Social Determinants of Sleep

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Abstract

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Humans typically sleep in highly built settings that isolate them from environmental regulators of sleep. In postindustrial, highly urbanized environments, these conditions are combined with social schedules that include long commuting times to meet strict school and work times. Together, these conditions have created a “social time” that represents a major determinant of sleep timing and quality.

My studies consist of sleep data from two human study populations living in the highly urbanized city of Seattle (Washington, USA) that represent unique contexts in which social time and the built environment have distinct effects on sleep.

University students have a late chronotype, or natural inclination to sleep and wake at later times of the day. Students are severely affected by their social obligations because their early school and work times conflict with their late chronotypes. The misalignment between their

circadian and social times is described as social jetlag and leads to inadequate sleep duration and quality. Social jetlag and insufficient sleep duration are linked to many health conditions, such as obesity and heart disease.

The Covid-19 pandemic shutdown caused workplaces and universities to become remote, which led to little to no commute and more flexibility to choose betimes. We recorded actimetry and light data in students before-Covid (2019), during-Covid (2020), and after-Covid (2021). Compared to before- and after-Covid, during-Covid there was a decrease in the discrepancy between school day and weekend sleep timing, and a longer sleep duration during school days. Light exposure timing also showed higher coherence between school days and weekends during-Covid. Importantly, while interindividual variance in sleep parameters increased during-Covid intraindividual variation did not change, suggesting that increased freedom to choose bedtimes allowed university students to default to their own circadian time and align it better with their social time.

People experiencing homelessness are typically not attending school or are unemployed, and unlike students their circadian and social times are more aligned. In contrast, the main challenge they face is the lack of an appropriate environment for optimal sleep. The homeless population in Seattle also has a variety of sleeping environments. We recorded actimetry and light exposure in homeless adults living in tents, tiny houses, permanent or overnight indoor shelters during the winter and summer. We also recorded this data in adults living in stable housing conditions to compare to the unhoused communities. Our results show that both the timing of sleep and its quality is affected by the homelessness conditions and seasons. We also see a drastic difference in light exposure timing and duration due to the differences in Seattle photoperiod in summer versus winter.

Both of these studies show the impact of the social environment on a persons’ sleep timing and quality.

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Chapter 1. INTRODUCTION

Sleep is a central aspect of animal life and has an effect on both physical and mental wellbeing [1]. Under natural conditions humans are diurnal (day-active) animals with their nighttime sleep lasting a third of their 24-hour day and collectively lasting a third of their lifetime. The timing and duration of these night-sleep bouts can vary day-to-day based on many factors.

Modifications to a person's sleep timing and circadian rhythm affect many physiological processes. Human sleep-wake patterns can be modified by different environmental factors. Among those environmental factors are light and temperature, but geographical location (e.g., urban vs. rural) and environmental conditions including household locations, noise, and safety levels can have an effect on sleep. Social interactions such as school and work can also modify sleep timing, especially in young adults. My research uses a field-based approach in the urban setting of Seattle to understand how altering one's environment can modify sleep patterns.

1.1 REGULATION OF SLEEP TIMING

An individual's sleep timing and duration can be explained by the two-process model of sleep regulation (Figure 1.1). This simple model depicts the interaction between homeostatic sleep pressure and circadian wake propensity [2][3]. Homeostatic sleep pressure (process S) builds while a person is awake, so the longer time spent awake the desire to sleep increases. Circadian wake propensity (process C) is controlled by the body's internal circadian clock and is usually entrained to the 24-hour light-dark (LD) cycle. When the homeostatic pressure reaches its highest point, and the circadian propensity is low enough, the difference between the two will cause a person to fall asleep. Sleep will persist until the homeostatic pressure is at its lowest and circadian propensity is beginning to rise.

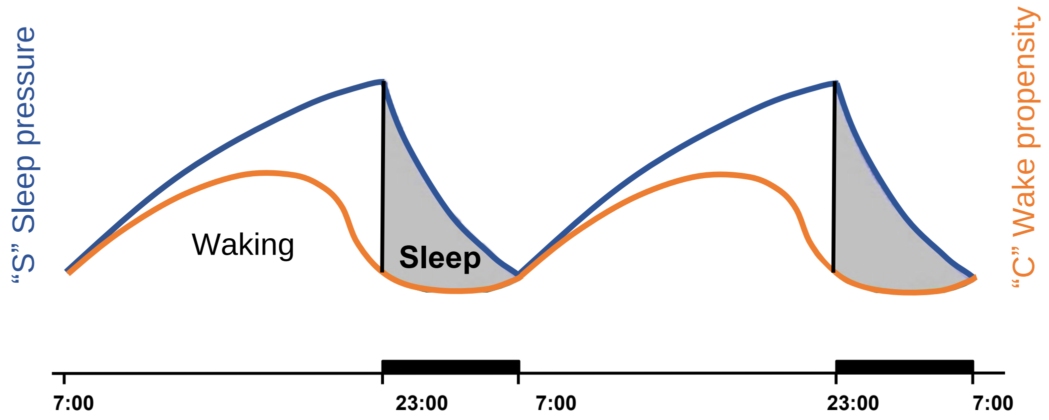

Figure 1.1 Two process model of sleep regulation. The model represents the interaction between the circadian (process C) and homeostatic (process S) processes across 24-hour days. The sleep bout (grey shaded area) begins when the homeostatic sleep pressure (blue line) is highest and the circadian propensity for wake (orange line) is low. The sleep bout ends when circadian wake propensity is rising and homeostatic sleep pressure is at its lowest.

The independent variation of these two processes can affect sleep timing. Changes to the homeostatic sleep pressure slope or changes to the circadian period, amplitude or phase will ultimately affect the timing of their interactions (Figure 1.2). For example, if homeostatic sleep pressure slope is decreased and circadian phase is unchanged, the difference between the two processes that leads to sleep onset will be reached later in time. On the other hand, if circadian phase is advanced or delayed and the slope of process S is unchanged this difference will be reached earlier or later, respectively.

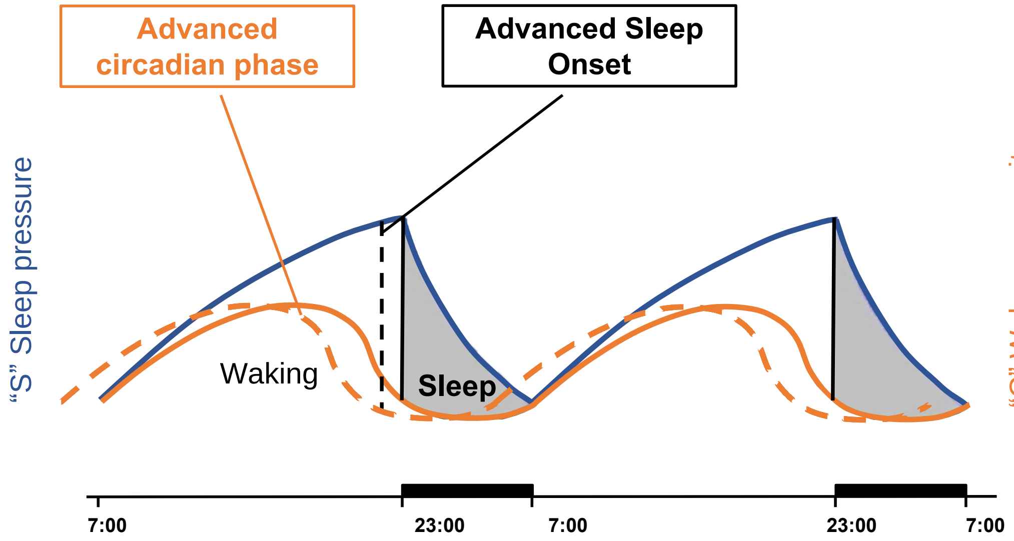

Figure 1.2 Altered two process model of sleep regulation. The model represents an advanced circadian phase (dotted orange line) and unchanged homeostatic process. Due to the advanced circadian phase, sleep onset is advanced, and is illustrated by the black dotted line.

