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THE EFFECT OF LIGHT ON CIRCADIAN ENTRAINMENT: RISK MITIGATION TECHNIQUES FOR SHIFTING FROM DAY TO NIGHT FLIGHT OPERATIONS

by

Nita Lewis Shattuck, Panagiotis Matsangas, James Reily, Meghan McDonough, and Kathryn B. Giles

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14. ABSTRACT

A midair collision in the early morning hours of December 6, 2018 resulted in the tragic deaths of six US Marine Corps aircrew members and the loss of two aircraft, a KC-130 tanker and an F/A-18. The mishap occurred around 2 AM during a routine nighttime air refueling training mission off the coast of Japan. In the investigation that followed, fatigue was identified as a major contributor; the transition from day to night flights was called out as a problem area that continues to plague aviation commands. Subsequent investigations confirmed findings and requested help from the Naval Postgraduate School (NPS) Crew Endurance Team to study the problem and make recommendations for safer transition from day to night flight operations. The study goal was to provide recommendations to the fleet regarding the limitations and best practices for shifting aviators from day to night operations. After reviewing the scientific literature, NPS designed a study to determine the efficacy of high energy visible (HEV) light exposure in shifting the circadian rhythms of study participants. The project was a hybrid study of military aviators who, as graduate students at NPS, continued normal daily schedules but came into the laboratory for 6 to 8 hours on three consecutive evenings. The study attempted to replicate the patterns of aviators who could potentially be required to abruptly shift to night flight operations.

Results showed that a single 4-hour exposure of blue-enriched white light (~1000 lux) successfully delayed the circadian phase of all participants an average of 1 hour 19 minutes (range 53 minutes to 1 hour 56 minutes). Melatonin onset was delayed in all participants. This circadian shift is estimated to be a 10-fold increase over what would be achieved without the HEV light. Light was shown to have an alerting effect with participants reporting less sleepiness and reduced subjective workload with improved flight performance. Conclusions from the literature review and our study indicate that circadian entrainment in military operational settings should use light management as the dominant method for shifting the circadian clock. In general, it is expected that higher rates of adaptation (i.e., more rapid entrainment) will occur by aligning and applying multiple synchronization methods simultaneously, i.e., light management combined with strategically timed exercise, meals, melatonin, and caffeine. Based on these conclusions, we developed general recommendations and two circadian synchronization plans for crewmembers switching from day to night operations. One plan shows a schedule that prepares for night operations shifting over multiple days. The other shows a schedule for crewmembers required to shift from abruptly without notice. These plans warrant further development in an operational environment to ensure they can be implemented safely and effectively.

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A midair collision in the early morning hours of December 6, 2018 resulted in the tragic deaths of six US Marine Corps aircrew members and the loss of two aircraft, a KC-130 tanker and an F/A-18. The mishap occurred around 2 AM during a routine nighttime air refueling training mission off the coast of Japan. In the investigation that followed, fatigue was identified as a major contributor; the transition from day to night flights was called out as a problem area that continues to plague aviation commands. Subsequent investigations confirmed findings and requested help from the Naval Postgraduate School (NPS) Crew Endurance Team to study the problem and make recommendations for safer transition from day to night flight operations.

The study goal was to provide recommendations to the fleet regarding the limitations and best practices for shifting aviators from day to night operations. After reviewing the scientific literature, NPS designed a study to determine the efficacy of high energy visible (HEV) light exposure in shifting the circadian rhythms of study participants. The project was a hybrid study of military aviators who, as graduate students at NPS, continued their normal daily schedules but came into the laboratory for 6 to 8 hours on three consecutive evenings. The study attempted to replicate the patterns of aviators who could potentially be required to abruptly shift to night flight operations.

Results showed that a single 4-hour exposure of blue-enriched white light (~1000 lux) successfully delayed the circadian phase of all participants an average of 1 hour 19 minutes (range 53 minutes to 1 hour 56 minutes). Melatonin onset was delayed in all participants. This circadian shift is estimated to be a 10-fold increase over what would be achieved without the HEV light. Light was shown to have an alerting effect with participants reporting less sleepiness and reduced subjective workload with improved flight performance.

Conclusions from the literature review and our study indicate that circadian entrainment in military operational settings should use light management as the dominant method for shifting the circadian clock. In general, it is expected that higher rates of adaptation (i.e., more rapid entrainment) will occur by aligning and applying multiple synchronization methods simultaneously, i.e., light management combined with strategically timed exercise, meals, melatonin, and caffeine. Based on these conclusions, we developed general recommendations and two circadian synchronization plans for crewmembers switching from day to night operations. One plan shows a schedule that prepares for night operations shifting over multiple days. The other shows a schedule for crewmembers required to shift from abruptly without notice. These plans warrant further development in an operational environment to ensure they can be implemented safely and effectively.

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I. INTRODUCTION

A. BACKGROUND

A midair collision in the early morning hours of December 6, 2018 resulted in the tragic deaths of six Marine aircrew members and the loss of two US Marine Corps aircraft, a KC-130 tanker and an F/A-18. The mishap occurred around 2 AM during a routine nighttime air refueling training mission off the coast of Japan. In the investigation that followed the mishap, fatigue was identified as a major contributor and the transition from day to night flights was called out as a problem area that continues to plague aviation commands. Subsequent investigations confirmed this finding and requested help from the Naval Postgraduate School's Crew Endurance Team to study the problem and make recommendations for safer transitions from day to night flight operations.

The US military operates 24 hours a day, 7 days per week. It is no surprise that fatigue and sleep issues continue to appear in mishap reports. A recent Naval Safety Center study found twenty percent of naval aviation accidents over a 5-year period were caused in part by fatigue and fatigue-related issues, with an estimated cost of $842M (Durning & Kelly, 2020). Night flight operations are acknowledged to be more demanding due to multiple factors. These factors include reduced visibility from lack of natural light, a heightened reliance on flight instruments, and the possible requirement for night vision goggles. When crewmembers are not entrained to working nights, night flights may coincide with aircrew circadian low points, magnifying their already elevated risk levels. Crewmembers who are not well-rested prior to night flights face even more risk (Bendak & Rashid, 2020).

The transition from day flights to night flights is particularly challenging due to the need to realign one's circadian rhythm. Aviation leadership is consistently confronted with decisions about how to manage the risks associated with night operations, especially with how to help aircrew adjust to night shift work with its accompanying change in circadian rhythms. We call this adjustment to a different work shift "circadian entrainment". This technical report contains the results of a recent study conducted at the Naval Postgraduate School focusing on a novel approach to speeding up circadian entrainment using high-energy visible (HEV) light. In this document, the term "day flights" is used for flights that occur after sunrise until the end of evening twilight (EENT); the term "night flights" refers to flights from EENT to sunrise.

B. STUDY SCOPE

In 2019, the Assistant Commandant of the Marine Corps requested a Department of the Navy (DON) aviation sleep management study and adjustment of aviation operations policies. The information found in the current policies regarding the role of circadian rhythms in aviation (Commander Naval Air Forces (CNAF) M-3710.9 and Navy Medicine (NAVMED) P-6410) has remained essentially the same for multiple years, without specific guidance for the safe transition from day to night flights (BUMED, 2000; Commander Naval Air Forces, 2017). Identifying this gap in guidance, the Headquarters Marine Corps (HQMC) commissioned the Naval Postgraduate School (NPS) Crew Endurance Team to conduct an aviation sleep management study, leveraging lessons learned from the NPS Crew Endurance Team's research efforts from the past two decades.

NPS designed an experimental protocol and executed a study to explore means of speeding up the rate of circadian entrainment when shifting from days to night operations. The ultimate goal of the project was to provide recommendations to the fleet regarding best practices for shifting aviators from day to night operations, while mitigating pilot fatigue and facilitating circadian re-alignment.

C. STUDY OBJECTIVES

This study had four objectives:

- Review and summarize the scientific literature on:
    - human circadian physiology and operational performance; and
    - the relationships among light exposure, alertness, performance, and human circadian entrainment.
- Provide updated recommendations on:
    - The limitations, amount of time needed, and best practices for immediate shifting of aircrew from day to night operations with multiple take-off/landing times.

    - The limitations, amount of time needed, and best practices for gradual shifting of aircrew from day to sustained night operations.
- Explore the ability to shift an individual's circadian rhythm using a single, strategically placed high energy visible (HEV) light treatment measured using Dim Light Melatonin Onset (DLMO), the gold standard for assessing circadian phase.
- Determine whether nighttime flight performance improves following this strategic administration of HEV light.

The results of this empirical study provide additional guidance for operational commanders seeking to reduce risk when transitioning aircrew from day to night sorties.

D. REPORT STRUCTURE

Chapter II of this report reviews the literature related to sleep and circadian rhythms. Chapter III describes the methods, tools, and procedures used to conduct the laboratory experiment. Chapter IV describes the results of the experiment and Chapter V provides our conclusions and discusses their importance as they pertain to the study objectives. Chapter VI offers recommendations to potentially reduce the time needed to adjust to a shift from day to night flights in field conditions. Chapter VII provides potential routes for future research.

This report has two appendices. Appendix A shows the approach plates we used in the three flight scenarios. Appendix B shows the intensity of ambient light exposure for each participant throughout the study.

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II. LITERATURE REVIEW

A. REGULATION OF SLEEP AND CIRCADIAN RHYTHMS

Sleep is necessary for human health and functioning. Insufficient sleep and circadian misalignment are associated with a host of negative outcomes including poor performance (Bolin, 2019; Ganesan et al., 2019; Postnova, Lockley, & Robinson, 2018), inattention, fatigue and sleepiness (Ganesan et al., 2019; Postnova et al., 2018), depressed and irritable mood (Bauducco, Richardson, & Gradisar, 2019; Bolin, 2019), impulsive behavior (Grant & Chamberlain, 2018), poor decision-making (Chen et al., 2017; Killgore, 2010), compromised learning and memory (Killgore, 2010; Walker, 2008, 2009, 2010), and poor overall physical (Chellappa, Vujovic, Williams, & Scheer, 2019; Hansen, 2017; Kervezee, Shechter, & Boivin, 2018; Khan, Malik, Gupta, & Rutkofsky, 2020; Morris, Yang, & Scheer, 2012; Strohmaier, Devore, Zhang, & Schernhammer, 2018) and mental health (Walker, Walton, DeVries, & Nelson, 2020). A deep understanding of sleep and circadian rhythms and their interaction is necessary to intervene effectively and improve human performance.

As seen in Figure 1, sleep and wake are regulated by two physiological processes: a sleep-dependent homeostatic process (process S) and a sleep-independent circadian process (process C). Simply stated, process S, the pressure for sleep shown in blue, builds up during waking and declines during sleep. Process C, the circadian system shown in black, is responsible for the ~24-hour cycle in human physiology that regulates the timing of events such as sleep, alertness, mood, and hormone release at specific times of day. The difference between the two processes, actual sleep pressure, is shown in green and fluctuates over the course of the day and night. The result of the interaction between these processes is that sleep is favored after wakefulness accumulates across the day (Process S) and at specific times in the 24-hour day (Process C), shown in Figure 1. Figure 1 also illustrates the effect of sleep deprivation, shown in red in the diagram.

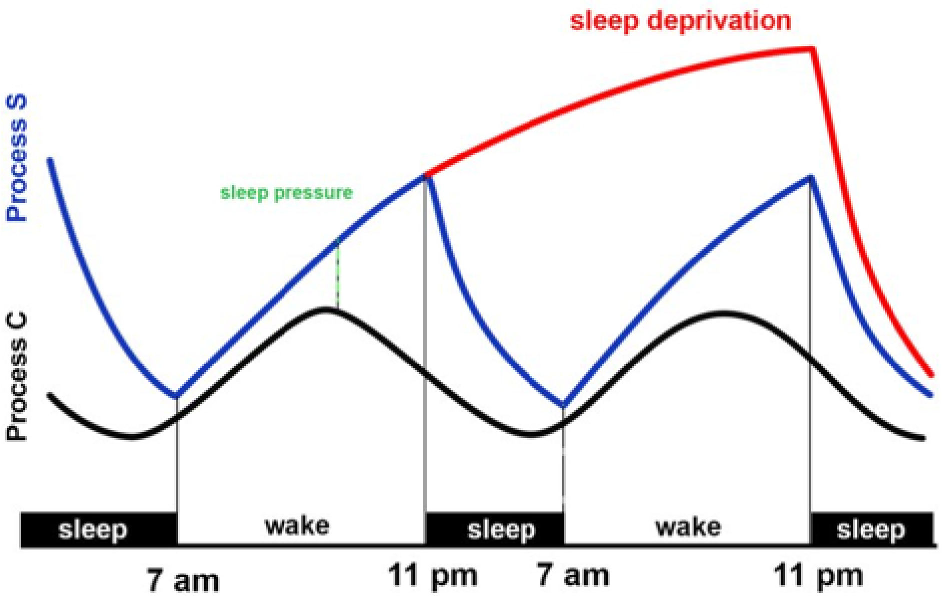

Figure 1. Process C and Process S. Adapted from Borbély (1982)

Incontrovertible scientific evidence shows that risk increases significantly at circadian low points (an individual's "biological night"). Risk is increased further at these low points when individuals do not get adequate sleep, or when they transit time zones (a.k.a. jetlag). Of course, sometimes all these things happen simultaneously, setting up perfect conditions for things to go wrong. "Circadian misalignment" is the term used to describe what occurs when an individual's circadian clock is not aligned with their work and rest schedule. As seen in Figure 2, the risk of motor vehicle accidents peaks at two periods over a 24-hour cycle: during the night and early morning hours and in the early afternoon. This figure also shows the timing of some major accidents, including the midair collision of the two USMC aircraft on 6 Dec 2018.

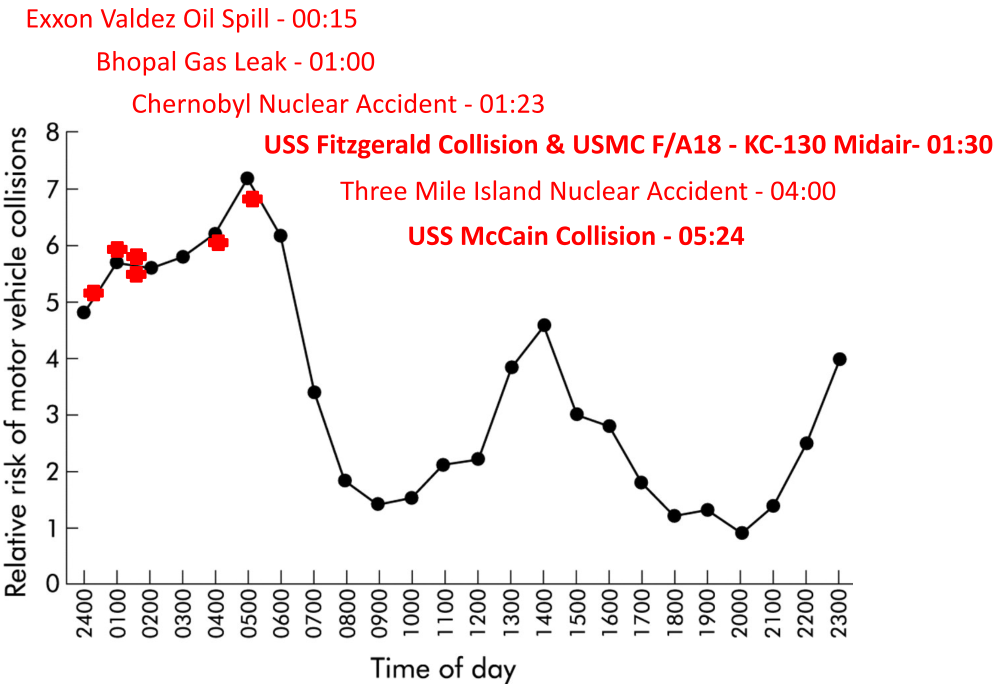

Figure 2. Time of Day and Major Mishaps. Adapted from George (2004) and Garbarino, Nobili, and Beelke (2001).

B. CIRCADIAN ENTRAINMENT AND ZEITGEBERS

Earth's daily axial rotation in orbit around the sun creates the light/dark and temperature cycles on earth. Thus, most organisms on earth demonstrate an internal timing system with a period of ~24 hours, consistent with earth's solar light/dark cycle; circadian rhythms are most responsive to environmental cues, including light. These environmental signals or stimuli are called "zeitgebers", a German word that means "time-giver". Zeitgebers can entrain and/or reset one's internal circadian rhythms to align with their external environment (Cajochen, Chellappa, & Schmidt, 2014; Koukkari & Sothern, 2006).

The gold standard for measurement of the circadian system in humans is by sampling the hormone melatonin in saliva, blood, or urine where it shows up as a metabolite. Melatonin secretion occurs during the biological night; by monitoring its onset in dimly lit conditions, the timing of dim light melatonin onset (DLMO) can be used as a circadian phase marker. In other words, DLMO tells us what time it is in the brain and specifically, the point at which "biological night" begins in an individual.

1. Light as a zeitgeber

Light is the most potent stimulus for entraining the circadian system. Appropriately timed delivery of the correct type of light is a powerful tool for aligning endogenous circadian rhythms to each other and to the external environment. However, light can be an equally powerful disrupter of human circadian rhythms if applied inappropriately. Three factors are critical to administer light that affects the circadian system in a predictable way: 1) the timing of light administration; 2) the intensity of the light; and 3) the spectral characteristics of the light. High-energy visible (HEV) light contains the spectral characteristics that are the most effective at impacting the circadian system (Cajochen, 2007; Cajochen et al., 2014; Rimmer et al., 2000).

When light enters the eyes, it activates specialized cells within the human eye that contain a specific photopigment that is sensitive to light. These specialized cells are called intrinsically photosensitive retinal ganglion cells (ipRGCs) and the photopigment is called melanopsin (see Figure 3). Photic information is transmitted from the ipRGCs to the eye to the suprachiasmatic nucleus (SCN) in the brain via the retinohypothalamic tract (Gooley et al., 2001). The master mammalian oscillator or circadian clock is in the suprachiasmatic nuclei (SCN) of the hypothalamus and has a strong influence on the timing of sleep and wake (as well as other biological and behavioral systems). The SCN interprets this light information and directs the pineal gland to secrete melatonin and communicate with the peripheral circadian clocks in various other tissues in the human body (e.g., liver, kidney, skin, etc.). When internal rhythms are aligned with the external environment, human performance is optimized. When internal rhythms are misaligned with the external environment (e.g., in the case of jet lag or shiftwork), performance and sleep are degraded.

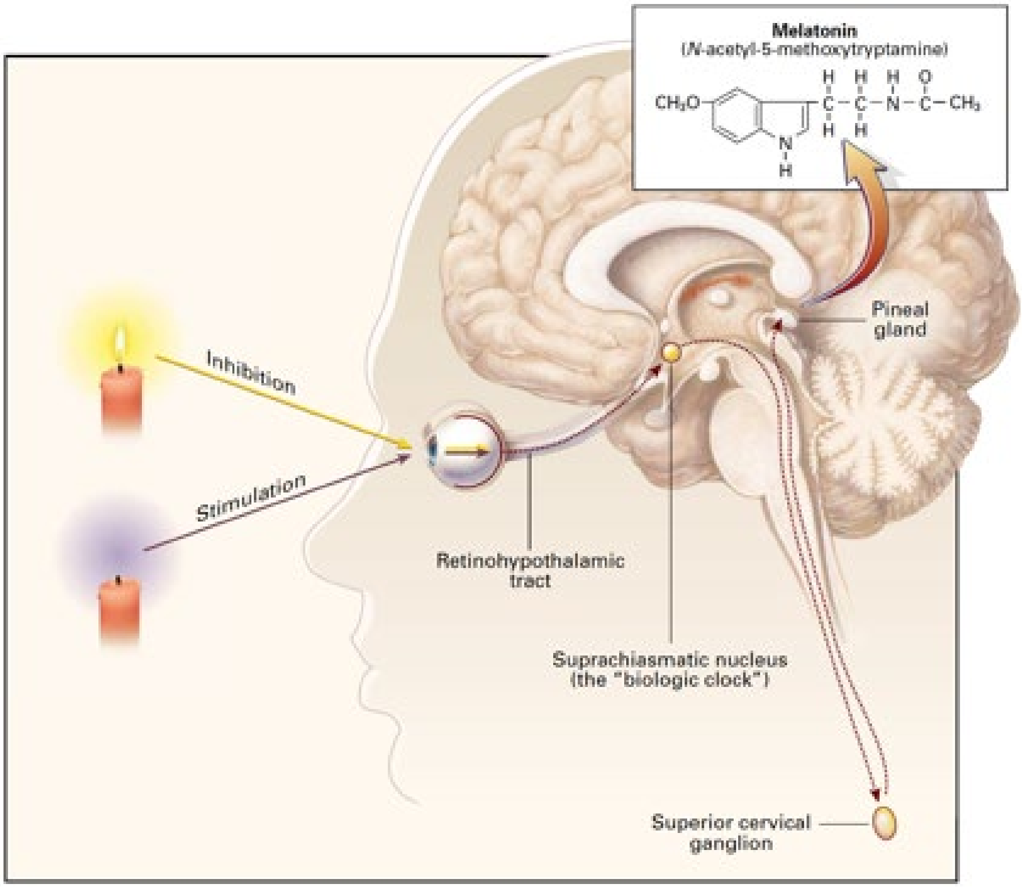

Figure 3. The effect of light on the activity of the pineal gland and thereby the secretion of melatonin. Diagram from Brzezinski (1997).

As shown in Figure 4, melatonin typically displays a robust ~24-hour rhythm (Arendt, 2005; Hofstra & de Weerd, 2008) and is typically aligned with the solar night in humans; however, ambient light suppresses the production of melatonin (Blume, Garbazza, & Spitschan, 2019; Burgess & Fogg, 2008). Light is the most effective zeitgeber for the circadian system. Much is known about how to use light to affect the circadian system and achieve the desired outcomes compared to other zeitgebers in humans.

