Couturier, et al., 2018), they were sufficient to effect meaningful change in participants' sleep, fatigue, and projected performance. It is possible that even shorter periods of use may be effective. Moreover, it is possible that some benefit may be derived by utilizing only one type of PLTD (i.e., wearing only blue-light glasses or only blue-blocking glasses). Future research should be conducted to determine the optimal amount of time that each type of PLTD should be worn in order to maximize sleep and circadian benefits while minimizing potential operational and personal impacts.

Device sourcing. In addition to exploring additional options for *how* PLTD devices are used, it is also prudent to consider *which* PLTD devices are used. When considering PLTDs, attention must be directed to the devices' comfort, durability, security, and cost.

Though most participants in the present experiment did not voice any major complaints about their comfort while wearing the blue-light PLTDs, a number of respondents felt that the blue-blocking glasses were uncomfortable and cumbersome (see Table 3). If PLTDs are deployed in the fleet, it will be important to ensure that the devices are comfortable enough that Sailors choose to wear them. As blue-blocking glasses are available from a number of manufacturers and in a number of styles (the safety-goggles style was chosen so that they could be worn over participants' existing prescription eye glasses, if required), it would likely be possible to have Sailors choose the style that they personally find to be the most comfortable. The only requirements for blue-blocking glasses are that they filter light in the range of approximately 470 nm and that they are durable enough to withstand submarine life.

The requirements for blue-light glasses are slightly more stringent, as they are battery-operated devices that have the ability to introduce unwanted security concerns within a submarine environment. Many of the commercial-off-the-shelf (COTS) blue-light devices presently on the market are controlled by a Bluetooth-connected mobile application (including the AYO glasses marketed on the company's website at the time of this study). Bluetooth-enabled devices do not comply with the Submarine Force's PED policy (COMSUBLANT/COMSUBPACINST 2075.1D), and therefore cannot be taken onboard an active U.S. Navy submarine. For the present experiment, we worked with AYO, Inc. to have blue-light glasses produced that did not require any communication with electronic devices. If a different company is used to supply PLTDs to the fleet, similar security concerns should be taken into consideration.

Blue-light glasses also must have sufficient battery life to operate without the need for a constant wired electricity source. AYO glasses were easily charged through a re-chargeable case (which also served to protect the glasses when not in use) that provided up to 10 hours of use time between charges. Given that electrical outlets may not always be readily available in submarine berthing areas, the ability to use the glasses for multiple days without requiring a wired charge is crucial.

The overall cost for the PLTDs employed in the present study was low, with a landed cost of less than $150 per person ($120 per pair of AYO blue-light glasses; $11.20 per pair of UV Process Supply blue-blocking glasses). Using these values, the expected cost to outfit a crew for a deployment is under $20,000. If purchased in bulk, it is likely that the per-unit cost could be even lower.

Conclusions

As demonstrated in the present study, PLTDs provide a low-cost, low-burden countermeasure for sleep-based issues onboard submarines. PLTDs were found to be effective, unobtrusive, and well-liked by the Sailors who used them. The use of PLTDs was supported by the submarine's leadership, and PLTDs would likely be utilized with high levels of compliance if integrated into the fleet. Most importantly, PLTD use resulted in marginal improvements to sleep quantity, sleep quality, and clinical measures of sleepiness, and to statistically-measurable improvements to projected performance scores. Given these preliminary indications of success, the Submarine Force should conduct or support follow-on research to determine the most effective devices for purchase, and should encourage PLTD use when practical.

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