Interestingly, the misalignment between these two processes may lead to disrupted sleep and shortened sleep duration. For instance, jetlag, caused by travel across time zones, can lead to acute changes in process S without changing process C, leading to mistimed sleep until the circadian clock entrains to the new time zone.

Not only does the two-process model of sleep regulation explain the effect of acute environmental changes but it can also explain specific sleep traits. Chronotype, a person's natural inclination to fall asleep and wake up at a certain time of day, can be explained by the interaction between the two processes. "Larks" prefer waking up and falling asleep at earlier times of the day than "night owls", who prefer later sleep onsets and offsets. This can be explained by an earlier circadian phase in larks (Figure 1.2).

These two processes not only affect sleep timing, but they also affect 'sleep architecture'. Two basic types of sleep can be identified: non-rapid eye movement (NREM) and rapid eye movement (REM) sleep. These sleep stages can be detected through electroencephalography

(EEG) and electromyography (EMG) due to their distinctive cortical waves and levels of muscle activity. NREM is characterized by—among other features—high amplitude slow frequency waves, or slow wave sleep (SWS), while REM sleep shows low amplitude and high frequency waves similar to those during wakefulness, but also shows muscle atonia. The sleep architecture defined by the alternation between sleep stages depends on the interaction between the circadian and homeostatic processes. A high homeostatic pressure—typically at the beginning of the sleep bout when process S is high—is characterized by high levels of NREM SWS [4][5]. On the other hand, a high circadian drive to sleep – typically towards the end of the sleep bout when process C is at its minimum – is characterized by high levels of REM sleep. As the night progresses, homeostatic pressure decreases and the circadian influence increases, leading to a decrease in SWS and increase in REM, respectively.

The circadian and homeostatic processes can be altered by environmental and social factors, which in turn alter chronotype and change sleep phase, duration, and quality.

1.2 LIGHT AND SLEEP TIMING

One of the key properties of circadian rhythms is that they are endogenous biological processes. In other words, these rhythms are self-sustained and persist in absence of any environmental cues. The endogenous period of circadian rhythms is close to, but not exactly, to 24-hours. The human circadian clock has a period that is on average longer than 24-hours [6][7][8]. The mismatch between the endogenous (~24-hours) and the environmental (24-hours exactly) creates the need for humans and other organisms to conform to the external 24-hour period of the environment through the process of ‘entrainment’, a second key property of circadian rhythms.

In virtually all species, including humans, the LD cycle is the main environmental cycle that entrains the circadian system. Light can achieve this entrainment via two mechanisms – altering the period of the clock or altering the phase of the clock [9]. In humans, entrainment is typically achieved by daily delays or – more commonly – advances of the circadian phase. Discrete exposure to light exposure is able to cause phase advances or delays depending on the circadian phase at which pulses are presented [9][10][11]. Light exposure in the late subjective night causes a phase advance and light exposure given in the early subjective night causes a phase delay. This in turn effects sleep timing, with evening and morning light exposure delaying and advancing sleep phase, respectively. As stated before, the human circadian period is on average longer than the period of the 24-hour LD cycle. Therefore, humans typically must advance their phase daily to entrain to the shorter 24-hour cycle.

A second mechanism by which light can modify sleep timing is through the regulation of the hormone melatonin. This hormone is released from the pineal gland and the timing of its synthesis and release is regulated by the central pacemaker within the suprachiasmatic nucleus (SCN) in the hypothalamus. As a result, melatonin is only released at night, and acts as a cue for the brain, signaling the timing of the biological night. Evidence also shows that melatonin is acutely inhibited by light [12]. Participants exposed to light in the middle of the night (2am - 4am) had significantly decreased melatonin concentration that rose again one hour after light exposure stopped, showcasing lights' acute effect on melatonin release [13]. Thus, light exposure in the evening is able to delay the onset of melatonin release through both its acute inhibition and by delaying the circadian clock and in turn the melatonin rhythm. Delaying melatonin release at night will in turn delay an important sleep-inducing "nighttime signal" for the brain.

Finally, light has an acute sleep-inhibiting effect on sleep that is, in principle, independent of the delaying effects that evening light has on the circadian pacemaker. Thus, exposure to light in the evening induces alertness and this acutely affects the one's ability to fall asleep and delays sleep onset. This induced alertness is not only achieved by electric light stimulation but also by light-emitting screens [14][15][16].

1.3 NATURAL VERSUS ELECTRIC LIGHT

Both natural and electric light are among the many environmental variables that modify sleep timing. The modernization of society has introduced electrical lighting to lengthen people's evenings and, in turn, delayed sleep timing. A study done in which participants living in Colorado (aged 30.3 ± 8.5 years) compared the dim light melatonin onset (DLMO), offset, and sleep timing after one week where participants were able to maintain their normal daily schedules with exposure to electric evening light and after one week in which they were camping and only exposed to natural light [17]. The DLMO represents not only an accurate measure of the timing of melatonin release but also the gold standard to measure circadian phase [18]. Wright et al. found melatonin onset and offset to be much more aligned to the natural light timing after one week of camping, with ~2-hour melatonin onset advance compared to the electric light group. Not only was melatonin timing advanced, but sleep timing was also advanced under natural light compared to electric light. This group of participants contained both early and late chronotypes when undergoing their normal routines, but chronotypes shifted earlier when in the camping environment. Furthermore, late chronotypes had the most drastic advance in melatonin onset when only exposed to natural lighting. This effect of electric light is not only seen in highly urban societies, but also in more rural indigenous communities.

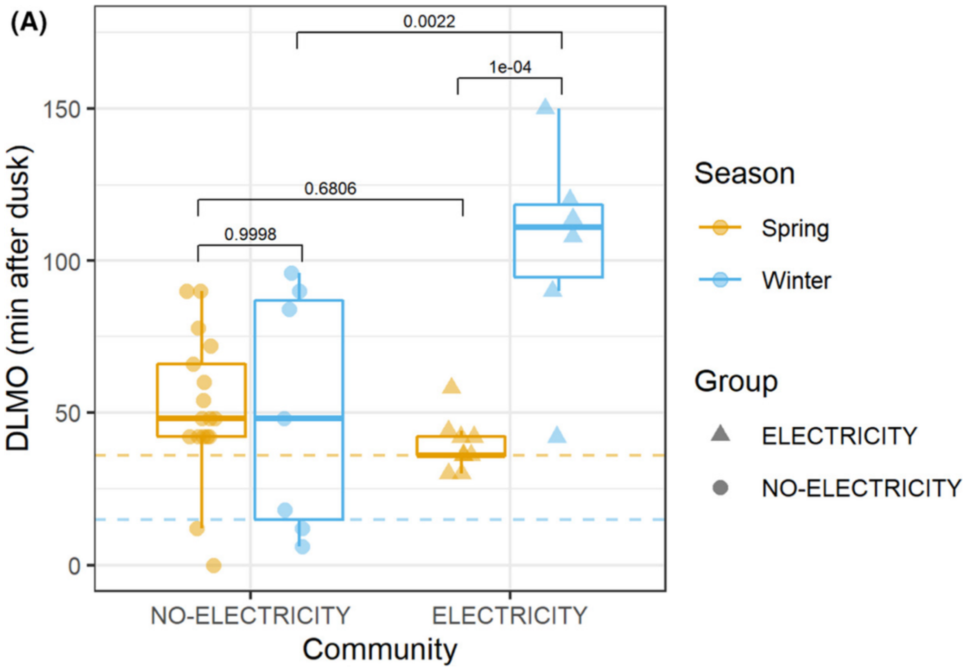

Figure 1.3 Dim-light melatonin onset (DLMO) in Toba communities with and without electricity. Boxplots with points representing the timing of each participant's melatonin onset after dusk measured through salivary samples during spring and winter. Melatonin onset is significantly delayed during winter in the electricity community compared to the no-electricity community. Brackets represent P-values from Tukey's comparisons after linear model fit. (n = 6 & 9 (electricity); 7 & 17 (no-electricity)).