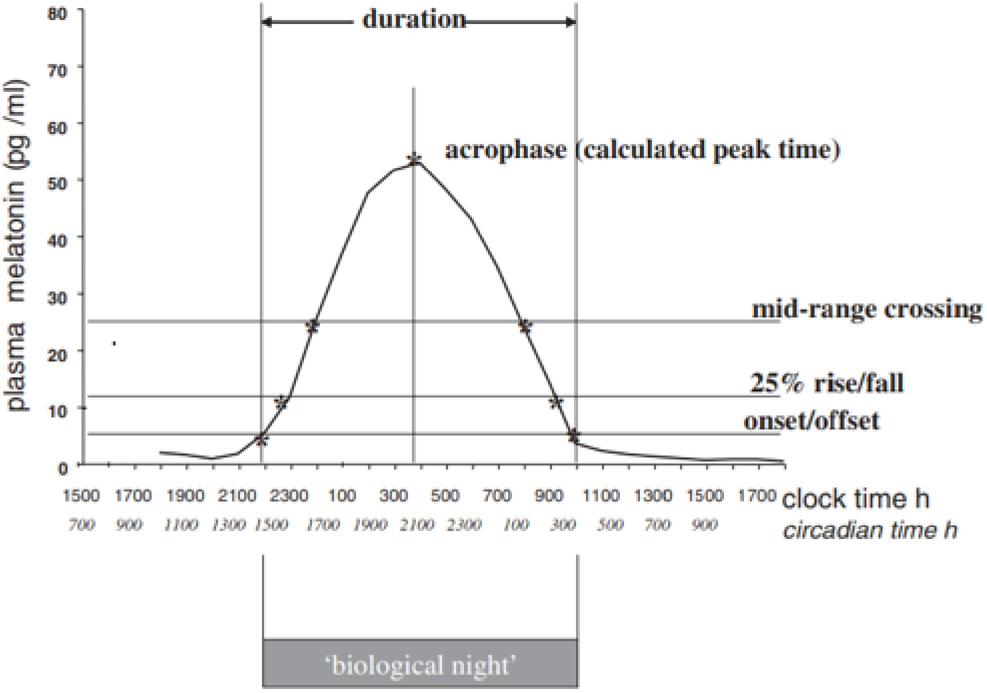

Figure 4. Melatonin in Humans (Arendt, 2005).

2. Physical Exercise as a Zeitgeber

While light is the most influential zeitgeber for the circadian system, other factors may have an influence as well. Although less is known about physical exercise and food/eating as zeitgebers, the timing of exercise and eating may offer additional benefits or challenges to sleep, circadian rhythms, and wake time functioning.

Data from several studies suggest that physical activity may be a tool that can be used to assist in entraining human circadian rhythms. For example, in healthy young adult males adapting to a phase-delayed sleep/wake schedule in a dim light setting, individuals who exercised in the evening for three 45-minute bouts, separated by one hour each, exhibited a greater phase-delay in melatonin secretion compared to individuals who did not exercise (Barger, Wright, Hughes, & Czeisler, 2004). Notably, the timing, duration, and intensity of exercise are important mediators of the relationship between the circadian systems and physical activity (Buxton, L'Hermite-Balériaux, Hirschfeld, & Cauter, 1997; Buxton, Lee, L’Hermite-Balériaux, Turek, & Van Cauter, 2003). Moderate exercise of longer duration produced a more effective phase delay in melatonin secretion than an intense exercise of shorter duration (Buxton et al., 1997; Buxton et al., 2003). In studies of adults adapting to a new schedule – e.g., shift workers changing to a night shift or airline crew adjusting to a new time zone – individuals who engaged in exercise exhibited accelerated physiological entrainment to the new schedule, as compared with individuals who refrained from exercise (Eastman, Hoese, Youngstedt, & Liu, 1995).

The current state of evidence regarding exercise as a zeitgeber in humans is that 1) exercise can alter circadian rhythms in the absence of strong light cues, but the intensity and duration of the exercise are important (Baehr et al., 2003; Barger et al., 2004; Miyazaki, Hashimoto, Masubuchi, Honma, & Honma, 2001; Van Reeth et al., 1994; Yamanaka et al., 2010); and 2) appropriately timed exercise, when combined with light, offers benefits over light alone.

3. Food as a Zeitgeber

Feeding behavior is regulated to a great extent by the body's central and peripheral clocks. Hormones related to hunger and satiety exhibit clear patterns of secretion throughout the 24-hour day. Emerging evidence suggests a reciprocal relationship between feeding behavior and circadian rhythms, such that the timing and composition of meals may serve to entrain the body's clocks (Asher & Sassone-Corsi, 2015; Johnston, 2014; Johnston, Ordovás, Scheer, & Turek, 2016). Notably, there is evidence that some of the body's peripheral clocks – especially those related closely to feeding behavior, termed "food entrainable clocks" – are more sensitive to entrainment by meal timing than the body's master clock, which regulates sleepiness and sleep (Damiola et al., 2000; Kräuchi, Cajochen, Werth, & Wirz-Justice, 2002; Stephan, 2002; Stokkan, Yamazaki, Tei, Sakaki, & Menaker, 2001; Wehrens et al., 2017). The nutritional and caloric composition of meals is also an important entraining characteristic of food (Kräuchi et al., 2002).

C. LIGHT MANAGEMENT AND ITS IMPORTANCE IN THE MILITARY

Light is a major disturbing factor for sleep in operational environments (Matsangas & Shattuck, 2021; Matsangas, Shattuck, & Saitzyk, 2020; Shattuck & Matsangas, 2017). Managing light exposure and protecting the circadian system is particularly important for military personnel, who frequently engage in 24-hour operations, shiftwork, and rotating watchstanding schedules (Miller & Nguyen, 2003; Ryan, Matsangas, Anglemyer, & Shattuck, 2017). Innovations that allow the warfighter to control or manage their light exposure, either through personal or ambient light management devices, will almost certainly result in improved circadian entrainment, better quality and quantity of sleep, enhanced warfighter readiness, and better crew performance. Moreover, managing light exposure could reduce circadian misalignment and mitigate the alertness and performance decrements that are often associated with this misalignment as the warfighter travels across time zones, rotates through different watchstanding schedules, or engages in night-time operations.

Berthing areas, in particular enlisted berthing in the naval environment where many sailors sleep in the same compartment, present unique challenges for mitigating light intrusions during sleep opportunities (Matsangas & Shattuck, 2017, 2020). Factors to be considered include the number of people sharing the sleeping compartment, the round-the-clock nature of military operations, whether the berthing compartment is the primary location for personal storage for enlisted personnel, and the lack of alternative spaces for privacy. At any given time, multiple individuals may be attempting to sleep, while other people may be awakening and preparing for watch, accessing personal belongings, or engaging in personal activities such as reading or watching movies, all within a small and confined space. These realities necessitate a light management approach that will allow for appropriate lighting for those who need it while preventing light intrusions for those who are attempting to sleep.

D. LIGHT MANAGEMENT METHODS

Strategic management of light exposure provides a promising approach for mitigating the negative effects of circadian misalignment and optimizing performance in an operational environment. The following sections address methods to supplement light exposure, limit light exposure, and the use of light for circadian alignment and stabilization.

1. Facilitating exposure to light

Several methods can be used to effectively deliver light to personnel. The major challenges of light delivery are ensuring that the spectral characteristics, intensity, and timing of the light that is being delivered are correct.

a. Circadian-targeted lighting

Circadian-targeted lighting is designed to support human circadian biology, ensuring that the spectral characteristics, intensity, and timing of the light being used are appropriate. It addresses these three challenges automatically by delivering light from multiple light form factors (e.g., overhead lighting, light boxes, light canvases, etc.) on a circadian-aligned schedule. One such system that has been studied extensively is from Circadian Positioning Systems, Inc. (CPS). This patented, data-backed lighting system is composed of a wearable patch, off-the-shelf-LED lighting which is dimmable and color-tunable, and software that uses sleep/wake data from wearables. The system has been used to deliver circadian-targeted lighting to enhance circadian alignment, sleep, performance, and alertness.

b. Light boxes

Studies at the Halley Bay Antarctic Survey Base have employed personal and communal light boxes to increase the light exposure for base personnel during the Antarctic winter, a time when the sun does not rise for several months. Increasing morning and evening bright light exposure in these conditions was found to have beneficial effects on circadian phase and cognitive performance (Corbett, Middleton, & Arendt, 2012). This group also investigated the effects of blue-enriched light compared to white light, which were individually assessed during multiple rotating 4- to 5-week periods. This series of studies found few improvements in sleep measures with the use of blue-enriched light boxes. However, the effects of light treatment on sleep behavior may have been constrained in this case by the highly regimented schedule for personnel on the base, and the ability to detect differences was likely limited by the small sample size (Francis et al., 2008; Mottram, Middleton, Williams, & Arendt, 2011).

While light boxes in both personal and communal areas appear to be an efficient means of delivering light treatment to groups of personnel, these devices have had limited success in prior studies (Corbett et al., 2012; Francis et al., 2008; Mottram et al., 2011). To be effective, this approach requires the individual to remain in the vicinity of the light boxes for the duration of the light treatment, often a minimum of 2 hours, thus hindering mobility, and in many cases, productivity. With this limitation, the utility of this approach in an operational environment is significantly diminished. Moreover, in situations where military personnel are living and working together in confined quarters and on several different watchstanding schedules, an ambient lighting schedule will only benefit the portion of the population whose assigned wake and sleep schedules are aligned with that of the provided lighting. For these reasons, it is proposed that light boxes may not be practical for an operational environment, and instead, personal wearable light treatment devices would be preferred.

c. Light Canvases

Advancements in LED lighting technology built into a rollable canvas make it possible to deliver light in a range of colors and intensities. Such lighting systems can provide bright, high-energy light at the beginning of the service member's workday and dimmer, low-energy light when they are preparing for sleep. One light canvas from CPS, Inc. has been designed for use inside a Navy rack to deliver lighting appropriate to the Sailor's watchstanding schedule (i.e., limiting blue light exposure or increasing blue light exposure).

d. Light-Emitting Goggles

Light-emitting devices can be used to facilitate circadian entrainment. Using blue light-emitting goggles and blue light-blocking glasses, a study with Special Forces operators showed that controlling light exposure successfully phase locked these operators as they traveled across 9 time zones (Chabal et al., 2018). The effect of light-emitting devices was also assessed with personnel from the Strategic Weapons Facility Pacific (SWFPAC) in Kitsap Naval Base (Moon et al., 2019). Results showed that 38% of the participants reported feeling less tired and 50% reported feeling more alert after using the light-emitting devices. Another study used blue light-emitting and blue-light-blocking goggles on crewmembers of a USN ship while underway (Shattuck & Matsangas, 2021). Results suggested that light-emitting goggles increased alertness.

2. Reducing exposure to light

a. Limit Screen Time

Light, and in particular blue light, is emitted from everyday devices such as smartphones, tablets, and computers. Exposure to blue light (e.g., from looking at your phone or watching TV in bed) during the late evening or nighttime will delay the secretion of melatonin. This phenomenon will in turn affect sleep onset (i.e., it will take longer to fall asleep) and result in later bedtimes. Sleep experts recommend avoiding the use of light-emitting devices two to four hours prior to bedtime.

b. Use Screen Filters

If exposure to light-emitting devices close to bedtime is unavoidable, screen filtering software can alter the type of light emitted by the screens. While some built-in night-time settings on devices can display an orange tint, distort images, and reduce viewing quality, several software programs are relatively effective at reducing blue light exposure. For example, F.lux® is a blue light filter application that reduces the level of blue light emitted from the display and boosts warmer colors such as red, yellow, and orange. Moreover, F.lux® can automatically adjust settings to the time of day in accordance with the ambient light levels. Iris® is an example of another blue light filter application. With Iris®, the user can choose from numerous modes and types within the settings menu (e.g., automatic, manual, paused). Windows 10 also comes with a built-in feature called “Night Light”. This feature allows a timer to be set which controls the lighting on the computer screen for a period of time (e.g., from sunset to sunrise).

Physical filters, considered by many as the easiest and best ways to reduce blue light exposure, are another means for filtering the light emitted from displays. In terms of screen filters, some blue light filters for PCs and other digital devices are just a clear piece of plastic material that covers the screen. These screen filters are coated with a material that limits the amount of blue light that gets transmitted and also contain antiglare properties. Screen filters may be more effective than blue light filter applications due to the impact of applications on color distortion and contrast reduction. While both the application packages and physical screens provide options for reducing blue light exposure, again actual application of these methods in operational conditions may prove problematic. Additionally, physical blue light filters are not usually made of durable material and may have to be regularly replaced which may further impact widespread application in operational environments.

c. Blue Light-Blocking Glasses

A growing body of research advocates the use of blue light-blocking glasses as a method of limiting blue light exposure prior to bedtime. In 2009, Burkhart and Phelps assessed the utility of blue-light-blocking (amber) glasses to improve well-being, comparing them to yellow-tinted (blocking ultraviolet only) glasses. Participants were asked to wear the glasses for 3 hours prior to sleep (Burkhart & Phelps, 2009). During the first week, participants completed sleep diaries. For the following two weeks, in addition to sleep diaries, participants wore blue light-blocking glasses. Results showed that participants who wore the amber lenses experienced significant improvement in sleep quality, mood, and positive affect relative to the control group. Another study conducted in 2017 by Ostrin and colleagues found that participants who wore blue light blocking glasses prior to bedtime showed a 58% increase in their nighttime melatonin levels (Ostrin, Abbott, & Queener, 2017). The use of these blue light-blocking glasses permits individuals to continue using digital devices at night but also improves sleep. Many prescription and over-the-counter reading glasses come with blue light filtering lenses.

In 2013, Rahman and colleagues at the University of Toronto investigated the melatonin levels of individuals exposed to bright indoor light who wore blue light-blocking goggles compared to those exposed to dim light without wearing goggles (Rahman et al., 2013). Results found that melatonin levels were approximately the same in both groups, thus strengthening the hypothesis that blue light is a potent suppressor of melatonin. Moreover, these findings suggest that shift workers and “night owls” (individuals who prefer working later in the day compared to preferring early mornings) may benefit from wearing eyewear that blocks blue light. While orange-tinted lenses block blue light, they also block other colors and as such would not be suitable for indoor use at night.

In 2015, van der Lely and colleagues investigated whether the use of blue light-blocking glasses in the evening, while sitting in front of an LED computer screen, influenced sleep-initiating mechanisms at a subjective, cognitive, and physiological level (van der Lely et al., 2015). This two-week study required participants (male teenagers) to wear blue light-blocking glasses for one week and clear lenses (the control condition) for another week during the evening hours while using LED screens. Results showed that the use of blue light-blocking glasses significantly attenuated LED-induced melatonin suppression in the evening relative to the clear lenses and was accompanied by reduced vigilant attention and subjective alertness prior to bedtime. They concluded that blue light-blocking glasses may be beneficial in protecting against the alerting effect of blue light exposure from LED screens and as such, may have the ability to negate the effects that modern lighting has on circadian physiology.

In 2016, active-duty enlisted military members used light-blocking glasses to improve sleep-related attributes by controlling exposure to light (Ryan et al., 2017). Results showed that daytime sleepiness levels decreased, and mood levels improved after wearing the glasses. In conclusion, research findings support the use of light-blocking glasses in the operational environment. However, more research is required to assess the specific potential benefits of light-blocking glasses.

3. Chronobiotics

The term “chronobiotic” denotes an agent capable of shifting the phase of the circadian time system, thereby re-entraining circadian rhythms (Cardinali, Furio, Reyes, & Brusco, 2006). As such, chronobiotics are potentially capable of accelerating the adaptation of the circadian clock to a new time zone or to a new work/rest schedule (Cheung, Vartanian, Hofer, & Bouak, 2010). It is beyond the scope of this study to discuss all types of chronobiotics. However, in this overview, we will focus on melatonin and caffeine.

a. Melatonin

Synthetic melatonin is the only widely available non-prescription sleep-inducing hypnotic. Melatonin has powerful chronobiotic properties (Dawson & Armstrong, 1996) and can be used to advance or delay the circadian phase. One advantage of melatonin over other hypnotics is that it facilitates sleep without degrading performance if sleep has to be interrupted (Paul, Gray, Kenny, & Pigeau, 2003). Because natural melatonin is normally released at the onset of darkness, it is important to administer synthetic melatonin at the appropriate point of the circadian rhythm to facilitate sleep (Krueger et al., 2011; Paul et al., 2001; Paul, Gray, Sardana, & Pigeau, 2003). Results from one study suggest that melatonin is better at advancing (shortening the day) than delaying (or extending the length of the day) the circadian rhythm (Sharkey & Eastman, 2002).

Our review of the literature suggests that appropriately timed administration of melatonin can effectively shift the circadian phase. In 1998, Suhner and colleagues compared the impact of various dosage forms of melatonin and placebo on jet lag symptoms induced by intercontinental flights over 6 to 8 time zones (Suhner, Schlagenhauf, Johnson, Tschopp, & Steffen, 1998). Volunteers received either 0.5-mg melatonin fast-release (FR) formulation, 5-mg melatonin FR formulation, 2-mg melatonin controlled-release (CR) formulation, or placebo. Results showed that the 0.5 and 5 mg FR formulations were more effective than the 2 mg CR formulation at facilitating circadian shifts. The 5-mg FR formulation significantly improved the self-rated sleep quality, shortened sleep latency, and reduced fatigue and daytime sleepiness after the flight. The lower physiological dose of 0.5 mg was almost as effective as the pharmacological dose of 5.0 mg. Only the hypnotic properties of melatonin (sleep quality and sleep latency) were significantly better with the 5.0 mg dose (Suhner et al., 1998).

In 2010, Paul and colleagues concluded a multi-year project for the Royal Canadian Air Force to ameliorate the effects of circadian desynchrony in the operational environment (Paul, Gray, Lieberman, Love, Miller, & Arendt, 2010). Findings from this project indicated that 3 mg of sustained-release (SR) melatonin taken approximately 5 hours before dim light melatonin onset (DLMO) provided the best phase advance of circadian phase, while 3 mg regular release melatonin taken approximately 9 hours after

DLMO provided the best phase delay. Based on their findings, Paul and colleagues concluded that 1 or 2 mg of SR melatonin may be most appropriate for facilitation of daytime sleep (Paul, Gray, Sardana, & Pigeau, 2004; Rajaratnam, Middleton, Stone, Arendt, & Dijk, 2004) with administration of hypnotics to be considered only if necessary. Of note, however, findings from another study demonstrated that a 0.5 mg of regular release melatonin dose can provide phase shifts similar to the 3 mg dose (Eastman & Burgess, 2009), but the 0.5 mg dose should be taken 3 hours later (i.e., about 2 hours before DLMO) to optimize a phase advance.

In summary, melatonin can be used to advance or delay the circadian phase when administered at appropriate times. However, for melatonin to be effective as a chronobiotic, it is critical that it is administered at appropriate times due to the complex interplay between the timing of administration, ambient light conditions, operational demands, the individual's biological rhythm, and individual differences in the rate and direction of adaptation (Arendt, 2009).

b. Caffeine

Caffeine is able to sustain or improve alertness when an individual is sleep-deprived or in situations of circadian misalignment (e.g., jetlag, night or rotating shiftwork) (Kamimori, Johnson, Thorne, & Belenky, 2005). Caffeine from coffee can take from 15 to 30 minutes after drinking on an empty stomach before alertness is increased or an hour if ingested after a meal. An advantage of caffeinated gum over coffee is that the caffeine is absorbed by the capillary-rich mucosal lining of the mouth, thus bypassing the stomach and providing an alertness benefit within 5 to 10 minutes of commencing to chew on it (Kamimori, Johnson, Belenky, McLellan, & Bell, 2004).

Even though caffeine is generally not seen as a true chronobiotic, a number of studies have demonstrated that caffeine consumption can affect the phase of the circadian system. In 2001, a study by Piérard and associates assessed the potential chronobiotic properties of slow-release caffeine, in comparison with melatonin, on resynchronization of endogenous melatonin and cortisol secretions after an eastbound flight incurring a time loss of 7 hours (Piérard et al., 2001). Results indicated that the administration of slow-release caffeine, as well as melatonin, allowed a faster resynchronization of hormonal rhythms during the 4 days following the eastbound flight.

In 2015, Burke and colleagues showed that evening caffeine consumption delays the human circadian melatonin rhythm *in vivo* and that chronic application of caffeine lengthens the circadian period of molecular oscillations *in vitro* (Burke et al., 2015). Results from this study showed that a caffeine dose equivalent to that in a double espresso consumed 3 hours before habitual bedtime induced a ~40-minute phase delay of the circadian melatonin rhythm in humans. This magnitude of delay was nearly half of the magnitude of the phase-delaying response induced by exposure to 3 hours of evening bright light (~3000 lux, ~7 W/m^2) that began at habitual bedtime. Furthermore, the same researchers found a caffeine dose-dependent lengthening of the circadian period.

E. RATE OF CIRCADIAN ENTRAINMENT

Given that the average free-running period of the human circadian clock is slightly longer than 24 hours (Burgess & Eastman, 2008; Wever, 1979), it is generally easier for humans' circadian rhythms to drift slightly later each day. This tendency makes it more difficult to advance the human circadian clock (i.e., shorten the day) than to delay it (i.e., extend the day) (Eastman & Martin, 1999; Mitchell, Hoese, Liu, Fogg, & Eastman, 1997; Shanahan, Kronauer, Duffy, Williams, & Czeisler, 1999). In terms of travel across time zones, this natural human tendency means that it takes longer to re-entrain the circadian clock when traveling eastward than westward (Aschoff, Hoffmann, Pohl, & Wever, 1975; Boulos et al., 1995). Based on earlier studies on passengers of trans-meridian flights, Aschoff and colleagues calculated an average phase delay of 92 minutes per day after westward flights and an average phase advance of 57 minutes per day after eastward flights (Aschoff et al., 1975).

Several studies using light as the main zeitgeber focused on assessing the rate of circadian adaptation when shifting the daily schedule by 12 hours from day to night work. Czeisler and colleagues used high-intensity light to promote circadian adaptation to a 12-hour shift from day to night work (Czeisler et al., 1990). Participants were exposed to 8 hours of 7,000-12,000 lux light during the simulated night shifts. The accumulated circadian shift was 9.6 hours over a 6-day period (~1.6 hours/day). In the same year, Eastman and Miescke assessed circadian entrainment with shifting sleep times and exposure to light while participants were living at home (Eastman & Miescke, 1990). The light treatment included an evening 2-hour exposure (~1770 to 2800 lux) followed by dim light for 6 hours after waking. Results showed that entrainment was achieved in 74% of the participants with a rate of adaptation of ~2 hours/day.

Gander and Samel (1991) used a daily 5-hour exposure to light (>3500 lux) in their laboratory-based study. Their results showed an average shifting rate of 2 hours/day during a 3-day period. In the same year, Dawson and Campbell (1991) conducted a laboratory study to assess circadian entrainment using light (4-hour exposure to 6,000 lux) during only the first day of shifting to the night schedule. Results showed an accumulating shift of 5 to 6 hours during the 3-day experiment.

Later, another study by Eastman and colleagues (1999) focused on circadian entrainment using light management while participants stayed at home. Light treatment included a daily 6-hour exposure to ~5000 lux of light and avoiding exposure to light during circadian inappropriate times. Results showed that circadian rhythms shifted on average 2.4 hours/day over the first four days when they phase delayed and 1.6 hours/day when they phase advanced. (Eastman, 1992; Eastman & Martin, 1999). Consequently, participants were almost fully adjusted by the fourth day of shifting when their circadian phase was delayed.

Other studies have used a combination of light and melatonin in addition to shifting the sleep schedule. For example, advancing the sleep schedule by 1 hour/day combined with intermittent bright light from light boxes (~5000 lux) for the first 3.5 hours after waking and melatonin in the afternoon can phase advance the circadian clock by about 1 hour/day (Revell et al., 2006). Later, Paul and colleagues evaluated an afternoon regimen of 3 mg SR melatonin with and without next morning green light treatment (1 hour, 350 lux) for circadian phase advance (Paul, Gray, Lieberman, Love, Miller, Trouborst, et al., 2010). The effects of melatonin and light were tested separately and then combined to determine if the total phase change is additive or synergistic. Results showed that the effect of using melatonin in the afternoon (average phase advance of 0.72 hours when administered independently of light) and being exposed to green light after waking up (average phase advance of 0.31 hours when administered independently of melatonin) was additive.

In conclusion, the findings presented here suggest that the rate of circadian entrainment depends on various factors to include the daily work/rest schedule, exposure to all zeitgebers, individual differences, and compliance with an appropriate circadian synchronization protocol. In general, it is expected that higher rates of adaptation (i.e., more rapid entrainment) can be accomplished if a battery of carefully aligned synchronization methods can be utilized.

F. REGULATIONS AND MILITARY-RELEVANT RECOMMENDATIONS

This section focuses on the provisions of existing regulations regarding the effect of circadian disruption and circadian entrainment in flight operations, and the transition from day to night flights.

1. Naval Air Training and Operating Procedures Standardization (NATOPS) General Flight and Operating Instructions Manual (CNAF M-3710.7)

The Naval Air Training and Operating Procedures Standardization (NATOPS) General Flight and Operating Instructions Manual (CNAF M-3710.7) Chapter 8 includes the minimum guidelines for the survivability of flight personnel (Commander Naval Air Forces, 2017). NATOPS emphasizes the need for adequately rested personnel and provides specific guidance for crew rest, sleep duration, and time awake for flight crew and flight support personnel. In terms of circadian desynchrony, NATOPS notes that changing local sleep/awake periods or rapidly crossing more than three time zones disrupts circadian rhythms. This condition is resolved only by accommodation to the new local time or sleep/awake pattern, with a duration that can be estimated by allowing 1 day for every time zone crossed in excess of 3. The accommodation period begins when a new daily routine is established. During that period, the aircrew is not grounded but can be expected to perform at a less than optimal level. Also, less intense flight profiles and close observation by the flight surgeon during the accommodation period may be desirable.

NATOPS notes that working night shifts for extended periods requires even longer times for adaptation (up to 4 weeks). Furthermore, individuals may never fully adapt to night shift work unless completely isolated from daylight exposure, and additional controls may be necessary for safe operations. NATOPS advises NAVMED P-6410 for specific fatigue countermeasures to adapt to and minimize disruption of circadian desynchrony (BUMED, 2000; Commander Naval Air Forces, 2017).

2. Performance maintenance during continuous flight operations: A guide for flight surgeons (NAVMED P-6410)

The NATOPS manual refers to NAVMED P-6410 (BUMED, 2000; Commander Naval Air Forces, 2017) as the guidance for fatigue countermeasures to adapt to and minimize disruption of circadian desynchrony. NAVMED P-6410 provides a single page of basic information on circadian rhythms and notes that "about seven consecutive days of shift work are required to adjust the body temperature cycle (and the associated performance peaks and valleys)" (BUMED, 2000, p. 5). Also, the "Strategies and Ideas" chapter of P-6410 includes the following information for working nights: "It takes about seven days to adjust to working nights. Working only three to four nights in a row starts the process of circadian desynchronization but doesn't complete the shift. Therefore, working a single night or seven in a row is better tolerated." (BUMED, 2000, p. 12). The document does not provide any guidance on how the shifting from day to night operations can be achieved.

3. Aviation Flight Regulations (US Army Regulation 95-1)

The purpose of US Army Regulation 95-1 is to establish policy and procedures for Army manned/unmanned aircraft operations, flight rules, crew requirements, and general aviation provisions (Department of the Army, 2018). AR 95-1 considers crew endurance as an integral part of the overall risk management program. The regulation also notes that it is the responsibility of the commander to design a crew endurance program tailored to their unit's mission and include it in their standard operating procedures. AR 95-1 references the Leader's Guide to Crew Endurance (Comperatore, Caldwell, & Caldwell, 1997).

4. US Army "Leaders Guide to Crew Endurance"

The "Leader's Guide to Crew Endurance" provides a) information to help leaders recognize the detrimental effects of stress, fatigue, and sleep deprivation on performance; b) guidance on controls that are available to leaders for reducing risk and optimizing performance; and c) tools for commanders and planners to use in developing individual crew endurance plans for their units (Comperatore et al., 1997).

Section III of the Guide, "Work schedules and the body clock", discusses general and specific countermeasures for night operations and shift lag when resynchronizing to a new work schedule. These countermeasures and methods include napping, pre-adaptation to the new work schedule, timed exposure to daytime and bright light, adjustment of meal schedules, coordination of unit activities, sleep-related habitability in the sleeping quarters, and other appropriate methods. Section IV, "The systems approach to crew rest", provides information on light management planning, sleep-related habitability in the sleeping quarters, and activities in the unit's daily schedule. Lastly, detailed guidance, to include daily schedules when shifting from day to night operations or from night to day operations, is included in Appendix F, Circadian Rhythms.

5. US Coast Guard Air Operations Manual - COMDTINST M3710.1I

The Coast Guard's Air Operations Manual prescribes policy, standards, instructions, and capabilities pertinent to all phases of Coast Guard flight operations and is intended for use by operational commanders, unit commanding officers, aircrews tasked with operations, as well as customers of Coast Guard aviation (United States Coast Guard, 2021).

COMDTINST M3710.1I has specific provisions for crewmembers in "reverse cycle operations", i.e., repeated nights of scheduled sorties or unscheduled flight operations of the same flight crewmember requiring crew mission time from 0000 to sunrise (0600 rather than sunrise for extreme latitudes). According to the manual, a flight crewmember is considered adapted to night operations ("night adapted") when having been placed in a night orientation for four or more nights. In such cases, the flight crewmember must be afforded adequate crew rest facilities allowing ten uninterrupted hours of daytime rest. Also, the crew member should be considered adapted for continuous reverse cycle operations by night four and for following nights. If not night-adapted, crewmembers may not be scheduled for more than two consecutive nights of reverse cycle operations (United States Coast Guard, 2021, p. 3.12).

6. Fatigue Risk Management Recommendations for Canadian Forces

Prior to 2010, the Canadian Defence Forces did not have a doctrine and training program for fatigue risk management. To fill this gap, Cheung and colleagues developed the "General Recommendations on Fatigue Risk Management for the Canadian Forces" based on best practices derived from the latest scientific findings and the collation of common policies from other military forces. That document focused on the management of sleep hygiene and circadian entrainment that enable aircrew to perform at their best (Cheung et al., 2010). The document provided specific recommendations on shift lag management (section 5.1.7), night operations (section 5.1.7.1), and trans-meridian travel (section 5.1.8). In particular, the document stated that it takes about two weeks of continuous night work to adjust the body clock when transitioning from morning to afternoon/nighttime duty hours. In contrast, it takes at least 3-7 days to resynchronize from nighttime to daytime duty.

Later in the same year, a project to optimize Canadian Forces' ability to manipulate circadian rhythms forward or backward to counter jetlag and shiftlag was concluded (Paul, Gray, Lieberman, Love, Miller, & Arendt, 2010; Paul et al., 2009). Funded by the Royal Canadian Air Force, the 4-year project consisted of seven studies. Four studies involved light treatment, two studies involved efficacy comparisons of three melatonin formulations to produce a phase advance and a phase delay. The final study involved a combination of melatonin and light treatment. Based on the findings of this project, combined with earlier research on optimal circadian entrainment, researchers developed two circadian-entrainment protocols using light and melatonin along with shifting sleep/wake times and avoidance of light at key times across a broad range of operational scenarios (Eastman & Burgess, 2009; Paul, Gray, Lieberman, Love, Miller, & Arendt, 2010). These two recommended schedules are found in Appendix C.

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III. METHODS

A. LABORATORY EXPERIMENT

1. Experimental design

The 10-day experimental protocol was based on a longitudinal within-subject research design conducted in hybrid conditions. The main experiment was conducted in controlled conditions in the Human Systems Integration Lab (HSIL), although participants were allowed to return home following each of the three evenings/nights of data collection. Because there was no vaccine for the COVID-19 virus, multiple measures were taken to ensure that all staff and participants were negative for the virus. In addition, only one participant was allowed in the testing room and only two staff members could be in the lab with the participant. All individuals wore masks when they were in the same room.

2. Participants

Students, staff, and faculty from the Naval Postgraduate School were allowed to participate in the study. Ten participants volunteered, all with aviation backgrounds in either the United States Army, Air Force, Marine Corps, or Navy. All participants were qualified aviators from their respective communities with varying amounts of flight experience representing diverse platforms. After preliminary examination, one male participant (Participant 04) was excluded from the analysis due to abnormally high salivary melatonin levels throughout the day and night. Therefore, the analysis was based on nine participants (one female and eight males). The NPS Institutional Review Board (IRB) approved the study protocol (NPS.2021.0012-EP3-4-7-A); all participants provided written informed consent before participating in the study.

3. Equipment and instruments

a. Questionnaires

We used two questionnaires to assess participant demographics, sleep habits, sleep tendencies, perceived fatigue levels, and workload ratings of the tasks they were conducting.

(1) Enrollment Questionnaire

The enrollment questionnaire consisted of a demographic section, items assessing flight experience, habitual use of nicotine products, use of caffeinated beverages, use of prescribed or over-the-counter medication, and whether the participant had ever been diagnosed with a sleep-related disorder. The questionnaire also included the self-administered morningness-eveningness questionnaire (MEQ-SA) (Terman, Rifkin, Jacobs, & White, 2001) which was used to assess participants' chronotype, an attribute of human beings related to their preference for waking earlier or later in the day. The MEQ-SA scale includes 19 multiple-choice questions. Scores range from 16 to 86, with scores less than 42 corresponding to evening chronotypes and scores higher than 58 indicating morning chronotypes. Although based on the original Horne and Östberg (1976) MEQ scale, the MEQ-SA has some stem questions and item choices rephrased to conform with spoken American English. Discrete item choices have been substituted for continuous graphic scales.

(2) Pre-flight Questionnaire

The pre-flight questionnaire included three standardized tools. The Epworth Sleepiness Scale (ESS) was used to assess average daytime sleepiness (Johns, 1991). The individual used a 4-item Likert scale to rate the chance of dozing off or falling asleep in eight different everyday situations. Answers for the eight items range from 0 to 3, with 0 being "would never doze," 1 being "slight chance of dozing," 2 being "moderate chance of dozing," and 3 denoting a "high chance of dozing." Respondents were instructed to "rate each item according to his/her usual way of life in recent times". Responses were summed to obtain the total Epworth score ranging from 0 to 24 with higher scores representing higher levels of daytime sleepiness. A score of more than 10 reflects above normal daytime sleepiness and a need for further evaluation (Johns, 1992). The ESS questionnaire has a high level of internal consistency, as measured by Cronbach's alpha, ranging from 0.73 to 0.88 (Johns, 1992).

The Karolinska Sleepiness Scale (KSS) was used to assess individual situational sleepiness (Åkerstedt & Gillberg, 1990; Kaida, Åkerstedt, Kecklund, Nilsson, & Axelsson, 2007; Kaida et al., 2006). The KSS includes a 9-point scale ranging from 1 (feeling extremely alert) to 9 (feeling very sleepy, great effort to keep awake, fighting sleep). Scores on the KSS are sensitive to hours of wakefulness and time of day effects with scores increasing with longer periods of wakefulness.

The Pittsburgh Sleep Quality Index (PSQI) was used to determine sleep quality (Buysse, Reynolds, Monk, Berman, & Kupfer, 1989). Individuals with a PSQI total score ≤5 are characterized as good sleepers, whereas scores >5 are associated with poor sleep quality.

(3) The Bedford Workload Scale (BWS)

A modified version of the Bedford Workload Scale (BWS) was used to assess cognitive workload. The original 9-item scale was developed to enable pilots to rate the workload when completing a specific task in flight (Roscoe & Ellis, 1990). The BWS scale rates task workload based on spare capacity to perform additional tasks ranging from “1 - Workload insignificant” to “10 - Task abandoned. Unable to apply sufficient effort”. The BWS was later modified to include 10 items/ratings that are reached by way of a decision tree. Through three yes or no questions, pilots rate workload for a specific task based on descriptors and associated ratings such as “1 - workload insignificant” to “10 - task abandoned, pilot unable to apply sufficient effort”. The ratings are broken down into four separate sections based on the questions; then pilots choose the best descriptor available from that section.

b. Devices

Participants were issued multiple electronic devices to assess their sleep schedules and exposure to light.

(1) Sleep assessment

Sleep patterns were assessed with two methods. The primary method was wrist-worn actigraphy assisted by activity logs, a validated method to collect objective sleep data in field studies (Meltzer, Walsh, Traylor, & Westin, 2012; Rupp & Balkin, 2011). The use of actigraphy followed existing recommendations (Ancoli-Israel et al., 2015; Morgenthaler et al., 2007). We used the Spectrum Plus actigraphs (Philips-Respironics [PR]; Bend, Oregon). Data were collected in 1-minute epochs and scored using Actiware software version 6.0.0 (Phillips Respironics; Bend, Oregon). The medium sensitivity threshold (40 counts per epoch) was used, with 10 immobile minutes as the criterion for sleep onset and sleep end (all values are the default for this software). Participants were instructed to wear the watch on whichever wrist felt more comfortable continuously unless participating in water sports or showering.

Figure 5. The Philips Respironics Spectrum Plus actigraph. Photo from www.usa.philips.com.

The second method to assess sleep patterns was the ŌURA rings, a wearable device that includes accelerometers, infrared light-emitting diodes for photoplethysmography, and a temperature sensor. Using proprietary algorithms and individualized personal information, the ŌURA app generates an individual’s scores for sleep, readiness, and activity. Based on these three categories, the app provides recommendations for daily routines and habits to improve one’s quality of life. The rings were worn for approximately ten days on whatever finger was most comfortable. Participants were instructed to always wear the ring, specifically at night while sleeping. Data from both devices, actiwatches and rings, were used to assess participants’ habitual bedtimes for scheduling their night sessions and to ensure that participants were maintaining a consistent bedtime and awakening schedule the week before the laboratory data collection.

Figure 6. The ŌURA ring. Photo from www.ouraring.com.

(2) HOBO Pendant data logger

The HOBO pendant data loggers capture light and temperature data and were used to assess participants' exposure to ambient light when not in the laboratory. Participants were instructed to wear the device outside their clothing on their upper arm for the duration of the study (approximately 10 days) while awake.

Figure 7. The HOBO pendant light and temperature data logger.

(3) Light exposure equipment

Circadian-targeted lighting was administered using light boxes, a patented system manufactured by Circadian Positioning Systems, Inc. (CPS), Newport, RI. CPS is a sleep and circadian rhythm-based technology company that has developed a closed-loop lighting system that tracks sleep/wake cycles and circadian patterns using an integrated hardware and software solution. The full system is composed of a wearable patch (Actigpatch), off-the-shelf LED lights (the light boxes) that are dimmable and spectrally/color-tunable, and a software platform driven by proprietary algorithms that use sleep/wake data to influence the delivery of circadian-targeted lighting to enhance circadian alignment, sleep, performance, and alertness.

Figure 8. CPS light box.

(4) Saliva samples

Saliva samples were collected using salivettes (Sarstedt, Germany), centrifuged and chilled immediately, and stored at −20°C within 7 hours of collection, in accordance with standard practices (Crowley et al., 2014).

c. Activity logs

Participants filled out a daily activity log throughout the study. The logs covered each 24-hour period in 15-minute intervals. Participants listed their daily activities to include meals, working out, caffeinated beverages, exposure to different kinds of light, sleeping, and listing of times when the actigraph was removed.

d. Assessment of flight performance

Flight performance was assessed using two identical flight simulator systems which included the X-plane 11 flight simulator software by Laminar Research installed on a desktop computer and a yoke/pedal/throttle-lever control interface. The simulated aircraft was a Cessna 152 with analog gauges. As shown in Figures 9 and 10, a desk located six feet behind the participant was used for the researcher to oversee and set up the different flight scenarios.

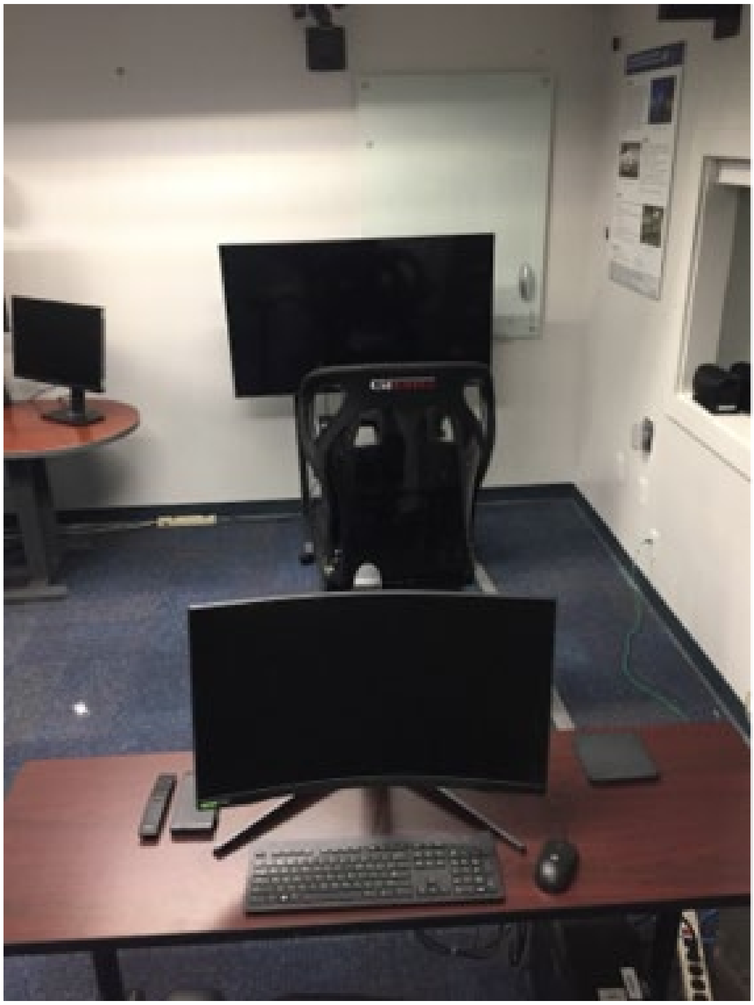


Figure 9. Flight simulator and controller.

Figure 10. Flight simulator.

Participants were exposed to four different flight scenarios, three that were repeated on multiple days. The first flight was a familiarization flight into the Seattle-Tacoma International Airport (SEA), which was administered during the morning of the first day of data collection. Then, on each of the three evening/night data collection events, three ~20-minute scenarios were used for the main data collection (flight scenario "A" to San Francisco – SFO, flight scenario "B" to McCarran International Airport – LAS, and scenario "C" to Martha's Vineyard – MVY). Using simulated environmental factors, scenarios A, B, and C were of increasing difficulty. Each scenario started in the vicinity of the final approach course 20 miles away from the runway. Participants were instructed to fly the plane using the pre-tuned instrument landing system (ILS) to maintain course and descent rate. Flight performance was assessed by three variables: airspeed, horizontal deflection, and vertical deflection.

(1) Airspeed

Participants were instructed to fly the plane by maintaining 60 knots as their indicated airspeed (IAS). Typically, the major factor affecting airspeed is aircraft pitch. Pitching the nose of the aircraft up by pulling back on the yoke will result in a reduction in airspeed. This effect will be somewhat delayed and will oscillate around the most stable trim and attitude configuration without any further input. Changing the nose pitch without modifying the power will result in a change in the rate of descent which will affect vertical deflection.

(2) Horizontal Deflection

Participants assessed their horizontal deflection using the Course Deviation and Glideslope Indicator (CDI). The indicator is designed to give a relative measurement over the width of the localizer beam. The full deflection of the CDI is 2.5 degrees. Negative numbers indicate positioning left of the center of the radio beam, whereas positive numbers indicate positioning to the right. Participants corrected deviation from course to the right or left by banking the plane in the opposite direction. Banking involves turning the yoke in the desired direction and pulling back slightly. Simply turning the yoke with no pushing or pulling will reduce the lift of the aircraft and increase the descent rate. The extent to which the participant pulls on the yoke could lead to no change or to a decrease in descent rate. Sharp turns or multiple turns without increasing power can result in a decrease of airspeed.

(3) Vertical Deflection

Participants assessed their vertical deflection on the CDI. Vertical deflection is controlled primarily by the throttle of the aircraft. Increasing throttle will decrease the rate of descent. Participants were instructed to follow the glideslope of the approach, or the vertical center of the localizer beam. That is, participants are not just flying at a level altitude; they follow a diagonal line that leads directly to the airport. Therefore, participants used the CDI to judge how far from the glideslope they were. If the bar is positioned in the bottom half of the gauge, it is indicating that the aircraft is above the glideslope. In such a situation, participants would need to decrease their throttle, to increase their rate of descent, to get closer to the glideslope.

4. Laboratory Set-up

From the outset, the study faced challenges due to the COVID-19 pandemic. The study was delayed until we received guidance and permission from the NPS Safety Office. We agreed to take multiple safety precautions to safeguard the health of both participants and study personnel. Consequently, two separate spaces of the HSIL were set up to be used for this study. Also, only one investigator and one participant were allowed to be in each space. Each space was further subdivided into two areas, one area included a flight simulator while the second area was used for the light exposure during the second night of the study. Participants were randomly assigned to one of the two spaces for the entirety of their participation in the study. In the light exposure area, the participant had the option of sitting in a comfortable chair or at a desk in a rolling chair for the period of time before the three flights. Ambient light in the light exposure area, which was provided by the CPS light boxes, was dim light on nights 1 and 3 and bright light on night 2.