Two communities of hunter-gatherer indigenous Toba/Qom in Argentina were studied by the de la Igelsia lab [19]. Both communities (ages 14-49 years) are genetically homogeneous, but one community has access to electricity and electric light while the other relies on natural lighting. This study examined sleep timing and duration in both communities during the summer and winter for a seasonal comparison, as daylight changes can be around 3 hours between these two seasons. For both seasons, participants with electricity had later bedtimes and sleep onsets with no change to their wake time, which in turn shortened their sleep duration. This effect was slightly smaller in the summer versus the winter, which can be explained by the higher electric light exposure in the community without electricity during this season. Circadian phase between these communities was later assessed using melatonin onset [20]. Melatonin samples confirmed sleep timing results for the winter, as melatonin onset in participants with electricity was delayed (Figure 1.3). This effect was not seen in the longer photoperiod of summer between communities. A similar study was done in Tanna Island, Vanuatu, with two Melanesian communities: one with and one without electricity and electric light access [21]. It was found that the group with electricity had increased exposure to light after sunset and delayed sleep onset. In turn, there was decreased sleep duration in the group with electricity and, interestingly, an increase in the number of naps per day compared to the community without electricity, suggesting an inadequate sleep duration. A recent study on University of Washington undergraduates showed that students had seasonal differences in sleep, with a later sleep timing during the winter and fall relative to spring and summer. Interestingly, the main predictor for the students' sleep phase was their daily exposure to daylight, which is remarkably decreased in fall and winter. The second predictor is their exposure to electric light in the evening, which also increases during the winter [22]. Therefore, daylight is important in entraining the circadian phase and regulating sleep timing, but electric light can interfere with this regulation.

1.4 SLEEP AND THE LUNAR CYCLE

The lunar month is an environmental signal that has generated controversy on whether it could alter human physiology. However, there is considerable evidence to support these claims, such as synchrony between lunar cycles and onset of women's menstrual cycles, suggesting a relevance of moon phases on human reproduction [23]. Moon phases have been shown to regulate behavior and physiology in marine organisms as well as other mammals [24][25][26][27]. As for the circadian relation to the lunar cycle, bipolar patients have been among the human populations analyzed to determine the effects of lunar cycles on sleep. A bipolar male (age 51 years) showed synchrony of his manic-depressive cycles to spring tides – with a period of ~15days – which also corresponded with respective periods of insomnia and polysomnia [28]. Another rapid-cycling bipolar male patient living in Seattle, WA (age 35 years) was studied to their mood and sleep timing corresponded with the moon's phase [29]. The patient's mood cycle synchronized with the 14.8-day spring cycle along with sleep onset and offset times suggesting synchrony to the 24.8-hour lunar day. A retrospective analysis conducted on 17 participants (age 21-31 years) with no mental or physical disorders showed lower subjective sleep quality, less total sleep time, and lower evening melatonin among other measurements around ±4 days around the full moon versus other lunar phases [30]. In contrast, a similar analysis of another sample failed to show a similar association [31]. The modulation of human sleep in association with the full moon was corroborated in a study done by the de la Iglesia lab along with a more precise measurement on the actual days modulation occurred.

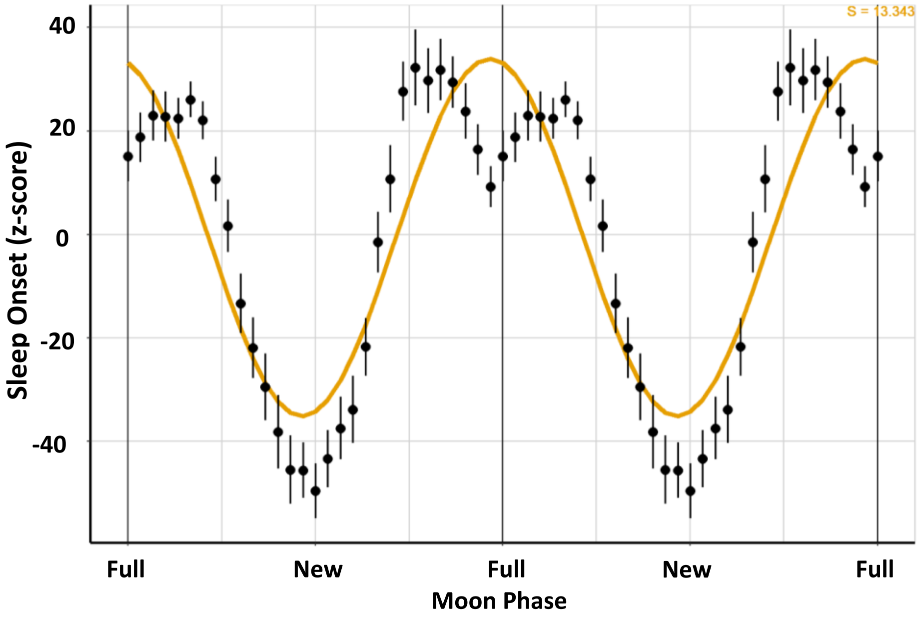

Figure 1.4 Sleep onset of UW undergraduate students is delayed on the nights preceding the full moon. Each point represents the average of sleep onset of all students recorded through wrist

activity over a consecutive 6-week period expressed as z scores. Data is double plotted and solid line represents the best fit sine wave with 30-day period (n = 19).

Our lab conducted an analysis on synchronization of human sleep to the moon cycle in the indigenous Toba/Qom Argentinean communities [32]. Three different communities were studied in order to understand the difference between more urbanized and rural communities: one in an urban setting with full access to electricity, a rural community with limited access to electricity, and another rural community with no access to electricity. It was found that sleep duration and onset were synchronized with the lunar month for all three communities, as sleep duration was lowest and sleep onset latest 3-5 days before the full moon. As expected, sleep duration was shortest and sleep onset latest in the urban community. Importantly, during those few days leading up to the full moon, moonlight is available during the early half of the night, allowing participants to extend their daytime activity similarly to how electric light does in urban environments. In other words, moonlight allowed participants to stay up longer, suggesting that electric light in urban settings mimics the natural effect of moonlight. Surprisingly, this modulation on sleep onset was also shown in undergraduate students living in Seattle, Washington despite the amount of light pollution in the city, making moonlight unlikely to be the environmental signal that influences sleep timing (Figure 1.4). This latter observation, and the presence of 15-day spring tide synchrony in bipolar patients suggests that humans can cue in on gravity changes associated with the lunar month, or other geophysical changes associated with moon gravity [33].

1.5 SLEEP IN ADOLESCENTS AND YOUNG ADULTS

During adolescence, individuals are known to go to bed and wake up at later times of the day, displaying a late chronotype. Chronotype can be measured estimating midsleep timing on weekends, which is considered to be the timing of sleep dictated by the circadian clock and released from social obligations [34]. Chronotype rises developmentally until it is highest around age 17-23 and decreases as we age [35]. Puberty contributes to developmental changes in the homeostatic and circadian regulation processes, and in concurrence with social changes, such as freedom to choose bedtime, these changes lead to later chronotype [36][37]. The circadian process is believed to be altered in two ways: 1) the circadian period appears to lengthen to create a later sleep onset (a study found a significantly longer period in participants aged 9-15 compared to the average period in adults) and 2) adolescents become less sensitive to morning light, which advances the circadian clock and sleep timing [38][39]. Adolescents also have altered homeostatic regulation with decreased accumulation of sleep pressure during wake periods, so they are able to stay awake longer [40][41]. One study tested this hypothesis using a sleep deprivation method and EEG recordings in young adults, as SWS is a marker for homeostatic/recovery sleep, to determine the rate of sleep recovery in adolescents. The sleep deprivation caused the more mature adolescents (Tanner stage 5 – mean age 14.2 years) to have a higher increase of slow wave activity, a quantitative measure of SWS, as well as a slower build-up of homeostatic sleep pressure during the wake period compared to younger adolescents (Tanner stage ½ - mean age 11.9 years)

Late chronotype in adolescents is not only due to biological processes, but also social changes such as reduced parental influence, increased evening social interactions, and late-night media associated with screen exposure. These social pressures create later bedtimes for adolescents, which combined with early school times that demand early rising, create inadequate sleep duration. A study done in the de la Iglesia lab showed the effect of later start times on high school students living in Seattle, WA [42]. With school start times ~1 hour later in 2017 compared to the previous year, students showed similar sleep onset, later sleep offset, and in turn longer sleep duration on school days in 2017, with no differences during weekends. There was also an observation of reduced social jetlag, or measure of difference in sleep timing on school days versus weekends. Typically, students have a misalignment between their circadian clock and their social clock, leading to social jetlag [43]. Compared to free days, sleep during week/school days is much earlier and shorter for adolescents due to social obligations. On weekends, they go to bed later, as dictated by their circadian clock, and make up for the lost sleep by increasing sleep duration.