5. Procedures

A one-time mass email was sent to the NPS student, faculty, and staff population containing information regarding the study along with a study flyer. Additionally, a call for volunteers including the study flyer was included on the NPS student muster page for two months.

The 10-day study was divided into two periods, a 7-day sleep/wake control period and a 3-day laboratory data collection period (Figures 11 and 12). On the first day of the sleep/wake control period, interested individuals were provided with information about the study. Volunteers signed a consent form and California Bill of Rights form, and completed the enrollment questionnaire. Participants were issued an actigraph and an activity log to document their sleep/wake patterns. As a secondary method to assess their sleep attributes and patterns, participants were asked to wear an Ōura ring. Also, participants were asked to wear a HOBO pendant data logger to assess their exposure to ambient light. All three devices (actigraph, Ōura ring, and HOBO logger) were worn throughout the study.

Participants returned to the lab two days before the laboratory data collection (i.e., Day 6 of the experimental protocol) to conduct a familiarization session. The purpose of this session was to familiarize participants with the simulator achieved through an ILS refresher flight to SEA provided by the X-plane 11 simulator. Next, participants flew the day variations of the three scenarios (A, B, C). Approach plates, weather overview, and a brief ILS refresher description for the flight scenarios were sent via email to the participants before the familiarization session. Appendix A includes the approach plates for the four flight scenarios used in the study.

Next, a researcher used data from the actigraph and the Ōura ring to assess the sleep/wake patterns of the participant and to identify his/her habitual bedtime. The last task of Day 6 was to schedule the four laboratory data collection sessions, one on the morning of Day 8 and the three evening sessions on Days 8, 9, and 10.

Participants returned to the lab on the morning of Day 8 for their first laboratory data collection session, the control condition. In the beginning of the morning session, participants completed the pre-flight questionnaire to assess their state before the commencement of the data collection. Next, participants performed the three flight scenarios (A, B, and C, in that order) in simulated daytime settings. The lab was illuminated at normal office lighting conditions. After each scenario, the participants provided a saliva sample and completed the KSS and BWS scales.

Participants returned to the lab for their three nighttime data collection sessions three hours prior to their habitual bedtime. Also, participants were instructed to have a light meal before their night session and to avoid caffeinated beverages for four hours before arrival. Before each night session, the positioning of the CPS lightboxes and the software configuration were verified using a CL-500A Illuminance Spectrophotometer Konica Minolta. For the Night 1 and Night 3 sessions, the space was kept at dim red-enriched light settings of less than 10 lux. For Night 2, lights were set at a blue-enriched white light setting of approximately 1000 lux (measured at eye level) for the first four hours of the data collection session. The first three hours of the light session took place before habitual bedtime and the last one hour after habitual bedtime. After the 4-hour exposure to bright light, participants were provided a 30-minute transition period in dim light (less than 10 lux) to allow dark adaptation for the night flight.

Upon participant's arrival for the night sessions, researchers verified that the participant was in good health, had maintained the regular sleep schedule, and had refrained from caffeine or nicotine products for at least four hours before arriving at the lab. For the first four hours of each of the night sessions, the participant was isolated in the light management room, abiding by the NPS restrictions in place due to COVID-19. During that 4-hr period, the participant was allowed to work on homework, read, watch movies, use the internet, etc. A researcher verified that the light output from any electronic devices was less than 10 lux. If a participant needed to go to the restroom, welder's goggles were worn to prevent hallway/restroom light exposure during the dim light periods of the study.

Each participant completed the KSS and provided a saliva sample every 30 minutes during each of the three nighttime sessions, 12 samples per night. The first salivary melatonin sample was scheduled 2.5 hours before their habitual bedtime with the last sample three hours after habitual bedtime. After the first four hours of the night sessions, the participant moved from the light management room to the simulator room to perform the three simulated flight scenarios. After each flight, each participant completed the KSS and the BWS, and provided a saliva sample. At the conclusion of the data collection, participants were instructed not to nap during the day between the night sessions.

The only difference between the second night session (Night 2) and Nights 1 and 3 was the light treatment, i.e., the bright (~1000 lux) light exposure for the first four hours when participants were in the light management room. On Night 2, eight salivary samples were collected in bright light conditions while the four final samples (when participants were performing the flight scenarios) were collected in dim light conditions (<10 lux). The timing of the data collections was such that participants were in the bright light setting (~1000 lux) for 1.5 hours after their habitual bedtime.

Figure 11 shows an overview of the 10-day experimental protocol. Figure 12 provides more detail by focusing only on the main laboratory data collection period.

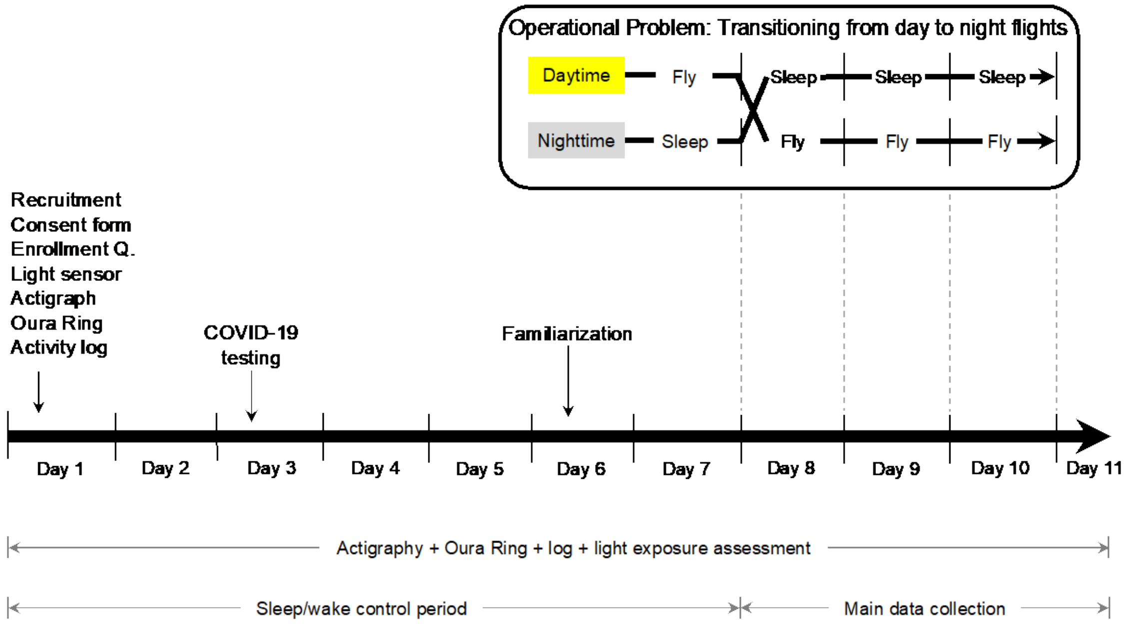
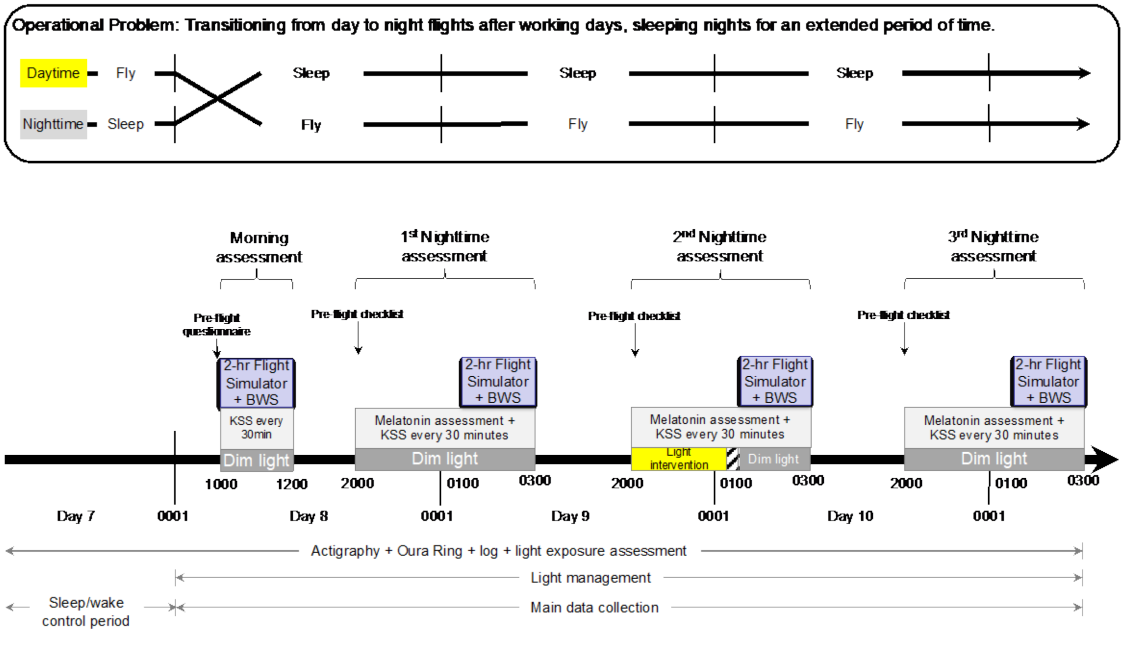


Figure 11. Overview of the experimental protocol.



▨ after light treatment denotes time for accommodating to dim light before the night flight

Assumption: Habitual bedtime = 2200

Figure 12. The experimental protocol during the main data collection period. The diagram describes a protocol tailored for a habitual bedtime of 2200.

6. Analytical Approach

a. Data Cleaning and Data Reduction Procedures

The actigraphic data were prepared for analysis based on a procedure developed and used in all our sleep-related field studies at NPS. The primary source for the sleep analysis was the actigraphy data, but sleep logs (diaries) assisted in the determination of start and end times of sleep intervals. Based on this comparison, we manually identified the start and end times of sleep episodes in the actigraphy data. The criteria used to determine whether we could use the data or whether imputation was required included the quality of the actigraphy data, the consistency of activity patterns over consecutive days, the amount of missing data, and the accuracy of the sleep log. Imputation was only applied to seven (1.75%) missing KSS values based on the average of the adjacent values.

b. Analysis Roadmap

Salivary melatonin levels were assessed by the SolidPhase Laboratory, Portland, Maine. Melatonin concentration in saliva was determined using radioimmunoassay (RIA; Alpco) with a sensitivity of 0.9 pg/mL, intra-assay coefficient of variation (CV) 7.9%, and inter-assay CV of 9.8%. A 4 pg/mL threshold was used to determine the DLMO through linear interpolation (Crowley et al., 2016). Circadian phase shifts were calculated by contrasting the DLMO in Night 3 (post-treatment) with Night 1 (baseline).

Descriptive analysis of the study sample resulted in demographic characteristics of the sample, and a description of participant state at the beginning of the main data collection period. Exposure to ambient light was determined by visual inspection of exposure patterns in the sleep/wake control and the main data collection periods.

Mixed-effects model analysis was used to assess differences in KSS and BWS scores between data collections, with a fixed effect of data collection session (Night 1, Night 2, Night 3) and a random effect of participant ID. Also, mixed-effects analysis was used to assess differences between the night data collection sessions. Airspeed deviation from 60 knots, horizontal deflection, and vertical deflection were used as the dependent flight performance variables. Fixed effects included data collection session (Night 1, Night 2, Night 3), flight profile (A, B, C), and their interactions, and the random effect was participant ID.

Post-hoc comparisons were based on the Tukey Honest Significant Difference (HSD) test accounting for multiple comparisons. The Wilcoxon signed rank test was used for pairwise comparisons of dependent continuous variables.

Statistical analysis was conducted with JMP statistical software (JMP Pro 16; SAS Institute; Cary, NC). Data normality was assessed with the Shapiro-Wilk W test. An alpha level of 0.05 was used to determine statistical significance. Summary data are reported as mean ± standard deviation (M ± SD) for continuous variables and as number/percentage (#, %) for categorical variables. All data underwent descriptive statistical analysis to identify anomalous entries.

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IV. RESULTS

A. PARTICIPANT CHARACTERISTICS

Participants' age ranged from 30 to 44 years. Our sample included participants from the U.S. Air Force, Army, Marine Corps, and Navy aviation communities with ranks from O-3 to O-5. Eight participants reported themselves as users of caffeine and two participants reported using nicotine products. Also, participants had an average morningness-eveningness (M-E) score of 56.6 ± 6.36. Based on their M-E score, one participant was classified as a "definitely morning type" and two as "moderately morning type," whereas six participants were "intermediate type." Habitual bedtimes ranged from 21:30 to 00:00. Detailed demographic information is shown in Table 1.

Table 1. Demographic Data

Age in years, M ± SD	34.0 ± 4.47
Gender, #	
Female	1
Male	8
Branch of Service, #	
US Air Force	1
US Army	2
US Marine Corps	2
US Navy	4
Rank, #	
O-3	5
O-4	2
O-5	2
Total flight hours, M ± SD	1282 ± 689
Flight hours in primary aircraft, M ± SD	987 ± 542

B. PARTICIPANT STATE AT THE START OF THE LABORATORY DATA COLLECTION PERIOD

Participant state was assessed at the beginning of the main data collection, i.e., on the morning of Day 8. The average ESS score was 4.40 ± 1.78 with all participants having normal average daytime sleepiness (ESS score ≤ 10). In terms of sleep quality, the average PSQI score was 4.60 ± 1.35, with two participants classified as "poor" sleepers (PSQI > 5).

C. EXPOSURE TO AMBIENT LIGHT

Analysis of light exposure patterns outside the laboratory showed that participants were mainly exposed to ambient light during the morning and afternoon hours. In general, this pattern was consistent during both the sleep/wake control period of the experiment (the first eight days) and the main data collection period. These findings suggest that, when not in the lab, participants were exposed to light at times that are known to counteract the expected phase delay effect of the light treatment of Night 2. Figure 13 shows light exposure for each participant, averaged by hour of day. Participant 09 wore his HOBO logger only during the sleep/wake control period. Average daylight conditions are denoted by the yellow background. Detailed information regarding participants' exposure to light is included in Appendix B.

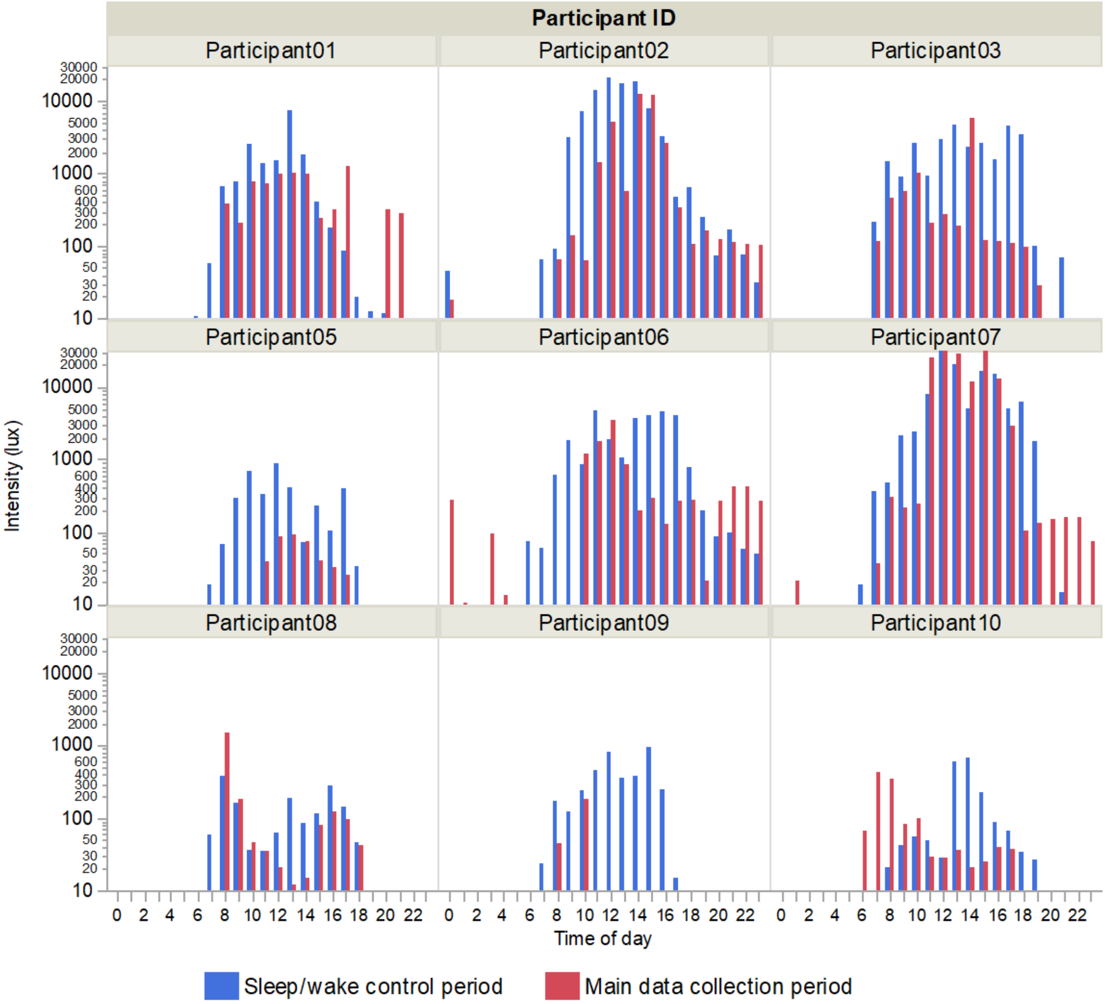

Figure 13. Average light exposure by hour of the day and experimental period for each participant.

D. CIRCADIAN ENTRAINMENT

Participants had varying levels of salivary melatonin, both at the beginning of the data collection sessions and the maximum level reached during each session. Melatonin levels of all participants, however, increased as time went on throughout the night for all three data collection nights. This pattern was clear on Night 1 and Night 3 when participants were in dim light conditions in the lab (<10 lux). As expected on Night 2, melatonin secretion was suppressed by approximately 90% while participants were in the bright light setting (~1000 lux), i.e., during the light treatment within which the first eight salivary melatonin samples were collected. The next four saliva samples for Night 2 were collected in dim light (<10 lux) while the participant was in the flight simulator. During this dim light period, salivary melatonin gradually increased. These results demonstrate that the bright light treatment successfully suppressed melatonin levels on Night 2. Aggregated melatonin levels are shown in Figure 14, whereas Figure 15 shows melatonin levels individually for each participant.

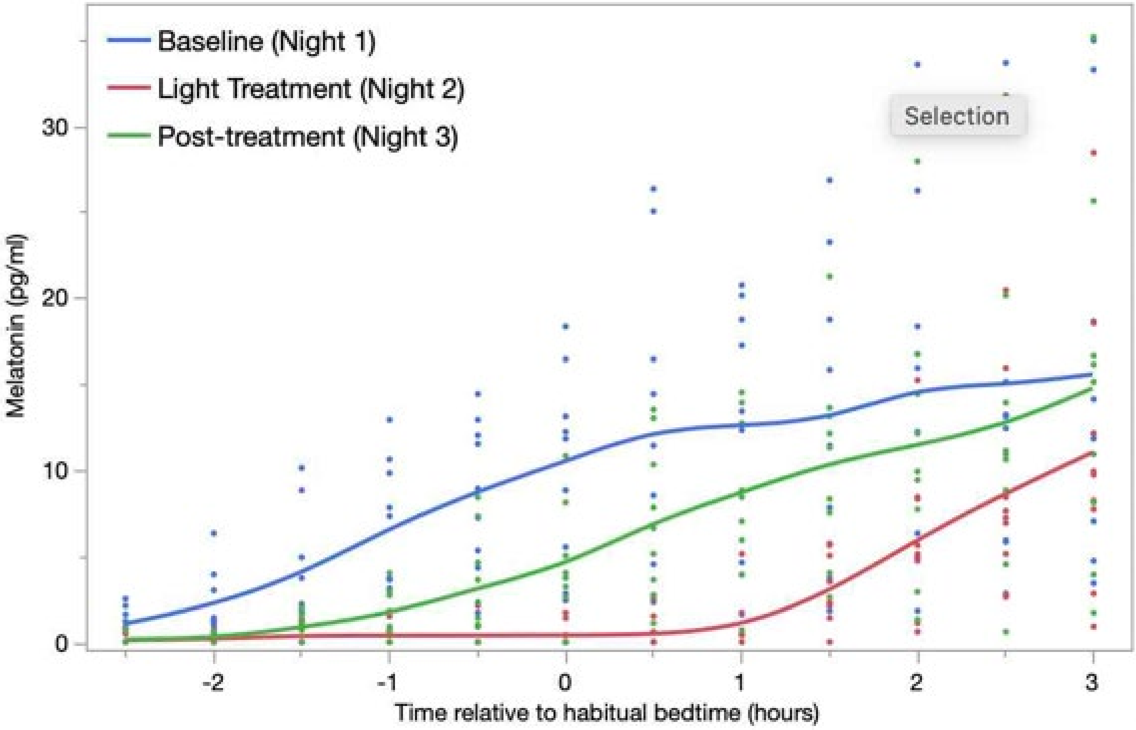

Figure 14. Salivary melatonin levels

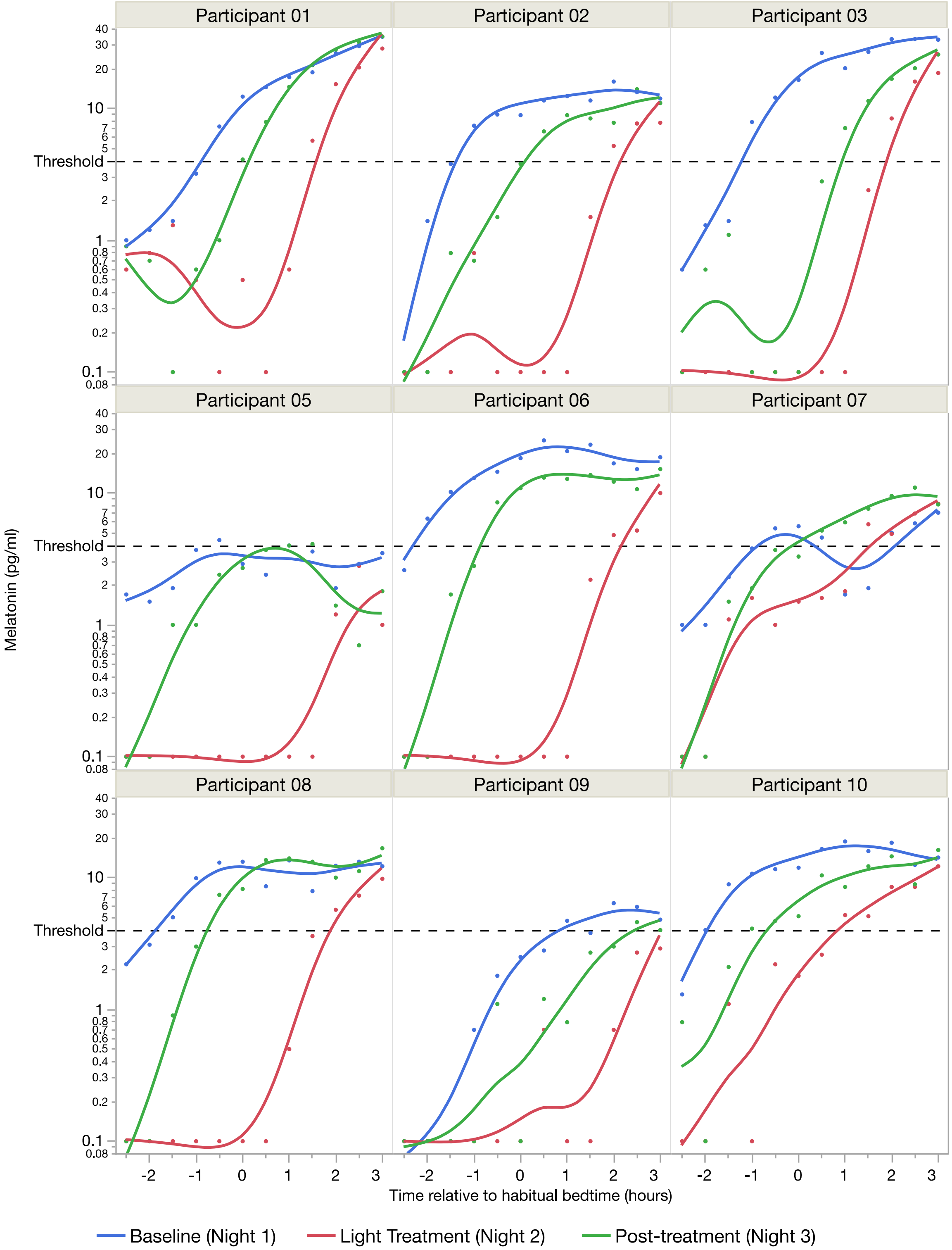

Figure 15. Salivary melatonin levels by participant.

The DLMO analysis showed that the light treatment exposure on Night 2 successfully delayed the circadian phase of all participants on Night 3. Specifically, the average phase delay was 1 hour 19 minutes ± 22 minutes (Wilcoxon Signed Rank test, S = 22.5, p = 0.004) ranging from 53 minutes to 1 hour 56 minutes. Circadian phase delay by participant is shown in Table 2.

Table 2. Circadian phase delay.

Participant ID	Phase Delay (hour:min)
Participant01	0:53
Participant02	1:30
Participant03	1:56
Participant05	1:44
Participant06	1:24
Participant07	1:08
Participant08	0:53
Participant09	1:28
Participant10	0:59

E. PARTICIPANT FATIGUE AND WORKLOAD LEVELS

We analyzed the sleepiness (KSS) data collected during the three nighttime data collection sessions. Mixed-effects model analysis showed that KSS scores increased consistently over the course of each of the three nighttime data collection sessions (p < 0.001), but the scores differed between nights (p = 0.006). Post-hoc analysis showed that KSS scores during Night 2 (the light treatment) were lower (less sleepy) than on Night 1 (baseline in dim light) (Tukey HSD test, p = 0.006). **Light exposure has an alerting effect with participants reporting less sleepiness.** Also, KSS scores during Night 3 (post-treatment) did not differ from Night 2 ($p = 0.675$), but were lower (better) than Night 1 ($p = 0.061$). These results suggest that reported sleepiness was lower (i.e., participants were more alert) the night following the light treatment compared to the baseline.

Next, we analyzed all the workload (BWS) data collected during the three nighttime sessions. Mixed-effects model analysis showed that BWS scores increased consistently over the course of each of the three nights ($p < 0.001$), but the scores differed among nights ($p = 0.001$). Post-hoc analysis showed that BWS scores during Night 2 (light treatment) were lower (better) than Night 1 (baseline in dim light) (Tukey HSD test, $p < 0.001$). **Light treatment reduced subjective workload.** Also, BWS scores during Night 3 (post-treatment) were lower (better) than on Night 1 ($p = 0.109$). These results suggest that self-reported cognitive workload was lower the night following the light treatment compared to the baseline.

Figure 16 includes KSS and BWS for all data collection sessions. The morning session was not included in the analysis; however, the corresponding data are included in the diagrams for completeness. The KSS trends are based on a spline smoother with lambda = 1.81. The BWS trends are based on a spline smoother with lambda = 3.24.

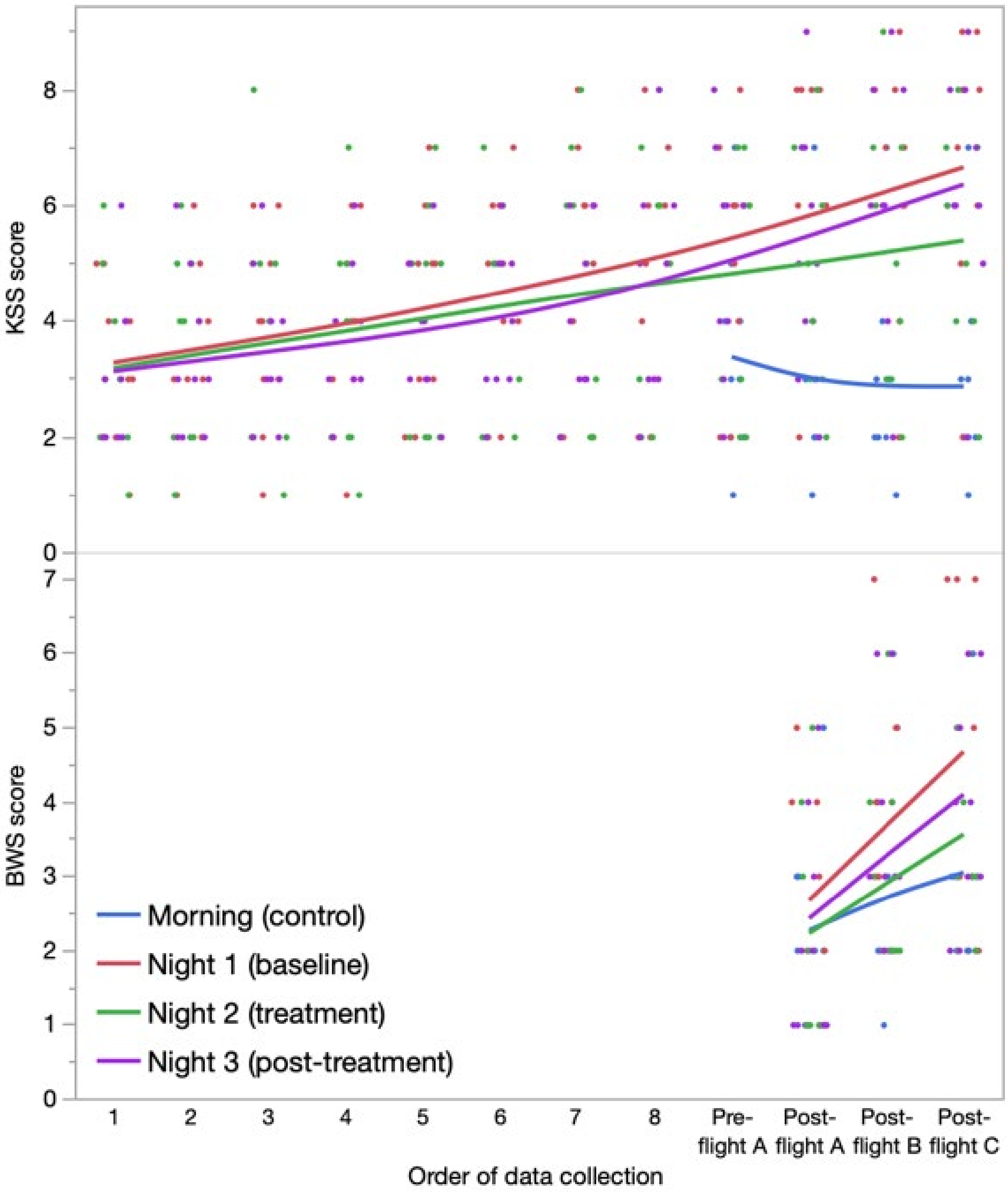

Figure 16. KSS and BWS scores

F. FLIGHT PERFORMANCE

Mixed-effects analysis showed that all three variables of flight performance (airspeed deviation from 60 knots, horizontal, vertical deflection) differed between data collection sessions (all $p < 0.001$). Specifically, the airspeed difference on Night 3 (post-treatment: M = 1.59 knots, SE = 0.347) was better (less) than on Night 1 (baseline: M =

1.75 knots, SE = 0.347; Tukey HSD test, $p < 0.001$) and on Night 2 (light treatment: M = 1.80 knots, SE = 0.347, Tukey HSD test, $p < 0.001$). The horizontal deflection performance on Night 3 (post-treatment: M = -0.062, SE = 0.016) was better (less) than on Night 1 (baseline: M = -0.072, SE = 0.016; Tukey HSD test, $p = 0.007$), but equivalent to Night 2 (light treatment: M = -0.062, SE = 0.016, Tukey HSD test, $p = 0.977$). In terms of vertical deflection performance, Night 3 (post-treatment: M = 0.183, SE = 0.016) was equivalent to Night 1 (baseline: M = 0.187, SE = 0.016; Tukey HSD test, $p = 0.017$), but better (less vertical deflection) than Night 2 (light treatment: M = 0.209, SE = 0.016, Tukey HSD test, $p < 0.001$).

V. CONCLUSIONS

Our review of the literature showed that the single most important cue for circadian synchronization is light. In addition, being physically active, the strategic use of physical exercise, and the use of "chronobiotics" (e.g., melatonin and caffeine) at appropriate times can assist circadian entrainment. Emerging evidence suggests that the timing of meals may also affect the circadian clock. The rate of circadian entrainment depends on various factors to include exposure to zeitgebers, daily work/rest schedules, individual differences, whether one is delaying or advancing the circadian phase, and the degree of compliance with an appropriate circadian synchronization protocol.

Based on these findings, we conducted a study in hybrid conditions to assess the efficacy of bright light exposure (to include timing, duration, and intensity of light exposure) for phase-delaying the circadian clock when individuals maintain a normal day-working /night-sleeping regime. From a behavioral and light-exposure perspective, the study protocol replicated the work/rest patterns of aviators in the field when they work on normal daylight conditions and are required to shift their circadian clock. Our results showed that a single 4-hour exposure to the blue-light-boosted setting of approximately 1000 lux successfully entrained (delayed) the circadian phase of all participants an average of 1 hour 19 minutes (range 53 minutes to 1 hour 56 minutes).

The importance of the study findings becomes clear if we consider that our participants were also exposed to some sunlight throughout the day, partially counteracting the entraining effect of the light exposure in the lab. Theoretically, the magnitude of the phase delay that could be achieved by the light treatment could be increased if aviators adopt and abide by a strict light management protocol throughout the day.

Taken together, findings from the literature review and from our study demonstrate *lux prima,* i.e., light is the primary means for circadian entrainment in the complex military operational environment. In short, **light management is the dominant method for shifting the circadian clock**. Light management includes two components: timing the light exposure to facilitate the shifting of the circadian clock; and avoiding light exposure at circadian-inappropriate times, i.e., when exposure to light impedes circadian entrainment. In general, it is expected that higher rates of adaptation (more rapid entrainment) will occur when using a battery of aligned synchronization methods, i.e., light management combined with appropriately timed physical exercise, meals, melatonin, and caffeine. Based on these conclusions, we developed preliminary recommendations that are described in Chapter VI.

A. STUDY LIMITATIONS

The study has several caveats. First, we had a small study sample. Recruiting only experienced aviators from the NPS community further limited an already small population and resulted in only ten volunteers. With a larger sample we would be able to assess the association between certain demographic factors (e.g., age, sex) and circadian entrainment.

Laboratory conditions cannot replicate the operational environment. Therefore, we used a hybrid study design in which we collected data both in and outside of the laboratory. Participants were allowed to leave the lab at night, return home to sleep and continue their normal daily activities. This approach increased the external validity of our findings while ensuring adherence to the light intervention in the laboratory. Conducting the study in an operational environment would yield the most valid results.

None of the three flight scenarios were considered challenging by the experienced pilots who volunteered to participate in the study. Future efforts should revise the flight scenarios to become more challenging and realistic.

Lastly, all our participants had fairly consistent sleep schedules as expected in an academic environment. These schedules differ significantly from the stressful and demanding operational environments.

VI. RECOMMENDATIONS

Safely transitioning from day to night flight operations is of paramount importance to the naval aviation community. The major purpose of this report is to provide recommendations for effectively managing this transition period and to reduce the time needed to adjust to and stabilize on a new schedule. Our recommendations have been developed based on several simple criteria.

- Recommendations must be simple and aligned with current scientific findings.
- They must be appropriate for operational conditions.
- Even though these recommendations can be applied as stand-alone improvements, effectiveness in operational conditions will be maximized if all recommendations are applied together as a single system.
- The recommendations do not require the need for any specialized equipment, but their effectiveness can be drastically improved if specialized light management devices are used, for example, high energy visible (HEV) light-emitting devices. The use of such devices can improve the rate of adaptation and more effectively ameliorate the dip in performance when transitioning between schedules.
- We avoided including pharmacological interventions. Pharmacologic interventions, including sleep-promoting agents and stimulants, can be effective in maintaining aircrew performance when used "…under the right circumstances, with clearly defined policies, and with rigorous oversight" (Davenport, Lowry, & Pinkston, 2012, p. 253). "However, such an approach in operational conditions is a two-edged sword that should be applied with caution and only as a tool of last resort as part of a balanced fatigue countermeasures and performance sustainment program" (Davenport et al., 2012, p. 253)

Our recommendations fall into two categories. The first category includes general recommendations. The second category includes two notional plans for consideration when transitioning from day to night flights. These recommendations are designed for aviation units whose personnel have minimal commuting to and from their workplace.

A. GENERAL RECOMMENDATIONS

1. Operational scheduling

- Adapting and then sustaining synchronization to night operations is a precarious process. Crewmembers must diligently adhere to a night schedule once they have completed the process of adapting to it. Factors such as collateral duty requirements, off-duty demands, etc. must be taken into consideration for the crewmember to remain adapted.
- Circadian planning should be an integral part of an overall fatigue management plan, both for trans-meridian operations, where jetlag is an issue, and for sustained operations, where night operations can pose a problem (Paul, Gray, Lieberman, Love, Miller, & Arendt, 2010). To the extent possible, operations schedulers should consider the constraints posed by human biology and circadian rhythms. Rapid changes in the timing of flight schedules always introduce additional risks and may jeopardize safety and performance.
- Be proactive. Whenever possible, allow adequate time (a minimum of one day for every 1.5 hours of change in the schedule) for the crew to adjust to the anticipated transition in their flight schedule.
- When shifting between day and night operations, adjust the entire work/rest schedule to include collateral and administrative duties, mealtimes, meetings, exercise opportunities, etc.
- Before crewmembers have fully adjusted to night operations, avoid flights in the second half of the night. This period is the circadian "trough" or "red zone", where alertness is at a low point. The red zone is always accompanied by higher levels of risk, even after partial night adaptation.
- Once crewmembers are adapted to night operations, maintain consistent mission flight times or confine them to a specific operational window (e.g., 2200 to 0400), when possible.
- Use validated fatigue prediction tools to assess the probable impact on the performance effectiveness of an operational schedule. One example of such tools is the Fatigue Avoidance Scheduling Tool (FAST) (by Fatigue Science). FAST is based on the Sleep

and Fatigue, Task Effectiveness (SAFTE^{TM}© 2000-2008 Fatigue Science) model, which was initially developed for the Department of Defense (DoD) (Eddy & Hursh, 2001; Hursh & Bell, 2001; Hursh et al., 2004). FAST is the official DoD-sanctioned model for predicting fatigue-related performance degradation. The Naval Safety Center requires FAST be applied to all mishap investigations (Department of the Navy, 2014).

2. Sleep hygiene

Sleep hygiene refers to a set of behavioral practices promoting good sleep that can optimize alertness and operational performance (Hauri, 1977). Crewmembers should apply these sleep-promoting behaviors to the extent allowed by operational commitments and duties.

- Allow at least 7 consecutive hours for the primary sleep period. Take advantage of every sleep opportunity.
- Exercise "sleep discipline" by keeping a consistent sleep schedule (same bedtime and awakening) every day.
- Keep a consistent bedtime routine when possible. Wear comfortable clothing in a dark, quiet, and cool sleeping environment.
- If unable to fall asleep after 30 minutes, do not remain in bed awake. Instead, get up to avoid associations of waking and anxiety with sleeping in the bed. Stay up for several minutes in low light levels (e.g., equivalent to the light level of candlelight) and try again; repeat, if necessary, until fatigue takes over and you fall asleep.
- If your daily work/rest pattern needs to change, (in general) rotate forward to avail yourself of the 24+ hour circadian clock. Staying up an hour later and sleeping in is easier than waking up an hour earlier. (Example: flying from the East Coast to the West Coast is easier than flying from the West Coast to the East Coast.)

3. Sleep environment

Sleep is most restorative when it occurs in a dark, quiet, cool, and well-ventilated space. Optimize the sleep environment by controlling the temperature, and reducing light, noise, and smells. Sleep-related habitability issues in the crew rest facilities can affect sleep quality and, consequently, crew alertness and performance (Matsangas & Shattuck, 2021; Matsangas et al., 2020). Crew berthing should be arranged by similar mission and sleep scheduling whenever possible to minimize sleep disruptions (e.g., noise and light) from activity in the sleeping areas.

4. Timing of sleep and naps

- When transitioning between day and night operations, develop a circadian synchronization plan with specific guidelines on the appropriate timing of sleep and naps. For more details, please refer to the “Circadian Synchronization Plans” section below.
- Napping (short sleep episodes) should be used to sustain performance when aviators are sleep-deprived, feel sleepy, or are expected to stay awake for extended periods of time. Naps will not fully alleviate the effects of sleep deprivation and should not be used as a substitute for obtaining enough sleep during the regular sleep period.
- Napping should take place before significant sleep loss has occurred.
- Restrict naps to less than 30 minutes to reduce sleep inertia (feelings of grogginess and disorientation). At least 30 minutes should be allowed after a nap before engaging in a mentally or physically demanding activity. Sleep inertia can last up to an hour after awakening from a long nap or after a long period of wakefulness.
- A short “power nap” will usually provide two to four hours of useful wakefulness (i.e., useful mental activity).
- “Caff-Naps”, drinking a cup of coffee or 150-200 mg of caffeine 20-30 minutes before a 20-minute nap, have been shown to be better at promoting alertness than either caffeine or a nap alone.
- When possible, reduce the period of sustained wakefulness (the length of time from the last major sleep period until the present) before flights to below eight hours (United States Coast Guard, 2021). That is, encourage crews to nap one to two hours before missions if their period of sustained wakefulness is approaching eight hours.
- When possible, aircrews should be allowed to nap inflight during long missions.

5. Light management

- When transitioning from day to night operations, develop a circadian synchronization plan with specific guidelines on exposure to light (either natural, artificial, or both). For more details, please refer to the “Circadian Synchronization Plan” section that follows.
- If the transition to night operations has already occurred, be sure to get bright light in the evening and during the first half of the night to help stabilize on this new schedule by using natural (sunlight) or artificial light (e.g., brightly lit indoor spaces or light-emitting devices).
- If the transition to night operations has already occurred, avoid exposure to natural or artificial bright light for the second half of your night shift and in the morning before you go to sleep. Use dark sunglasses with appropriate wavelength filters (e.g., blue blockers that screen out HEV and other light) in the morning following your shift and before bedtime.
- Avoid using any light-emitting devices (e.g., tablets, computers, smartphones) for at least 2 hours before you go to sleep or use them on the dimmest screen settings.

6. Use of sleep-related substances

a. Caffeine

- Do not use caffeine just for enjoyment; instead, use caffeine strategically. Regular use may lead to increased tolerance and reduced effectiveness.
- In general, do not use caffeine within 5 hours of bedtime.
- Using caffeine is recommended during night operations.
    - Use caffeine for the first half of the night to stay alert.
    - “Caff-Naps”, drinking a cup of coffee or 150-200 mg of caffeine 20-30 minutes before a 20-minute nap, have been shown to be better at promoting alertness than either caffeine or a nap alone.
    - For night shift workers, avoid caffeine during the second half of the night shift and in the morning before bedtime.

b. Alcohol

Do not use alcohol as a sleep aid. Although alcohol can be relaxing and can help one fall asleep, it suppresses melatonin and significantly worsens the duration and quality of sleep. Alcohol disrupts healthy sleep patterns (aka "sleep architecture"), thereby reducing the duration and quality of deep sleep (Smith & Smith, 2003).

c. Nicotine

Do not use nicotine products immediately before bed. Nicotine is a stimulant and contributes to respiratory problems.

7. Nutrition

- The timing of meals should be adjusted to align with the night operations schedule. For example, for night workers, breakfast should be provided upon awakening in mid-afternoon with appropriately sequenced meals to follow.
- Refrain from large meals at the following times:
  - before going to bed (~2 or more hours before bedtime to avoid indigestion).
  - before flights to avoid "meal inertia", i.e., impairment in attention immediately after eating a meal (Gupta et al., 2018).

8. Exercise

- Develop an exercise routine to include working out after awakening from the primary sleep period.
- Exercise enhances sleep quality. An hour of light exercise or other forms of aerobic exercise are good choices. Avoid vigorous exercise 1 to 2 hours before bedtime because it may have an alerting effect.

9. Training and education

The military operational environment is dynamic and is characterized by operational commitments and duties that are not under the control of individual service members. In such conditions, sleep hygiene should not be treated as a fixed set of rules but rather as the actual implementation of sleep-promoting behaviors in everyday life. Service members should be educated on the importance of sleep hygiene, how their performance will benefit when adhering to behaviors promoting healthy sleep, and how to avoid problematic sleep practices (Matsangas et al., 2020; Miller, Shattuck, & Matsangas, 2011).