A study done in Brazil measured social jetlag (difference between midsleep timing on school day compared to weekends) in middle school students attending either morning shift (7:00am – 12:00pm) or after noon shift (12:30pm – 5:30pm) classes [44]. They found not only a significantly decreased social jetlag in afternoon shift vs. morning shift students, but on average afternoon shift students had no social jet lag. This study provided further evidence of how early obligations can lead to insufficient sleep-in students, as it revealed that morning-shift students slept significantly less than afternoon-shift students, who slept ~9 hours on school days, as recommended for adolescents [45]. Finally, afternoon shift students had no difference in sleep duration on school days versus weekends, while morning shift students slept more on weekends. This data suggests that morning shift students are making up for their lost sleep during school days on the weekend, while afternoon students already have adequate sleep duration. In conclusion, modification to social obligations such as delaying school start times show positive effects in young adolescent sleep.

College students include older adolescents and young adults who face the same challenges as young adolescents with social obligations and sleep timing. Through sleep timing and chronotype questionnaires off-campus living undergraduates with early chronotypes showed lower hours of sleep debt (difference in hours of sleep on schooldays vs. holidays) compared to evening and intermediate chronotypes [46]. This suggests college students with evening chronotypes are not getting enough sleep during the school days and making up for that sleep during days when there are no obligations to wake up for. Another study found an average of 30 minutes social jetlag in university students, which was also linked to decreased academic performance, especially in later chronotype students [47]. This is not the only connection to sleep timing and academic performance, as a previous studies found that sleep onset time and day to day variation in sleep duration correlated with class performance [48], and that earlier wake and bedtimes were associated with better academic performance [49].

1.6 SLEEP AND THE COVID-19 PANDEMIC

The Covid-19 pandemic in 2020-2021 lead to many societal changes around the world. One of the major changes was workplaces and schools shutting down and implementing remote work and classes. Specifically for schools, there were both synchronous and asynchronous remote classes. Remote learning eliminated students’ commute to school and allowed for more flexible schedules and ultimately more flexible sleep schedules. The pandemic lead to a plethora of studies on how it affected sleep.

The studies regarding sleep and the Covid-19 pandemic had mixed results – some showing positive results and some negative. Participants 18 years and up living in France (n=1,005) participated in a survey during the pandemic inquiring about sleep problems/trouble sleeping during the pandemic and the use of sleeping aids before versus during the pandemic. The survey results showed 74% of participants reported having sleep problems during the pandemic [50]. Results were also broken down into gender and age, with women and participants <35 years old having more trouble sleeping than opposing groups. When assessing sleeping pill use, only 16% of responders reported sleeping pill use and this showed no significant difference before or after the pandemic lockdown. Another European (Austria, Germany, Switzerland)-based study used surveys to assess how the pandemic and lockdown affected social jetlag, sleep duration, and sleep quality [51]. First, these participants (n = 327 women, median age 26-35 years) showed decreased social jetlag – defined as difference between weekday and weekend midsleep – by 13 minutes during the lockdown. Furthermore, this study used the difference between weekday and weekend sleep duration as another proxy for social jetlag which also decreased during lockdown versus pre-lockdown. Participants' total sleep duration increased about 13 minutes for participants during lockdown. Finally, reported sleep quality during the lockdown increased by 0.25 points on a 0-25-point scale. The results of these two studies are demonstrative of the heterogenous group of results coming from studies surrounding sleep and the Covid-19 pandemic.

Most research regarding the Covid-19 pandemic and how it affected sleep timing and quality present both positive and negative results; however, the majority of studies focusing on adolescent sleep during the pandemic show positive results. Secondary school students (mean age = 12.8 ± 0.4 years) recorded wrist activity (actimetry), daily sleep diaries, and saliva samples for melatonin concentration analysis during in-person learning before classes were became remote [52]. Through the actimetry recordings, researchers found an increased sleep duration by 22 minutes on school days during remote learning compared to in person. Compared to in-person classes, the authors also saw later sleep onset and wake times during remote learning on school day and weekends. When analyzing DLMO, the difference between in person and remote learning DLMO was not significant. Lastly, questionnaires showed lower anxiety and sleepiness during remote learning versus in person. Overall, remote learning showed positive improvements in young adolescent students. A second study using sleep diaries showed that older adolescent high school students displayed later wake times and longer sleep duration on school days after Covid school closures compared to before [53]. This also led to a significantly decreased social jetlag for these students during the remote learning period. Another study on high school students (age 15.9 ± 1.2 years) used actimetry for analysis showing later bedtimes and wake times during school days and weekends during Covid-19 compared to baseline before the pandemic [54]. For these students, sleep duration was also longer on school days, but not on weekends, during the pandemic. The results for these younger adolescent populations show an overwhelmingly positive outcome for school aged adolescents. Overall, these students were able to sleep longer during the school days without the obligation of traveling to school for in-person classes, ultimately decreasing their social jetlag and need to make up for their loss of sleep on the weekends.

College students represent a unique population, different in several aspects form high school students. First, they include both adolescents and young adults. Second, they have more flexibility for scheduling classes and bedtime. Third, their social environment is different to the high school environment. A study done in collaboration with the de la Iglesia lab studied college students living in Boulder, CO prior to and during the Covid-19 stay at home order [55]. These students (n= 139, aged 22.2 ± 1.7 years) completed daily sleep logs that were used to analyze sleep timing. The results were similar to the previous studies on younger adolescents in that college students' school day waketime, bedtime, and midsleep timing were later during the stay-at-home order versus before. Social jetlag was also reduced during the stay-at-home order. These combined findings are considered a positive effect since social jetlag is shown to be correlated with poor health conditions [56][57]. Additionally, this study showed that students who spent a large amount of time in bed (TIB) devoted to sleep during school days before the pandemic decreased their TIB during the pandemic. This was opposite for students who had a shorter TIB before the pandemic. Overall, this study also demonstrated positive effects of the stay-at-home order for older adolescents adding to the argument that adolescents sleep help increased with remote learning.

The previous research showing the effects of the covid lockdown on college students was conducted through sleep diaries, while my study on the covid-19 shutdown was done using actimetry. I used wrist actimeters to record activity of college students attending the University of Washington and living in Seattle, WA (mean age = 23.5 years). This study followed 3 different cohorts of students in 3 different years: pre-shutdown (2019), during-shutdown (2020), post-shutdown (2021). We found that the difference between school day and weekend wake times, midsleep, and sleep duration was decreased during the shutdown compared to other years. We also found that sleep duration on school days was longer during remote learning. Our light exposure recordings further reiterated these findings as there was no difference of light exposure timing in the mornings or evenings between school days and weekends during the shutdown versus the other two years. We also analyzed variation to find that between student variation differed for most sleep parameters, but the within individual variation did not change for any sleep parameters. These results suggest that the increased freedom to choose bedtimes during the shutdown allowed students to default to their circadian timing, but their sleep timing was not reckless day-to-day even with that freedom.