B. CIRCADIAN SYNCHRONIZATION PLANS

Commands should implement a strategic daily plan when transitioning between day and night flight operations to reduce risk. These daily plans must involve the following: 7 hours for sleeping (in the dark); strict light management that controls light and dark exposure throughout the day and night; appropriately timed melatonin administration; and strategic use of caffeine. Existing circadian synchronization plans may include one or more of these methods. However, integrating and using ***all*** methods described above is the most effective means to reduce circadian misalignment and desynchrony. We present two alternative plans designed for different operational situations:

- Crewmembers switching from day to night operations prepare for night operations by gradually shifting their schedule (Figure 17).
- Crewmembers shift from day to night operations without a gradual transition between schedules (Figure 18). Note: Shifting in this way is dangerous and not generally recommended.

Note: The circadian synchronization plans presented here should not be implemented without prior testing in field settings.

1. While on day operations, flight crews pre-adjust to night operations using gradual shifting of their daily schedule.

The first circadian synchronization plan (Figure 17) assumes that the transition from day to night operations will be scheduled well in advance. In such a situation, crewmembers can be allowed to slowly adjust to the night schedule. The plan is based on the gradual delaying of the daily sleep (in bed in the dark) schedule by 1.5 hours per day augmented with a combination of melatonin administration and light and dark management (specifically, sunlight and/or artificial light, and light blocking glasses). A major consideration of this plan is the start and end times of night operations. For example, if night operations end at 0500 and the aircrew can get to bed by 0630, only 5 days would be required for adequate circadian entrainment to occur (assuming bedtime was at approximately 1000 during day operations).

The main characteristics of this circadian synchronization plan are the following:

- It is assumed that individuals will not be on the flight schedule for either days or nights for this entire 5-to-8-day adaptation period.
- Bedtimes should be delayed by 1.5 hours per day.
- Crewmembers are required to sleep two times each day, one major 7-hour sleep period and a 2-hour nap taken 9-10 hours after awakening from the major sleep period.
- To facilitate daytime sleep, it is recommended that crewmembers take sustained-release melatonin (2 mg) before bedtime. Crewmembers should also take 0.5 mg of fast-release melatonin immediately upon awakening from their major sleep period only during the circadian readjustment period when delaying the circadian phase.
- Crewmembers are exposed to bright light before sleep, either sunlight or artificial light (e.g., a light treatment device). Bright light exposure can be intermittent, with breaks of up to 20 minutes, but with a duration of at least 3 hours. Light received closest to the major sleep period has the greatest impact on adaptation, so breaks in lighting should be minimized around that time.
- Crewmembers must remain in a dark environment, avoiding light exposure during their major sleep period. Sleep masks (or eye masks) can help, but they may fall off during sleep. Darkening the room using a combination of continuously dim red light and enhanced light-blocking rack curtains may be most effective.
- Crewmembers should stay indoors in dim light after awakening and avoid going outdoors. If going outdoors is absolutely necessary, they should wear dark, blue-blocker wrap-around sunglasses if going outdoors.
- Mealtimes should be adjusted along with the sleep schedule to the extent possible.

If implemented successfully, we expect this plan to support full adaptation to night operations in a period of approximately 8 days or less, depending on the time that night operations end. As shown in Figure 17, the local daylight and dark periods are denoted by the horizontal yellow and grey bars at the bottom of the diagram. Sleep periods are shown with the pink horizontal lines, with pink circles indicating the start and end of the sleep period. The black horizontal lines ending in black circles represent ideal times for naps. “M SR” denotes the sustained-release melatonin ingestion, which always occurs immediately before the major sleep period. “M FR” denotes the fast-release melatonin ingestion, which always occurs immediately after the sleep period. “S” denotes the exposure to sunlight, whereas the “L” denotes the exposure to artificial light with an appropriate light device. “D” and greyed periods in the diagram indicate the need to stay indoors in dim light or wear very dark sunglasses if required to go outdoors during daylight. “C” denotes drinking a caffeinated beverage. This figure shows 8 days of delaying, but fewer days may be needed depending on when night operations end and the length of time from the end of night operations to actual bedtime. Sunlight, even on a cloudy day, can be effective when timed appropriately (e.g., before your night shift). The integration of strategic use of light interventions is the goal.

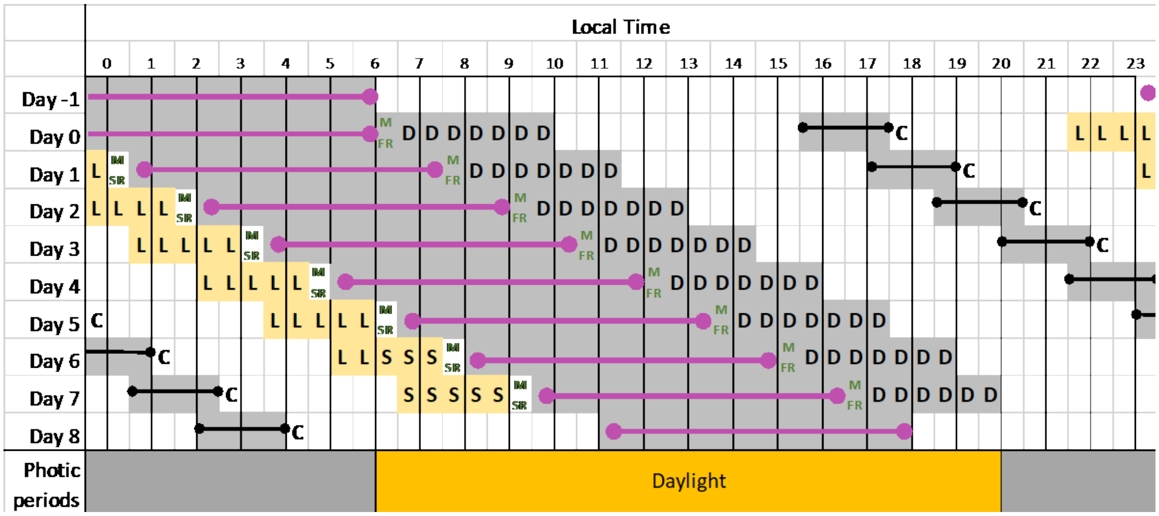

Figure 17. Circadian pre-adjusting from day to night operations by delaying the circadian phase. Note: This draft plan warrants further development in an operational environment to ensure it can be implemented safely and efficiently.

2. Immediately shifting from day to night operations.

Emerging threats and operational requirements may necessitate an immediate shift to support night operations. The second circadian synchronization plan (Figure 18), based heavily on guidance developed for the Canadian Forces and from work by Eastman and colleagues, assumes that the transition from day to night operations must take place immediately (i.e., less than 24-hour notice). A major caveat must be stated here: risk will be elevated significantly during the first few days of the transition, as the circadian rhythms of crewmembers will still require several days to adjust using this rapid transition of work/rest patterns. The main characteristics of the plan are the following:

- Crewmembers will be on the night flight schedule during and after the adaptation period.
- An increased and unavoidable risk for degraded performance and reduced alertness exists for at least the first four days of the transition, potentially even longer.
    - Reducing night operations during the second half of the night (after approximately 0300) is strongly recommended.
    - Allow for an extended sleep period, i.e., crewmembers should be allowed to sleep in as late as possible.
- To facilitate daytime sleep, we recommend crewmembers take sustained-release melatonin (2 mg) before bedtime. Crewmembers should also take 0.5 mg of fast-release melatonin immediately after awakening from their major sleep period during the circadian readjustment period (i.e., when delaying the circadian phase).
- Exposure to artificial light using a light-emitting device is recommended before night flights or during the night when not flying.
- Exposure to sunlight or bright artificial light before the major sleep period is recommended when entraining.
- Avoid sunlight or artificial light after awakening from the major sleep period.
- A long nap, 2 to 3 hours in duration, is recommended before the first night of the transition (evening of Day 0 in Figure 18) to reduce the length of sustained wakefulness on that day. This nap should end at least 2 hours before the start of the shift.

- A nap of an hour (or a “caff nap”) before night flights may be appropriate for some individuals. This nap should end at least 2 hours before the start of the shift.
- Mealtimes should be adjusted along with the sleep schedule.

As shown in Figure 18, the local daylight and dark periods are denoted by the horizontal yellow and grey bars at the bottom of the diagram. Sleep periods are shown with the pink horizontal lines ending in pink circles. The arrow at the end of some sleep periods denotes that crewmembers should be allowed to sleep in as late as possible. The black horizontal lines ending in black circles represent ideal times for naps. “M SR” denotes the sustained-release melatonin ingestion, which always occurs before the major sleep period. “M FR” denotes the fast-release melatonin ingestion, which always occurs after the major sleep period. “S” denotes the exposure to sunlight, whereas the “L” denotes the exposure to artificial light with an appropriate light device. “D” and greyed periods in the diagram indicate the need to stay indoors in dim light or wear very dark glasses if obliged to go outdoors during daylight. “C” indicates the use of a caffeinated beverage.

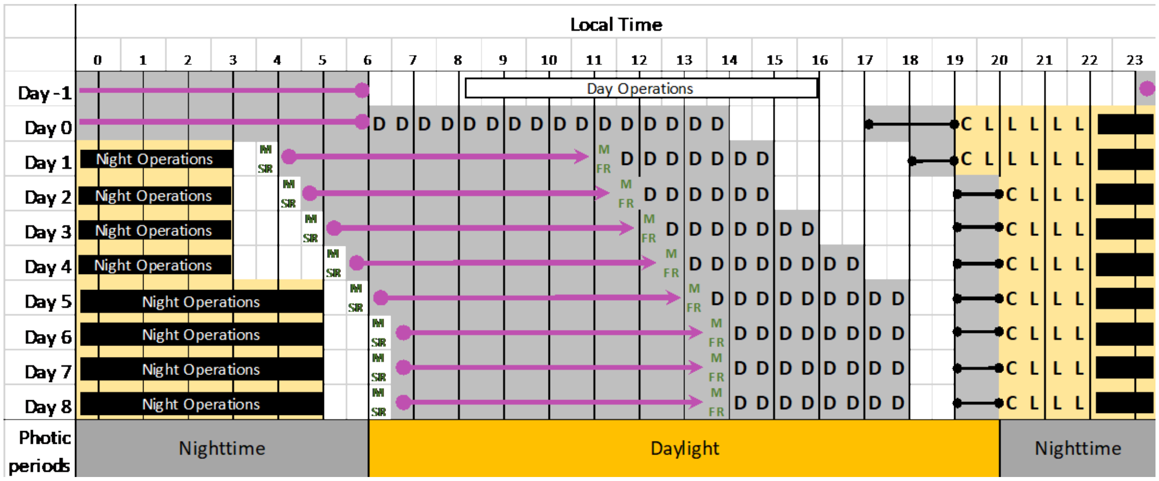

Figure 18. Immediate shifting from day to night operations (gradual circadian entrainment). Note: This draft plan warrants further development in an operational environment to ensure it can be implemented safely and efficiently.

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VII. FUTURE RESEARCH

Shiftwork and the requirement to transition to different work schedules are ubiquitous throughout the naval community. Consequently, we recommend conducting a follow-on study to build upon the findings of this study of single-night light exposure by extending the length of the light treatment to multiple consecutive nights. Increasing the number of nights of bright light exposure and/or increasing the number of follow-on assessment days could provide a better indication of the long-term effects of utilizing this bright light intervention method.

In addition, a study should be designed that combines and assesses the application of multiple circadian re-entrainment techniques. For example, high energy visible (HEV) light, caffeine, melatonin, and exercise could all be used on a group of volunteers for multiple days to assess how these factors combine to entrain circadian rhythms.

Finally, an operational test of the recommendations in this report should be initiated to verify and validate these study findings before being incorporated into naval aviation guidance and policy documents.

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APPENDIX A. APPROACH PLATES FOR FLIGHT SCENARIOS

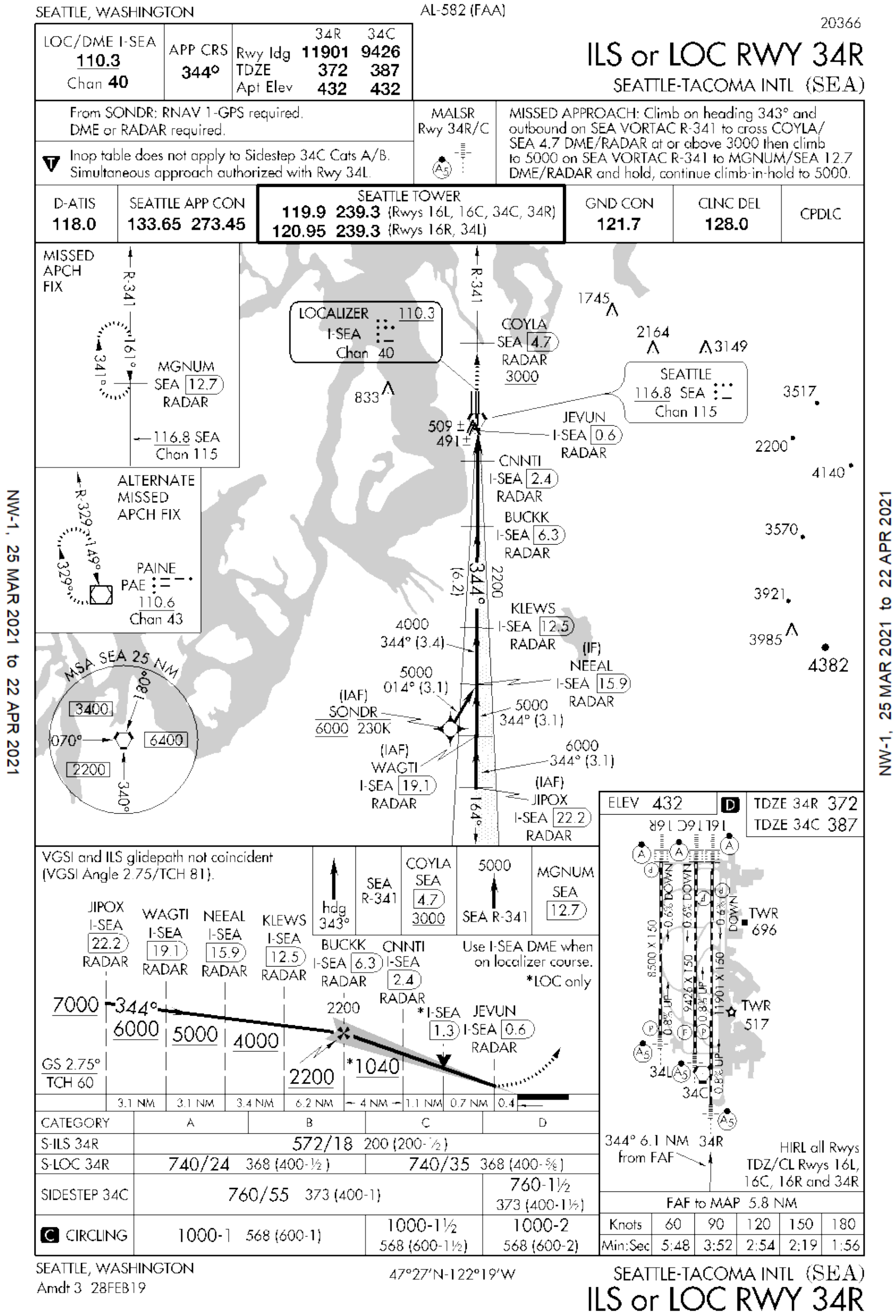
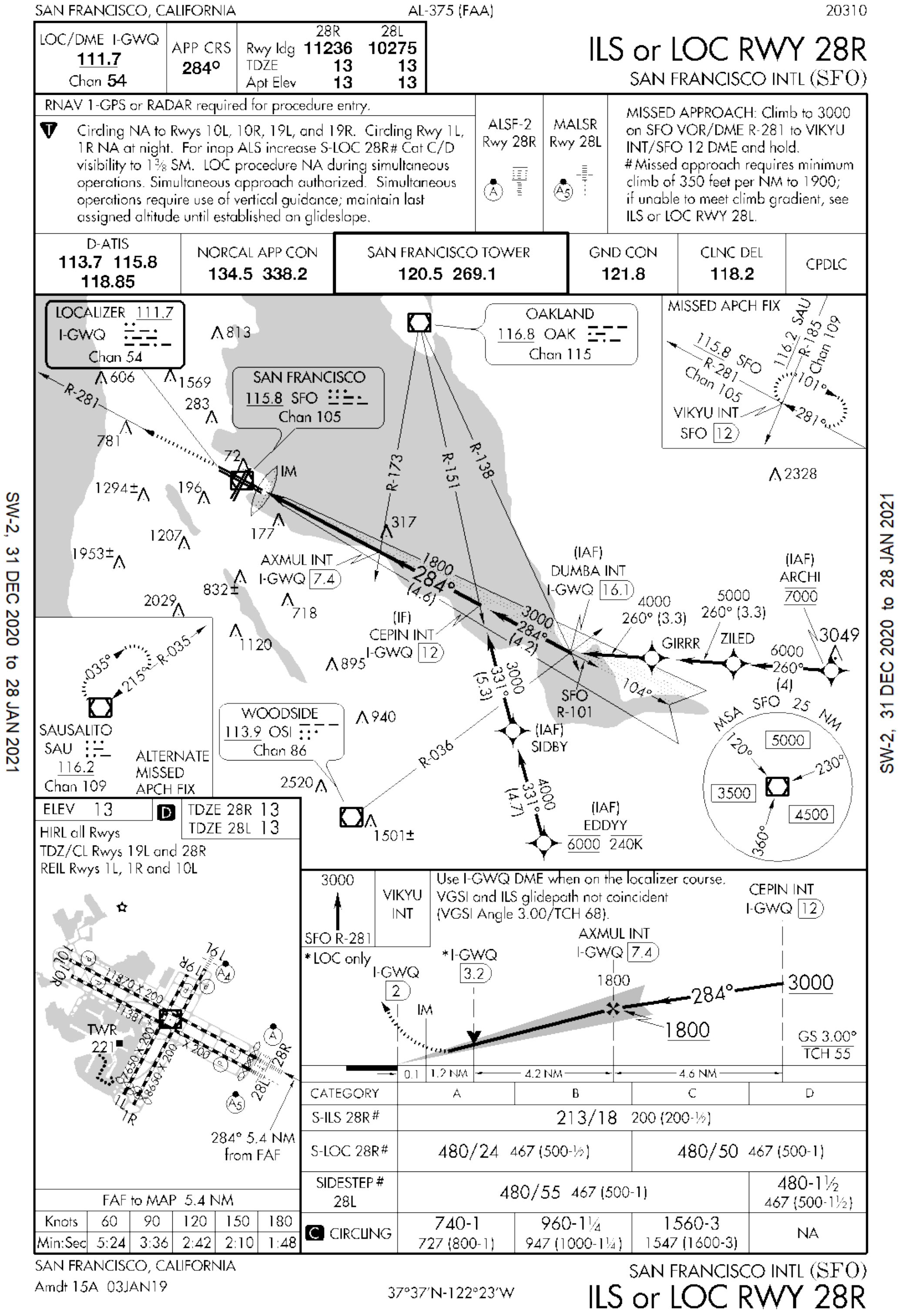


Figure 19. Approach plate for the familiarization flight.



LOC/DME I-GWQ	APP CRS		28R	28L
111.7	284°	Rwy ldg	11236	10275
Chan 54		TDZE	13	13
		Apt Elev	13	13

RNAV 1-GPS or RADAR required for procedure entry.

Circling NA to Rwys 10L, 10R, 19L, and 19R. Circling Rwy 1L, 1R NA at night. For inop ALS increase S-LOC 28R# Cat C/D visibility to 1⅜ SM. LOC procedure NA during simultaneous operations. Simultaneous approach authorized. Simultaneous operations require use of vertical guidance; maintain last assigned altitude until established on glideslope.

ALSF-2 Rwy 28R

MALSR Rwy 28L

MISSED APPROACH: Climb to 3000 on SFO VOR/DME R-281 to VIKYU INT/SFO 12 DME and hold.
Missed approach requires minimum climb of 350 feet per NM to 1900; if unable to meet climb gradient, see ILS or LOC RWY 28L.

D-ATIS	NORCAL APP CON	SAN FRANCISCO TOWER	GND CON	CLNC DEL	CPDLC
113.7 115.8 118.85	134.5 338.2	120.5 269.1	121.8	118.2	

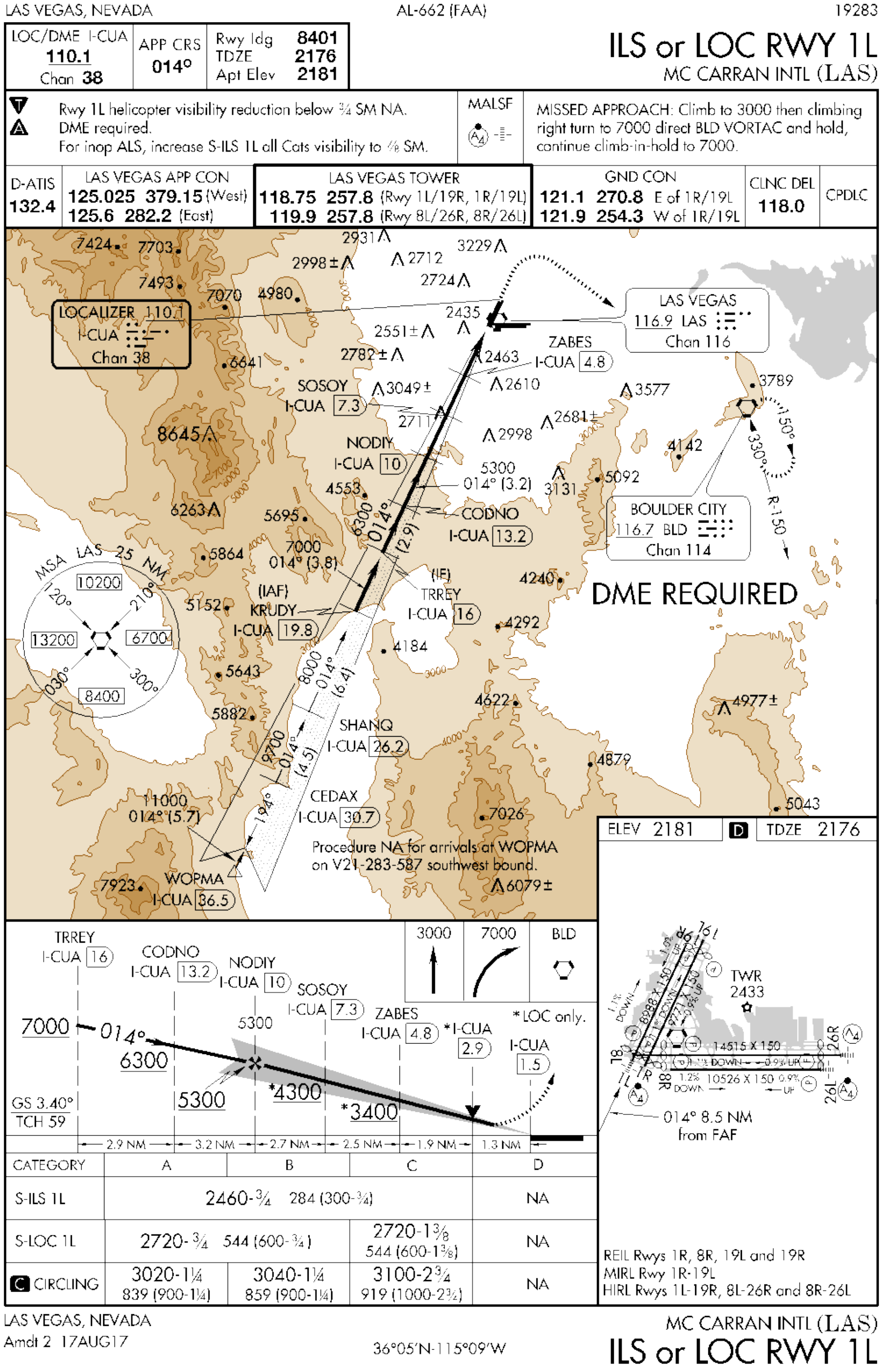
Use I-GWQ DME when on the localizer course. VGSI and ILS glidepath not coincident (VGSI Angle 3.00/TCH 68).