The Covid-19 pandemic brought many negative aspects to the world and negative sleep health for some groups of people. For adolescents, remote learning was the major aspect of change and is seen as negative due to challenges to learning and socializing. Although remote learning did have negative aspects, its impact on adolescent sleep has shown to be positive for students as it commonly showed decreased social jetlag and increased sleep duration. Social jetlag and inadequate sleep duration are common in adolescents due to social obligations such as school start times and are correlated with negative health conditions. Remote learning has shed a light on the importance of adolescence personal sleep timing and sleep health.

1.7 SLEEP AND THE HOMELESSNESS

Homelessness is a rising problem in America. According to the Department for Housing and Urban Development (HUD) on a single night in 2022, 582,500 people were experiencing homelessness in the United States. Specifically, in the Seattle (WA) urban area, HUD reported that in 2020, 11,571 people were experiencing homelessness on any given night. Not having housing has a negative impact on overall health, as people experiencing homelessness (PEH) were more likely to report diseases such as epilepsy, asthma, and chronic obstructive pulmonary disease (COPD) [58]. Although there seems to be an increase of health problems for these people, the resources for their healthcare are limited. The city of Seattle has taken steps aimed at alleviating the homelessness crisis by implementing encampments including indoor shelters, tiny homes, and tent cities. The effectiveness of these housing interventions on the health of PEH have yet to be studied.

Inadequate daily sleep is a salient health disparity for PEH as well as a potential metric for evaluating the impact of homelessness interventions have on peoples' health and wellbeing. Several dimensions of sleep are seen to be affected by homelessness. One aspect being inadequate sleep duration. Two studies found that PEH slept an average of 6.93 and 6.73 hours of daily sleep respectively [59][60]. This short duration was supported by a self-reported survey, where 75% of PEH reported getting less than the 7-9 recommended hours of sleep, with an average of 5.29 hours of sleep a night [61]. Through a survey conducted on people living in an indoor shelter, researchers found an association between reporting 7-9 hours of sleep a night and better self-rated health [62]. People who reported 7-9 hours of sleep had fewer days of reported poor physical health compared to people who reported less than 6 hours of sleep. Furthermore, inadequate sleep duration in PEH lead to unintentional falling asleep during the day [59][63].

The other aspect of inadequate sleep in PEH is sleep quality. A study found two thirds (67.2%) of its adult participants experiencing homelessness met poor sleep quality criteria [64]. Increased poor sleep quality was also associated with self-reported depressive symptoms, poor physical health, chronic health conditions, and loneliness. A second survey-based study found most participants rated sleep quality as "ok" and "poor" [61]. Overall, adults experiencing homelessness reported inadequate sleep on average 11.58 days out of 30 days in one survey and an average of 12.51 days out of 30 days in another [59][60]. Inadequate sleep, whether it is because of its duration or its quality, is linked with physical and mental health problems including cardiovascular disease, diabetes anxiety, pain, and depression [65][66][67][68]. These ailments in turn lead to reduced sleep quality, placing PEH in a positive feedback loop that decreases health and only exacerbates the disparities PEH experience.

In PEH, poor sleep can be attributed to many environmental factors, of which reduced safety and violence seem to be major contributors. When surveying PEH (age 18 or over) 20.6% of participants reported victimization (anyone using violence against you or any member of your family – mugging, fight, sexual assault) since living in the shelter [69]. In this same study, 55.7% of those participants reported witnessing violence in the shelter over the past month. A study in youths (18 - 25-year-old) experiencing homelessness found self-reported perceived safety of sleeping environment was correlated with reported sleep disturbances [70]. The safety of the sleep environment is both a critical determinant of sleep quality and a common concern of PEH. One participant stated "[I'm]...uncomfortable with surroundings, such as in areas around a bunch of people you don't know" (participant 15) and another "...sleeping outside and my surroundings and the people...constantly gotta watch my back" (participant 25) [61].

In summary, homelessness has a substantial negative impact on sleep, worsening any health condition and synergistically reducing overall health. Any strategy to reduce the adverse health outcomes and the health disparities of PEH should necessarily seek to improve sleep as a key outcome. Conversely, monitoring sleep with objective, non-invasive methods, such as wrist actimetry, represents a powerful tool for assessing both the wellbeing of single individuals experiencing homelessness and the effectiveness of specific interventions that politicians implement to combat the homelessness crisis.

Many government programs have been put in place to improve the homelessness epidemic. Specifically, in Seattle, WA different government sanctioned housing environments have been implemented including tiny houses, permanent shelters, overnight shelters, and tent cities. My study on people experiencing homelessness used actimetry to measure sleep timing and light exposure of PEH living in each of these different environments during winter and summer. Though we found no difference of sleep timing between the different environments, we did see a difference in sleep quality through average activity during the sleep bout and sleep regularity index (SRI), which assesses the stability of sleep from night to night. We also compared these measurements to people living in stable housing environments and found these housed individuals to have higher SRI and lower average activity during the sleep bout compared to some homeless environments. These data further reveal the sleep disparities PEH are facing and how drastic they are compared to housed individuals.

Chapter 2. SLEEP IN THE AGE OF COVID-19

2.1 INTRODUCTION

Adolescents have a natural inclination to go to bed later and wake up later in the day than adults and children [35] [37]. There are several proposed mechanisms to explain the late sleep timing in adolescents, with the most prevalent being modifications to the two-process model of sleep regulation [3]. This model presents the interaction between the homeostatic and circadian regulation processes and predicts sleep–wake timing and duration. Puberty leads to developmental changes in both processes, which presumably persist throughout adolescence and young adulthood. First, adolescents can have a longer circadian period [71] [6], which combined with their lower sensitivity to morning light and higher sensitivity to evening light [72], would result on an overall later circadian timing. Second, adolescents have altered homeostatic regulation with decreased accumulation of sleep pressure during wake periods, so they are able to stay awake longer [40] [73]. Third, adolescents and young adults have more autonomy in self-selecting their bedtimes and that combined with evening social and school-work activities contributes to later bedtimes. Although the exact mechanisms behind the delayed adolescent chronotype are still a matter of debate [74], it is clear that adolescents, extending to college students, display a delayed circadian phase and late timing of sleep [47] [48] [75] [76]

The late chronotype—or preference to sleep and wake up at a certain time—of college students leads to later bedtimes while their social responsibilities, like school and work start times, force earlier wake-up times than necessary for an adequate sleep duration. Furthermore, the misalignment between their biological and social timing leads to social jetlag (SJL)—the difference in sleep timing between school days and weekends [77] [34]. SJL is prevalent in university students, whose sleep onset is delayed and sleep duration is lengthened on free vs.

school days [47] [48] [75] [76] [55] [78] [22] . This timing difference has been confirmed in adults by dim light melatonin onset (DLMO), which showed late and moderate chronotypes have a delayed circadian phase on free days compared to workdays [79] [80]. SJL is also present in middle and high school students, and is clearly a consequence of early school times, as it is reduced or abolished by later school start times [44], [42]. Increased SJL is associated with mental and physical health problems as well as reduced academic performance [47] [57] [56], supporting the belief that aligning social responsibilities with the adolescent chronotype should represent a goal to improve health and performance of university students.

During 2020 - 2021, the COVID-19 pandemic led to many changes in society including the implementation of remote learning. Remote learning with both synchronous and asynchronously held classes removed the school commute time and allowed students to have more flexible schedules, changing sleep timing [55]. However, studies on the pandemic's effect on sleep have generated a heterogenous collection of results. While many studies showed improved sleep in the form of reduced SJL, increased sleep duration, and decreased sleep timing variability [51] [81]-[85], others revealed increased sleep disturbance [50] [86]. We analyzed sleep in US university students during the first months of the pandemic and found that the COVID-19 shutdown resulted in later sleep timing on school days and weekends, increased sleep duration in most participants, and reduced SJL [55].

However, our previous study, as well as others addressing sleep changes associated with the COVID-19 shutdown, are limited as they are based on sleep diaries or retrospective questionnaires, most of which are less accurate in assessing the times of sleep onset and offset than wrist actimetry. Although Ong et al. used ring-measured actimetry, this study was not conducted specifically with adolescents and young adults [82]. Furthermore, wrist actimeters can also record light exposure, which could change under social isolation and affect sleep timing. To determine changes more objectively in sleep timing in university students, we measured actimetry-based sleep in a cohort of students taking a class during the fall of 2020 (during-shutdown remote learning), under strict COVID social isolation, and compared it to two other cohorts of students taking the same class and within the same season in 2019 (pre-shutdown), before the pandemic, and in 2021 (post-shutdown) when the class and remaining courses had returned to a predominantly in-person format.

2.2 METHODS

2.2.1 *Participants*

We recorded data from 60 college students at the University of Washington (UW, Seattle, WA) in three separate years. The students were enrolled in the same fall quarter course (late September-early December) led by the same instructor. Activity and light exposure were recorded from 20 students in the pre-shutdown cohort (age range 21 to 26 [mean age = 23.5; 92% self-identified women 38% Caucasian, 15% Asian, 15% Hispanic, 46% other/no ethnicity identified]), 20 students in the during-shutdown cohort (age range 20–41 [mean age = 23.4; 95% self-identified women; 40% Caucasian, 25% Asian, 15% Hispanic, 5% Black, and 15% other/no ethnicity identified]), and 20 students in the post-shutdown cohort (age range 20–35 [mean age = 22.9; 90% self-identified women; 60% Caucasian, 10% Asian, 5% Hispanic, 5% Black, and 20% other/no ethnicity identified]). Pre-shutdown (Fall 2019), 100% of students were attending campus every day and taking all their UW classes in person. During-shutdown (Fall 2020), 10% of students were attending campus every day, 65% were going to campus some days but not every day, and 25% were not going to campus at all (the course from which students in this study were enrolled was fully remote but required students to come to campus once a week for actiwatch data downloads). Post-shutdown (Fall 2021) 40% of students were going to campus every day, 55% were going to campus some days but not every day, and 5% were not going to campus at all (the course from which students in this study were enrolled was hybrid, with an in-person lab and remote option for lectures). A chi-squared analysis of the proportion of students in each category showed a statistically significant difference between years (X2 = 36.05; p = 28.25×10^{-8}). Sleep recordings were done as part of a laboratory practice that included other self-collected biological data, which students received participation credit for recording and analyzing. At the end of the class, students signed an informed consent form for their anonymized data to be used in this or other research studies.

All studies were approved by the Human Subjects Division at UW (IRB Study number 00010431).

2.2.2 *Data Collection*

We recorded each participant's wrist activity and light exposure for 6 weeks pre-shutdown, 8 weeks during-shutdown, and 4 weeks post-shutdown using Actiwatch Spectrum Plus (Phillips, Respironics, Bend, OR), with loggers programmed to collect data in 1-min epochs. Students also submitted daily sleep logs through online forms asking their bedtime, wake time, nap time (if taken), meal (lunch and dinner) times, work/school times (if attended).

We obtained sunset and sunrise data from NASA's Jet Propulsion Laboratory HORIZONS Web-Interface (https://ssd.jpl.nasa.gov/horizons.cgi) with a 1-min precision. Plotted sunset and sunrise times represent the average of sunset and sunrise times for all days of recordings.

All preparation, analysis (including statistical analysis), and plotting of data were performed using R studio version 2022.12.0 + 353, unless otherwise indicated. A p-value of <0.05 was considered statistically significant.

2.2.3 *Inclusion Criteria*

Individual actograms were inspected with Philips Actiware (version 6.0.9) software to check for watch malfunction and that watches were worn an appropriate number of days during recording. Data were separated into school (Sunday 1200 - Friday 1200) and weekend (Friday 1200 - Sunday 1200 and the night before Veteran's Day) nights. During the recording period, students went through the transition of daylight savings time (DST) to standard time (ST); because this transition day was recorded in all three years it was not excluded from the analysis.

In final statistical analyses, students pre- and during-shutdown who missed recordings from more than 14 school days or 7 weekend days were not included. Students post-shutdown missing more than 7 school days, or 3 weekend days were not included in the analysis. Students who were night-shift workers or not residing in Seattle at the time of data collection were also excluded from the analysis. This led to 1 student excluded pre-COVID for missing too many days of recording, 4 students excluded during-COVID (2 students were not in Seattle and 2 students missed too many days of recording), and 6 students excluded post-COVID for missing too many days of recording.

2.2.4 *Sleep Parameters*

Actiwatch recordings were downloaded and exported using the Philips Actiware software. The software estimates sleep parameters including onset, offset, and duration from activity measurements.

Before data analysis, we used sleep duration measurements to detect and disregard outliers. We used the median absolute deviation (MAD) method setting a threshold of 3 MADs, using the Routliers package for R [89] [90]. Twenty-two values determined as outliers were removed from the analysis for any sleep parameter.

2.2.4.1 Statistical Analysis

Each participant's daily sleep events (sleep onset, sleep offset, duration, midsleep) were averaged for school days and weekends separately, leading to two values per parameter per participant. Data were analyzed using a linear mixed effects model (LMEM) using the lme4 package [91]. QQ plots for every LMEM fit were first analyzed to check normality. The model was then run on each sleep parameter separately considering condition (pre-, during-, or post-shutdown) and day type (school day or weekend) as factors and each participant as a random factor. Tukey post hoc comparisons were calculated to determine differences in the sleep parameters between years and day types. Gender was not used as a factor in any of our analysis as overwhelming majorities (≥90%) of participants each year self-identified as women.

To assess differences in interindividual variance of sleep parameters between COVID restrictions we used a Bartlett's test to conduct pairwise comparisons between years for school days and weekends separately, with an α of 0.025 to account for multiple comparisons.

To assess differences in intraindividual variance of sleep parameters between years we calculated the standard deviation of each sleep parameter across all days recorded for each participant irrespective of whether they corresponded to school days or weekends. Then, a one-way ANOVA or Kruskal-Wallis test was used to compare intraindividual variances between years for groups that respectively had homogenous variances or not.

2.2.5 *Light Exposure*

All light exposure data was analyzed using the Actiwatch white-light lux reading. The first and last daily exposure times to a specific light intensity were determined using the 1-minute epoch raw light data for each individual. We analyzed the mean time of the first and last exposure to a 50-lux light intensity for each student separately for school days and weekends. Importantly, 50 lux is not necessarily a circadian threshold for non-visual responses [8],[92], but instead it was chosen as an arbitrary value that would likely be above the threshold for circadian photic stimulation for most of the young adult participants (similar results were seen if 5 and 100 lux were set as the threshold value).

2.2.5.1 Statistical Analysis

Differences in light exposure times between years and type of day were analyzed using a similar LMEM that was used for sleep parameters. QQ plots were inspected, then the model with COVID condition and day type as factors, and participant as a random factor, was run on first and last exposure separately.

2.2.6 *Waveform Analysis*

To determine differences in overall activity and light exposure, raw 1-minute activity and light data for each student was binned into means of 10-min intervals. After 10-min light data were log-transformed, both activity and light were smoothed by a one-hour running average. The resulting data were used to generate individual 24-hour activity and light waveforms for each student and day type. Individual waveforms were in turn used to generate mean waveforms, leading to six light and six activity waveforms (2 school day types x 3 years).