CATEGORY	A	B	C	D
S-ILS 28R#	213/18 200 (200-½)			
S-LOC 28R#	480/24 467 (500-½)		480/50 467 (500-1)	
SIDESTEP # 28L	480/55 467 (500-1)			480-1½ 467 (500-1½)
CIRCLING	740-1 727 (800-1)	960-1¼ 947 (1000-1¼)	1560-3 1547 (1600-3)	NA

FAF to MAP 5.4 NM

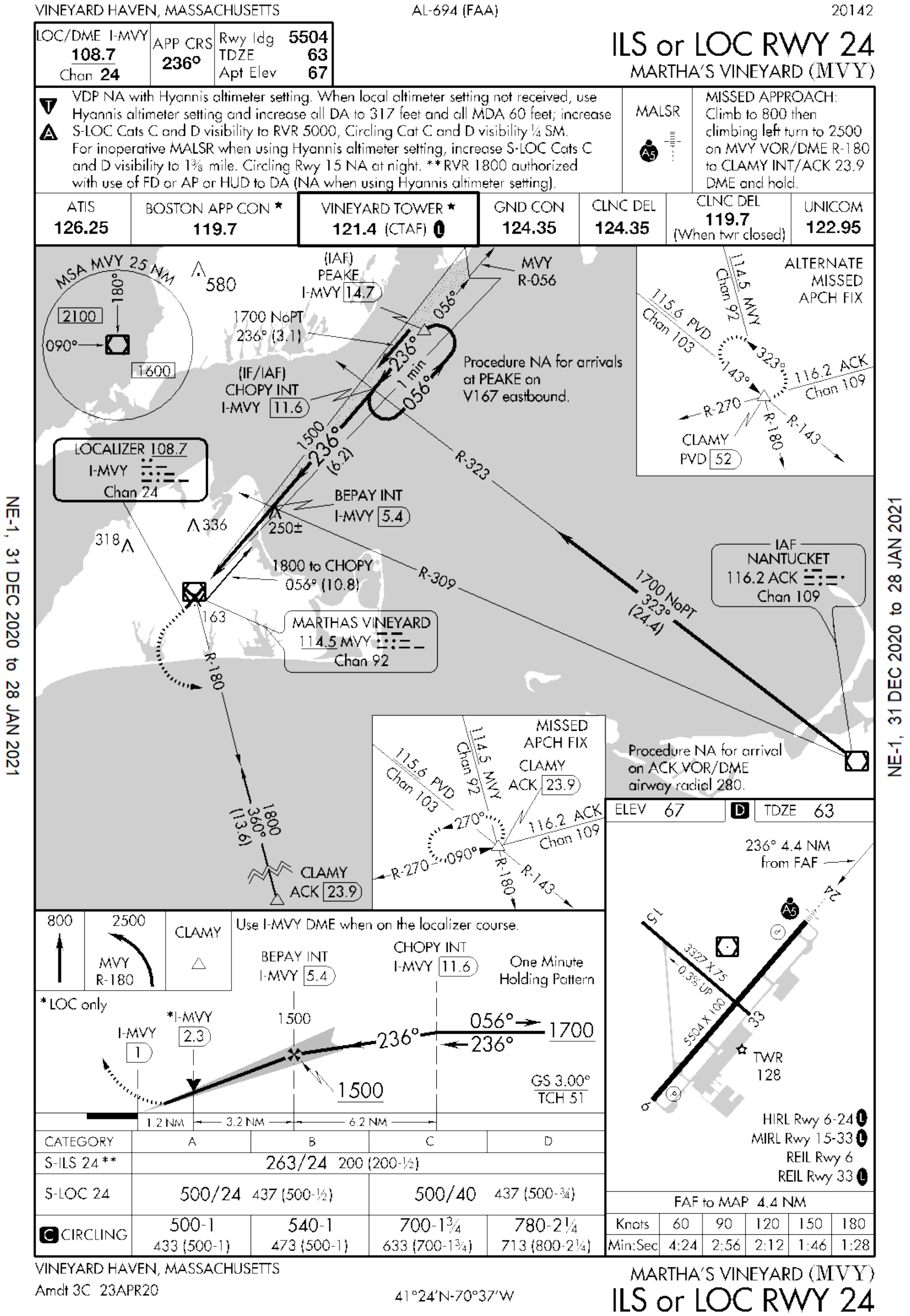
Knots	60	90	120	150	180
Min:Sec	5:24	3:36	2:42	2:10	1:48

Figure 20. Approach plate for the first flight scenario “A” (low difficulty).



CATEGORY	A	B	C	D
S-ILS 1L	2460-¾ 284 (300-¾)			NA
S-LOC 1L	2720-¾ 544 (600-¾)		2720-1⅜ 544 (600-1⅜)	NA
CIRCLING	3020-1¼ 839 (900-1¼)	3040-1¼ 859 (900-1¼)	3100-2¾ 919 (1000-2¾)	NA

Figure 21. Approach plate for the first flight scenario “B” (medium difficulty).



LOC/DME I-MVY	APP CRS	Rwy ldg	5504
108.7 Chan 24	236°	TDZE	63
		Apt Elev	67

VDP NA with Hyannis altimeter setting. When local altimeter setting not received, use Hyannis altimeter setting and increase all DA to 317 feet and all MDA 60 feet; increase S-LOC Cats C and D visibility to RVR 5000, Circling Cat C and D visibility ¼ SM. For inoperative MALSR when using Hyannis altimeter setting, increase S-LOC Cats C and D visibility to 1⅜ mile. Circling Rwy 15 NA at night. **RVR 1800 authorized with use of FD or AP or HUD to DA (NA when using Hyannis altimeter setting).

MALSR

MISSED APPROACH: Climb to 800 then climbing left turn to 2500 on MVY VOR/DME R-180 to CLAMY INT/ACK 23.9 DME and hold.

ATIS	BOSTON APP CON *	VINEYARD TOWER *	GND CON	CLNC DEL	CLNC DEL	UNICOM
126.25	119.7	121.4 (CTAF)	124.35	124.35	119.7 (When twr closed)	122.95

Procedure NA for arrivals at PEAKE on V167 eastbound.

Procedure NA for arrival on ACK VOR/DME airway radial 280.

Use I-MVY DME when on the localizer course.

CATEGORY	A	B	C	D
S-ILS 24 **	263/24 200 (200-½)			
S-LOC 24	500/24 437 (500-½)		500/40 437 (500-¾)	
CIRCLING	500-1 433 (500-1)	540-1 473 (500-1)	700-1¾ 633 (700-1¾)	780-2¼ 713 (800-2¼)

FAF to MAP 4.4 NM

Knots	60	90	120	150	180
Min:Sec	4:24	2:56	2:12	1:46	1:28

Figure 22. Approach plate for the first flight scenario "C" (higher difficulty).

APPENDIX B. LIGHT EXPOSURE PROFILES

Figure 23 shows the distribution of intensity levels of light exposure by participant throughout the entire study.

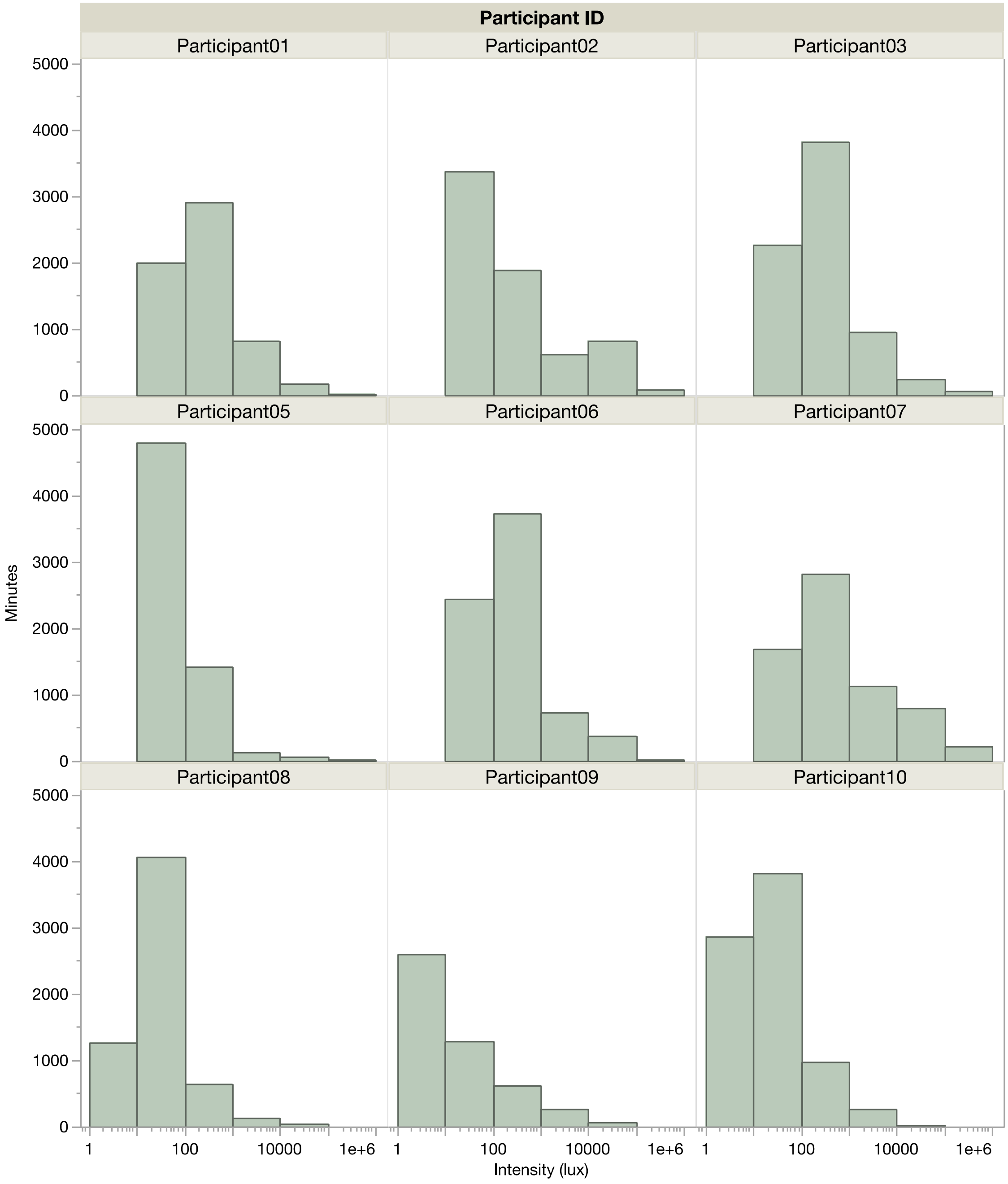


Figure 23. Distribution of light exposure levels of light exposure by participant.

Figures 24 to 32 show detailed information regarding the intensity of exposure to ambient light by participant.

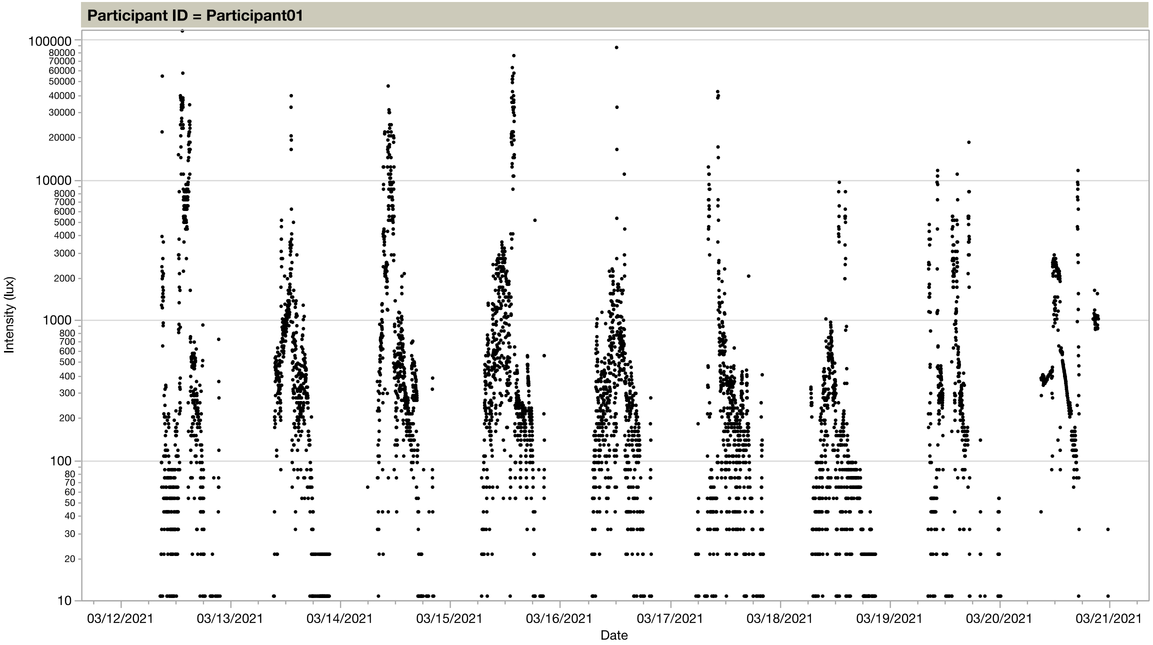


Figure 24. Intensity of exposure to ambient light (Participant01).

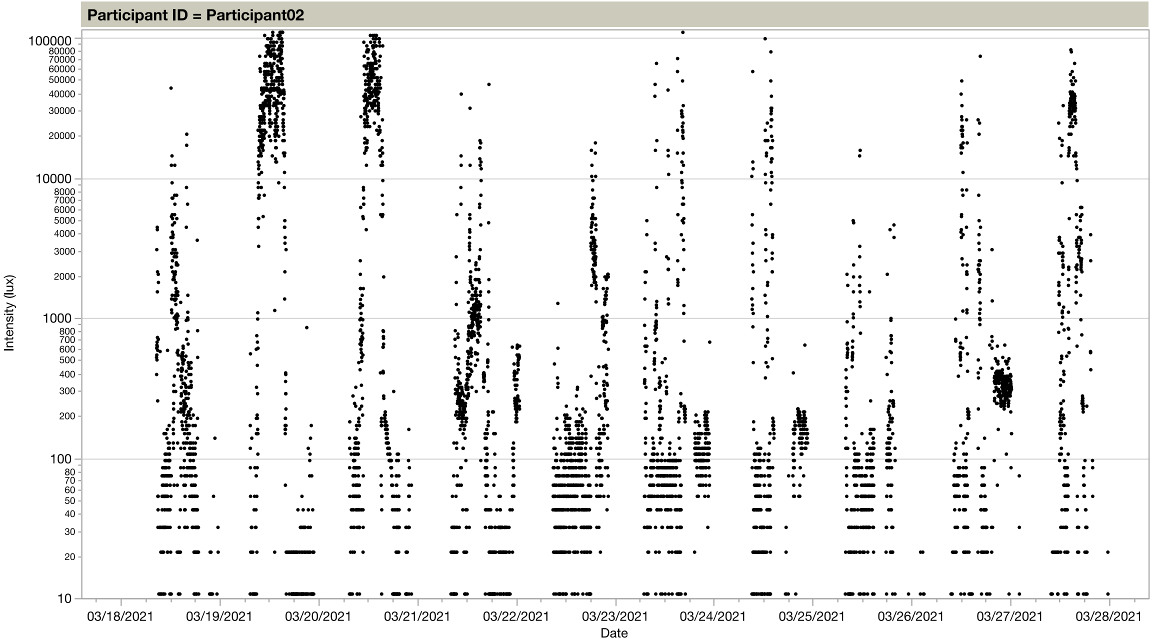


Figure 25. Intensity of exposure to ambient light (Participant02).

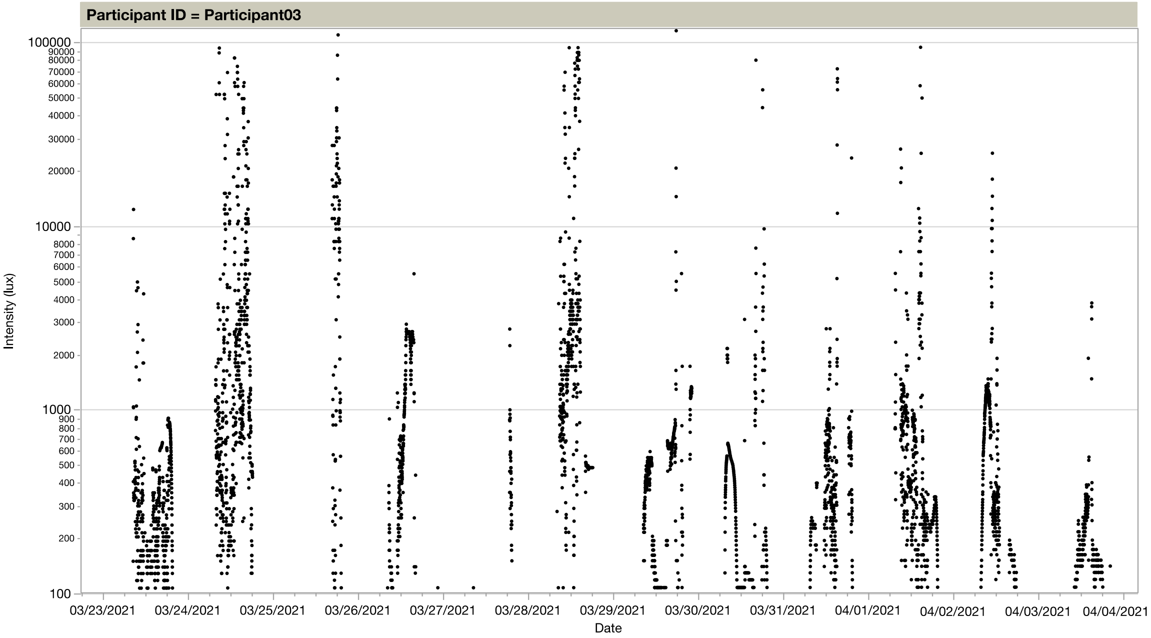


Figure 26. Intensity of exposure to ambient light (Participant03).

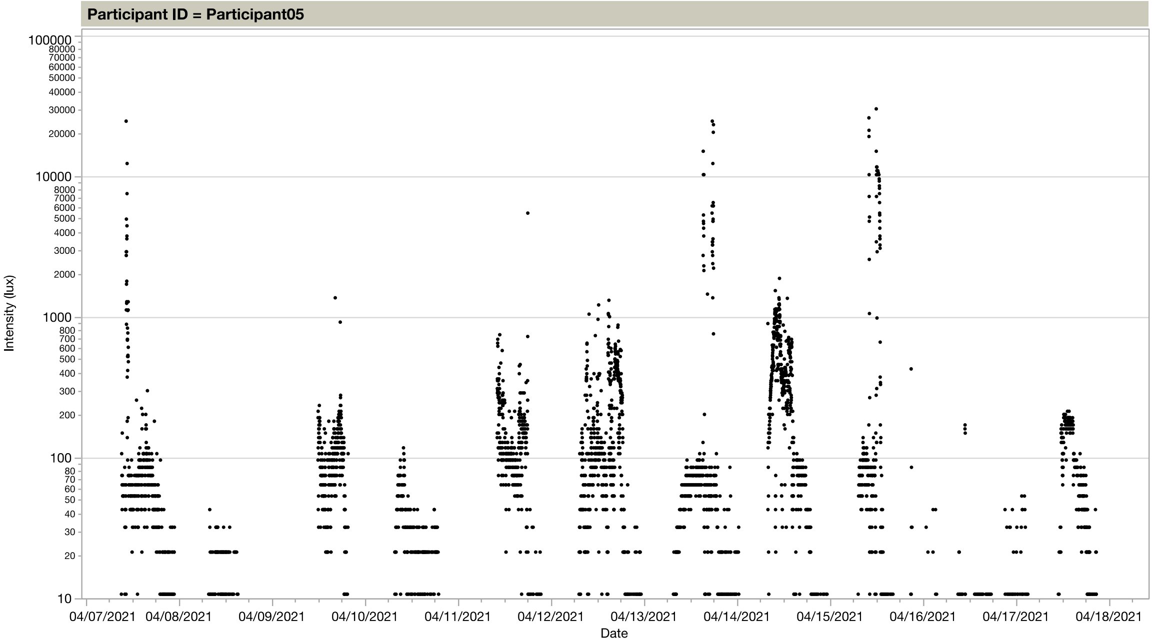


Figure 27. Intensity of exposure to ambient light (Participant05).