2.2.6.1 Statistical Analysis

To test whether the 24-hour patterns of activity and light exposure differed between school days and weekends, we used, for each condition (pre-, during-, or post-shutdown) a two-way repeated measures ANOVA with day type and clock time as within-participant factors. In cases in which day type (school day vs. weekend) or the interaction was statistically significant, and after visual inspection of the waveforms, we compared the school day vs. weekend activity (or light exposure) during the morning (5:00 - 11:00) or evening (18:00 - 2:00). For this comparison, we added the cumulative activity counts (or lux intensity) for each student within each interval and used paired Student t-test to compare school vs. weekend to test the prediction that activity and light exposure would be delayed on weekends relative to school days.

Time windows for morning and evening analysis were chosen based on visual inspection and the slope of the waveforms. The evening time window was longer than the morning due to the use of electricity in the evening, which decreases the slope of descending activity and light exposure.

Analysis of school day or weekend waveforms between COVID conditions was done using a two-way mixed ANOVA with year as a between-participants factor and time as a within-participants factor. Only the interaction for the light analysis yielded a significant effect, and the morning and evening light exposures within the same intervals defined above were compared between COVID conditions with a one-way ANOVA.

2.3 RESULTS

2.3.1 *Covid stay-at home restrictions and sleep timing between school days and weekends*

Our analysis of actigraphic sleep indicated that during the COVID stay-at-home restrictions students displayed a better alignment between their school day and weekend sleep timing than during pre- and post-shutdown conditions when classes were fully or mostly in-person. Figure 2.1 displays the timing of sleep parameters under different COVID restrictions. We used an LMEM to find associations between changes in sleep and COVID restrictions and Tukey comparisons for post hoc comparisons. Table 2.1 displays results from the type III ANOVA analysis.

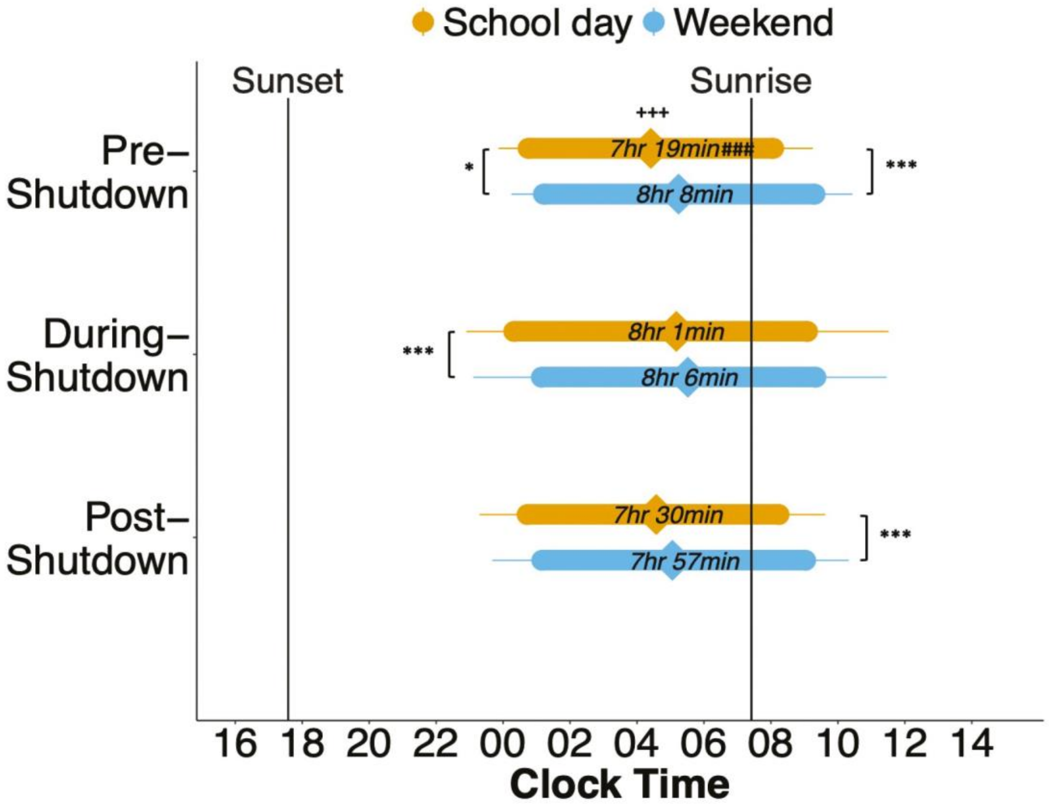

Figure 2.1 Sleep patterns pre-, during- and post-shutdown restrictions. Bar plots of the average sleep duration, onset, and offset. Diamond shapes within the bar plots represent the midpoint of sleep. Sleep plots per year (pre-shutdown [2019], during-shutdown [2020], and post-shutdown [2021]) are displayed separately for school days and weekends. Error bars represent the standard deviation. n = 19 (pre-), n = 16 (during-), n = 14 (post-). Symbols represent the result of post hoc Tukey comparisons between school days and weekend: +++P < 0.001, difference in midsleep; ###P < 0.001, difference in sleep duration; *p < 0.05; ***p < 0.001, differences in sleep onset or offset. Note that the lengths of the bars do not necessarily reflect the duration indicated in hours and minutes because the average duration is not calculated as the

difference between average onset and average offset. See Table 2.1 for linear model statistical results.

Sleep onset showed an effect of the type of day (Table 2.1), but no effect of COVID restriction or the interaction. Pre-shutdown students fell asleep 27 min later on weekends than school days (00:45 ± 53 min and 1:12 ± 58 min, $p = 0.049$). During-shutdown students fell asleep 49 min later on weekends than school days (00:20 ± 1 h 25 min and 1:09 ± 2 h 2 min, $p \leq 1 \times 10^{-4}$), but post-shutdown this difference was not significant (00:44 ± 1 h 26 min and 1:10 ± 1 h 29 min).

Sleep offset showed an effect of the type of day and of the interaction, but no effect of COVID restriction. Students woke up 74 min later on weekends than school days pre-shutdown (8:04 ± 1 h 11 min & 9:18 ± 1 h 8 min, $p = < 1 \times 10^{-4}$) and the weekend delay in wake time was of 48 min post-shutdown (8:14 ± 1 h 24 min and 9:02 ± 1 h 18 min, $p = 2.09 \times 10^{-3}$). In contrast, during-shutdown students woke up at similar times on school days and weekends (9:05 ± 2 h 26 min and 9:20 ± 2 h 7 min, $p = 0.7663$).

Midsleep was delayed on weekends compared to school days but showed no difference between COVID restrictions or an interaction. Pre-shutdown weekend midsleep was 50 min later than school days (4:24 ± 59 min and 5:14 ± 54 min, $p \leq 1 \times 10^{-4}$). In contrast, there was no discrepancy between midsleep times either during-shutdown (5:10 ± 2 h 40 min and 5:30 ± 2 h 15 min, $p = 0.451$) or post-shutdown (4:35 ± 1 h 18 min and 5:03 ± 1 h 23 min, $p = 0.170$).

Students' sleep duration showed a significant effect of type of day and of the interaction but not of COVID restrictions. Pre-shutdown, students slept 50 minutes longer on weekends (7 h 19 min ± 42 min and 8 h 08 min ± 1 h 9 min, $p \leq 1 \times 10^{-4}$). In contrast, during-shutdown (8 h 01 min ± 1 h 17 min and 8 h 06 min ± 1 h 25 min, $p = 0.998$) and post-shutdown (7 h 30 min ± 33 min and 7 h 57 min ± 35 min, $p = 0.251$) students displayed no difference in their sleep duration. Visual inspection of the data (Figure 2.1) suggested longer school day sleep duration during- than pre-shutdown; a student t-test between these two groups yielded a significant difference pointing a bout of sleep that was on average 42 min longer during-shutdown ($t = 2.035$; $p = 0.049$).

Table 2.1 Results for type III analysis of variance for each sleep parameter.