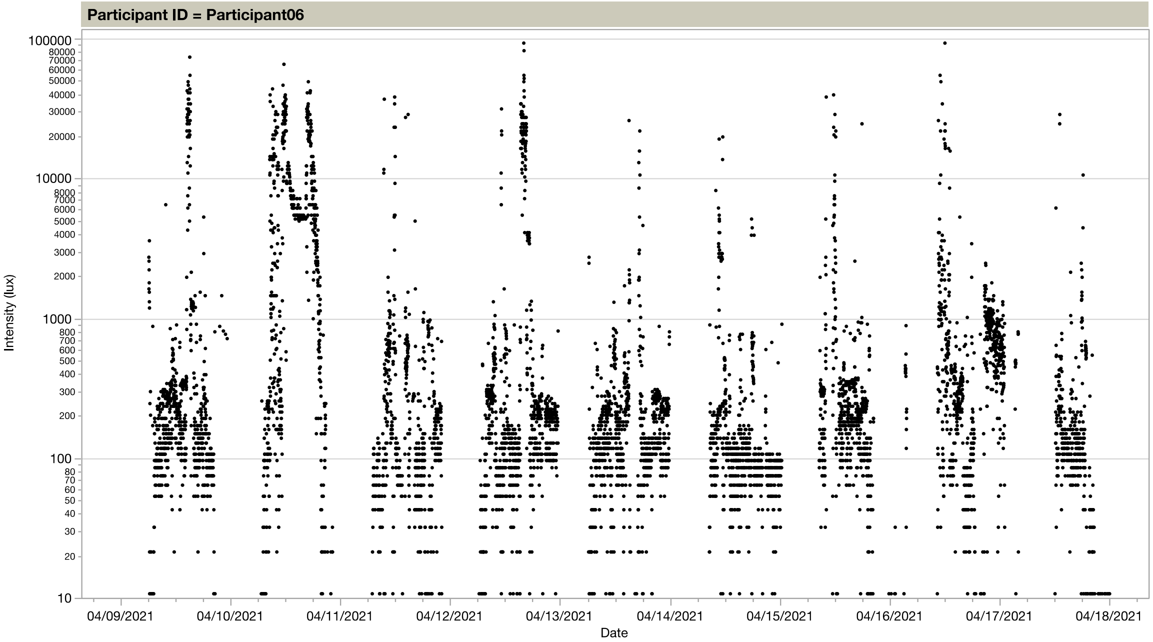


Figure 28. Intensity of exposure to ambient light (Participant06).

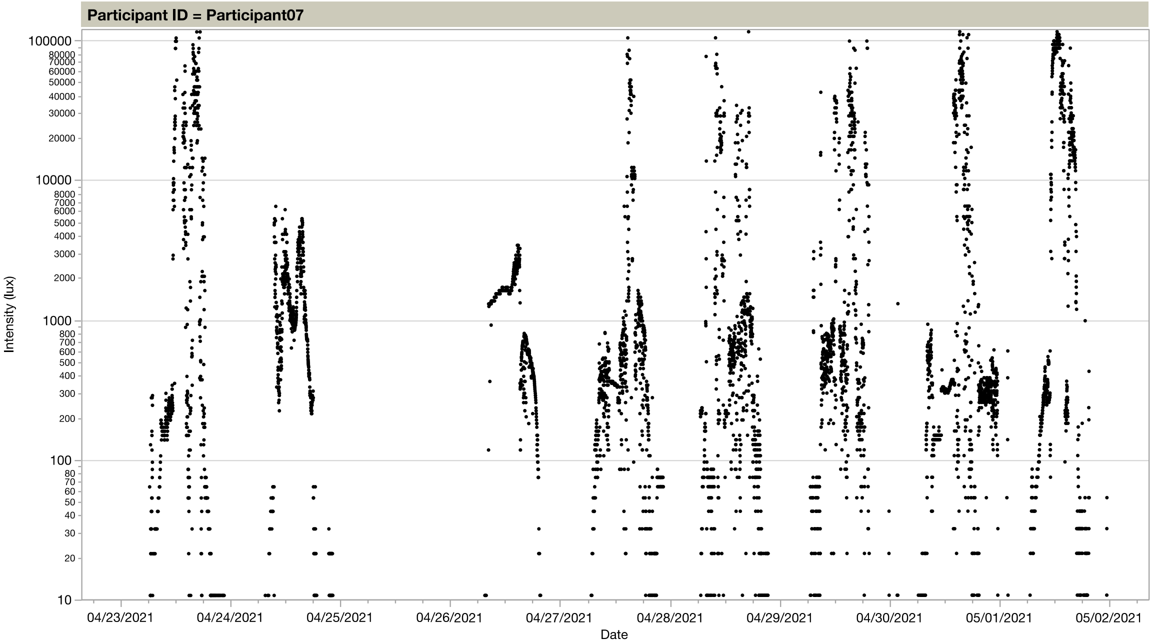


Figure 29. Intensity of exposure to ambient light (Participant07).

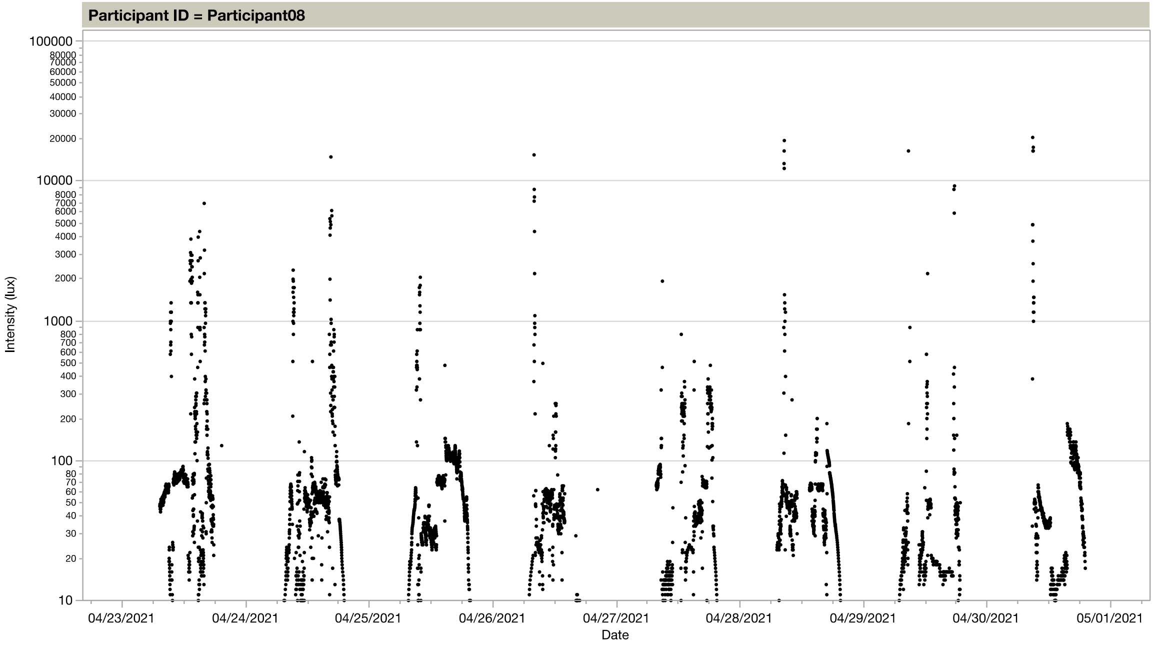


Figure 30. Intensity of exposure to ambient light (Participant08).

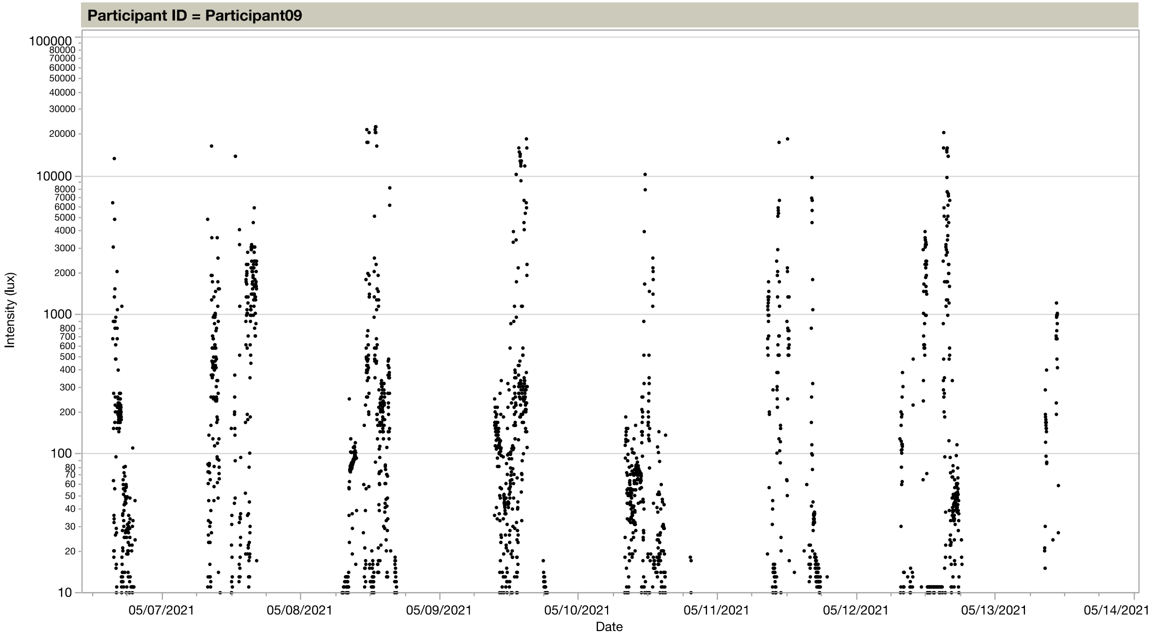


Figure 31. Intensity of exposure to ambient light (Participant09).

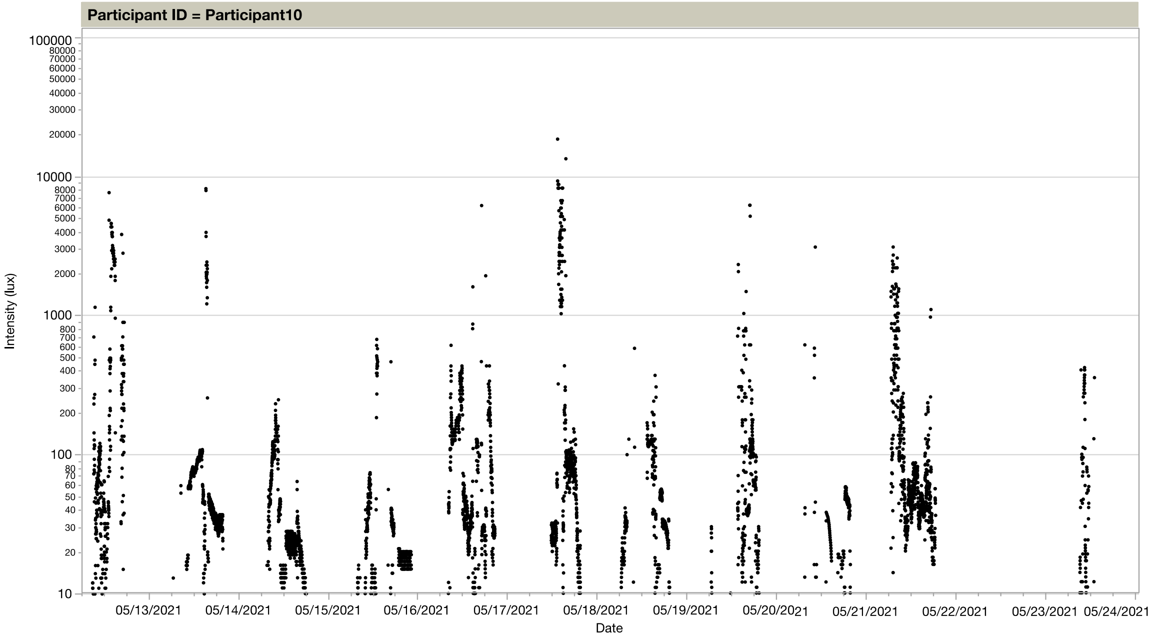


Figure 32. Intensity of exposure to ambient light (Participant10).

APPENDIX C. SYNCHRONIZATION SCHEDULES FROM CANADIAN FORCES

This section shows an example of circadian shifting by 8 time zones, i.e., traveling eastwards from Trenton, CA (UTC -04:00, daylight savings time) to Camp Mirage, UAE (UTC +04:00) to include an intermediate stop in Baden, Austria (Paul, Gray, Lieberman, Love, Miller, & Arendt, 2010). The synchronization plans shown in the following sections were developed based on the work by Eastman and Burgess (Eastman & Burgess, 2009) and in collaboration with Dr. Eastman. The plans include recommendations for melatonin and light exposure prior to and during travel, and at the destination, to optimize circadian adjustment. It should be noted, though, that these methods are applied during flights. These synchronization plans may be especially appropriate for personnel transported as passengers.

The first alternative plan is based on advancing the circadian phase (shifting to the left or shortening the day). While still in Trenton, there is a 5-day pre-adaption period to Camp Mirage time by advancing the circadian phase between the 2nd and the 6th of April (the flight takes place at 1000 on April 7th). The treatment uses a combination of:

- Shifting bedtimes earlier by one hour per day.
- Ingestion of a 0.5 mg dose of melatonin approximately five hours before bedtime.
- Exposure to light after awakening -- either sunlight or an artificial light source.

Figure 33 shows the phase advancing synchronization schedule, which assumes an advance of 1-hour per day with appropriate light and melatonin treatment. The local photic period is denoted by the horizontal yellow bars. The vertical bold black lines in the yellow horizontal bars illustrate the minimum photoperiod (at the winter solstice). Vertical red lines in the yellow horizontal bars illustrate the current photoperiod. “M” denotes the melatonin ingestion. “S” denotes the exposure to sunlight, whereas the “L” denotes the exposure to artificial light with the light treatment device. Sleep periods are shown with the pink horizontal lines beginning and ending in pink circles. The black triangles represent the body’s core temperature minimum, an indicator for the circadian clock.

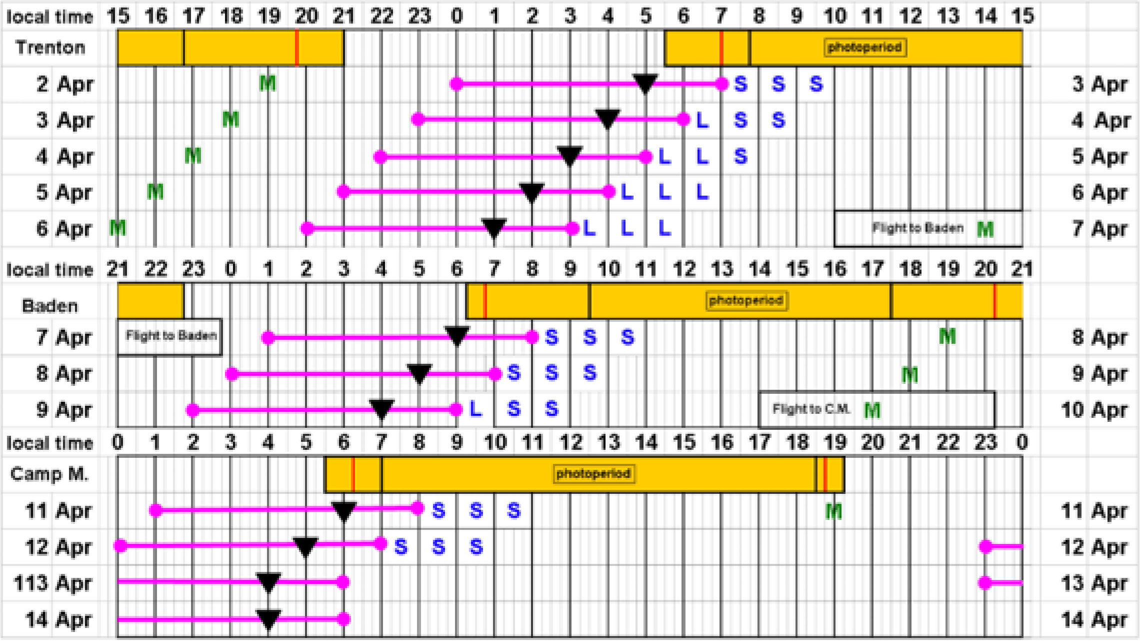


Figure 33. Circadian synchronization example by advancing the circadian phase. Travel from Trenton to Camp Mirage. Diagram from Paul et al. (2010).

The second alternative plan for the travel from Trenton to Camp Mirage is based on delaying the circadian phase (shifting to the right or extending the day). While still in Trenton, there is a 5-day pre-adaption period to Camp Mirage time by delaying the circadian phase between the 2nd and the 6th of April. The treatment uses a combination of:

- Shifting bedtimes later by 1.5 hours per day.
- Ingestion of a 0.5 mg dose of melatonin after awakening.
- Exposure to light before sleep, either sunlight or artificial light using a light treatment device (typically used when exposure to light is required during a time of darkness).

Figure 34 shows the phase delaying synchronization plan, which assumes a delay of 1.5-hour per day with appropriate light and melatonin treatment. The local photic periods are denoted by the horizontal yellow bars. The bold vertical black lines in the yellow horizontal bars illustrate the minimum photoperiod (at the winter solstice). Vertical red lines in the yellow horizontal bars illustrate the current photoperiod. “M” denotes the melatonin ingestion. “S” denotes the exposure to sunlight, whereas the “L” denotes the exposure to artificial light with the light treatment device. “D” indicates the need to stay indoors in dim light or wear very dark glasses if obliged to go outdoors during daylight.

Sleep periods are shown with the pink horizontal lines beginning and ending in pink circles. The arrow on the right end of the pink bar within the flight to Baden and at the beginning of the rows on April 11 and 12 indicates that this is a good time to sleep and that remaining asleep longer is encouraged, as it is whenever the sleep schedule is gradually delayed. The black bars with an arrow on each end represent ideal times for naps.

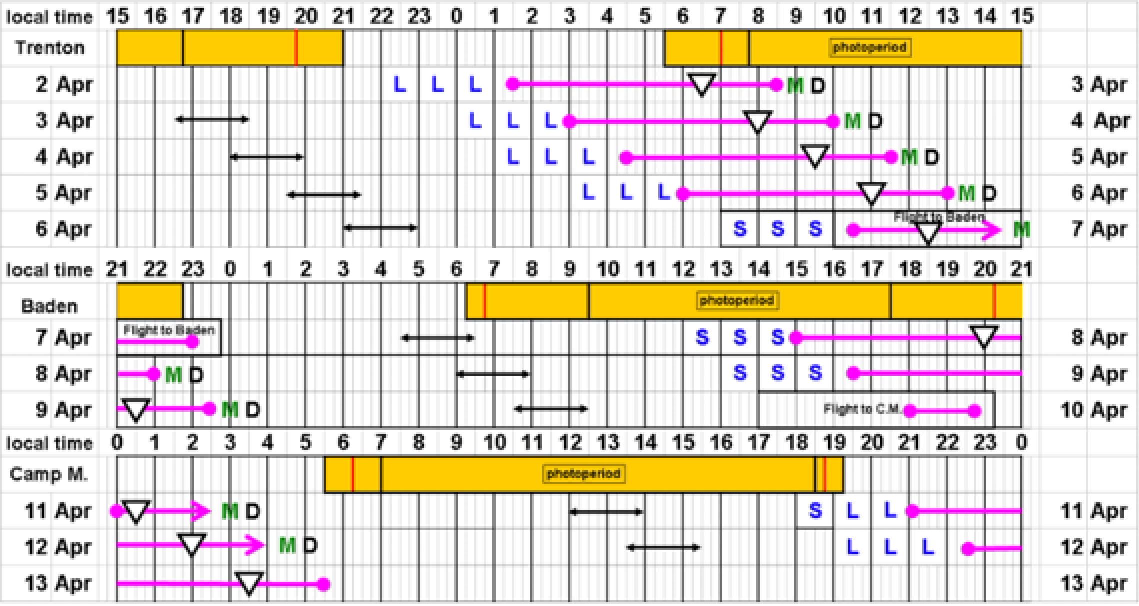


Figure 34. Circadian synchronization example by delaying the circadian phase. Travel from Trenton to Camp Mirage. Diagram from Paul et al. (2010).

The third part of these recommendations includes the return flight from Camp Mirage to Trenton. The synchronization model was based on delaying the circadian phase. As shown in Figure 35, the current schedule includes a combination of:

- Shifting bedtimes later by 1.5 hours per day.
- Ingestion of a 0.5 mg dose of melatonin after awakening.

- Exposure to light before bedtime -- either sunlight or artificial light using a light source.

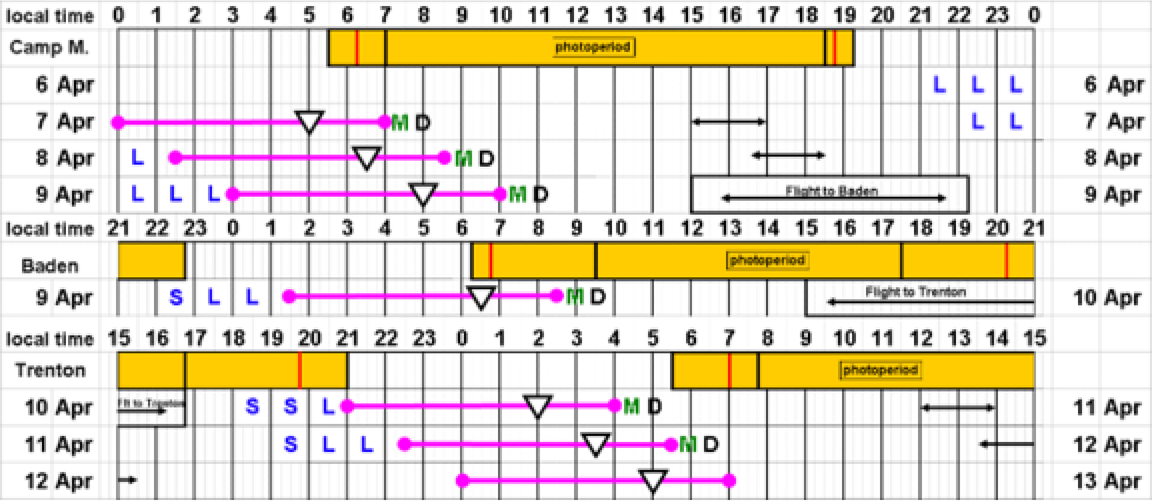


Figure 35. Circadian synchronization example by delaying the circadian phase. Travel from Camp Mirage to Trenton. Diagram from Paul et al. (2010).

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