	Fixed effect	**F-Value**	**p-value**
Sleep Onset	COVID condition	$F_{(2,46)} = 0.16$	0.8553
	Day	$F_{(1,46)} = 29.37$	**2.1×10^{-6}**
	Interaction	$F_{(2,46)} = 1.41$	0.2555
Sleep Offset	COVID condition	$F_{(2,46)} = 0.63$	0.5371
	Day	$F_{(1,46)} = 42.00$	**5.5×10^{-8}**
	Interaction	$F_{(2,46)} = 6.36$	**3.6×10^{-3}**
Midsleep	COVID condition	$F_{(2,46)} = 0.55$	0.5800
	Day	$F_{(1,46)} = 22.04$	**2.4×10^{-5}**
	Interaction	$F_{(2,46)} = 1.65$	0.2032
Sleep Duration	COVID condition	$F_{(2,46)} = 0.68$	0.5126
	Day	$F_{(1,46)} = 14.89$	**3.5×10^{-4}**
	Interaction	$F_{(2,46)} = 3.62$	**3.46×10^{-2}**

SJL did not differ under different COVID restrictions (one-way Kruskal–Wallis ANOVA $p = 0.1649$) although it showed the same trend revealed by our LMEM analysis of midsleep (50 min ± 34 min pre-shutdown; 20 min ± 1 h 11 min during-shutdown; 29 min ± 33 min post-shutdown).

Our waveform analysis further supported the general conclusion of increased alignment in sleep parameters between school days and weekends during peak COVID (2020) restrictions. There was an effect of time of day on activity irrespective of COVID condition (Figure 2.2A). There was a statistically significant interaction between time of day and type of day for activity pre-, during-, and post-shutdown. Morning and evening comparisons of activity revealed that pre- and post-shutdown, students were active later during mornings and evenings of weekends than those of school days (Figure 2.2A). In contrast, during COVID the timing of activity was only later in the evening but not in the morning on weekends (Figure 2.2A). The analysis of variance of activity waveforms between COVID restrictions only revealed an effect of time of day both for school days and weekends (Figure 2.2B).

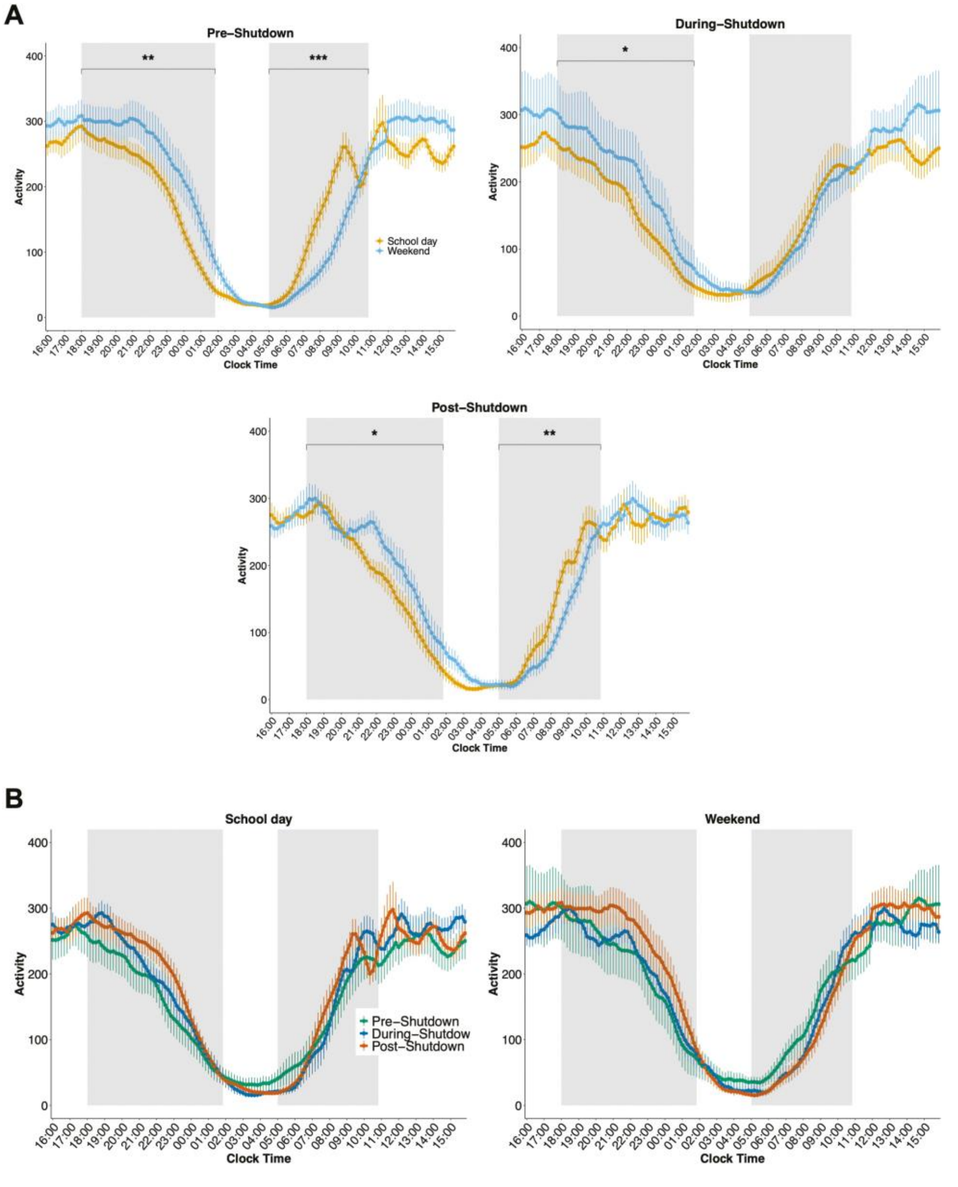

Figure 2.2 Activity waveforms compared between (A) days and (B) COVID restrictions. Dots represent average activity level of students for each time point, split either between days or COVID restrictions, and SEM for error bars on points. Grey shaded areas represent morning and

evening time windows in which cumulative activity was compared between groups. $*p < 0.05$, $**p < 0.01$, paired t-test analysis.

2.3.2 *Covid stay-at home restrictions and interindividual and intraindividual variability in sleep timing and duration*

To determine the degree to which COVID restrictions affected sleep timing choices, we analyzed interindividual variability (Figure 2.3) in sleep timing between COVID restrictions through a Bartlett’s test. On school days (Table 2.2), sleep timing was more variable between participants during-shutdown than pre-shutdown according to all sleep parameters except sleep onset. The increased variance in sleep duration and midsleep during COVID restrictions decreased post-shutdown.

Table 2.2 Interindividual variability in school day sleep parameters under different restrictions. Top values represent the effect size for school day sleep parameters measured as the standard deviation difference between compared years. Negative values indicate that the variability (standard deviation) was lower on the column header than the row header and vice versa. Values in brackets represent Bartlett's test *p*-values (boldface indicates statistical significance). For example, school day sleep offset pre-shutdown was less variable than during-shutdown.

Sleep Onset	Pre-COVID	During-COVID	Post-COVID	**Sleep Offset**	Pre-COVID	During-COVID	Post-COVID
Pre-COVID				Pre-COVID			
During-COVID	0.5319 0.0635 (-)			During-COVID	**1.2528** **4.69x10^{-3}** **(-)**		
Post-COVID	0.5358 0.0703 (-)	0.0038 0.9922 (-)		Post-COVID	0.2103 0.5277 (-)	1.0425 0.0479 (+)	
Midsleep	Pre-COVID	During-COVID	Post-COVID	**Sleep Duration**	Pre-COVID	During-COVID	Post-COVID
Pre-COVID				Pre-COVID			
During-COVID	**1.6872** **1.42x10^{-4}** **(-)**			During-COVID	**0.5770** **1.94x10^{-2}** **(-)**		
Post-COVID	0.3260 0.2695 (-)	**1.3612** **1.33x10^{-2}** **(+)**		Post-COVID	0.1595 0.3419 (+)	**0.7365** **3.81x10^{-3}** **(+)**	

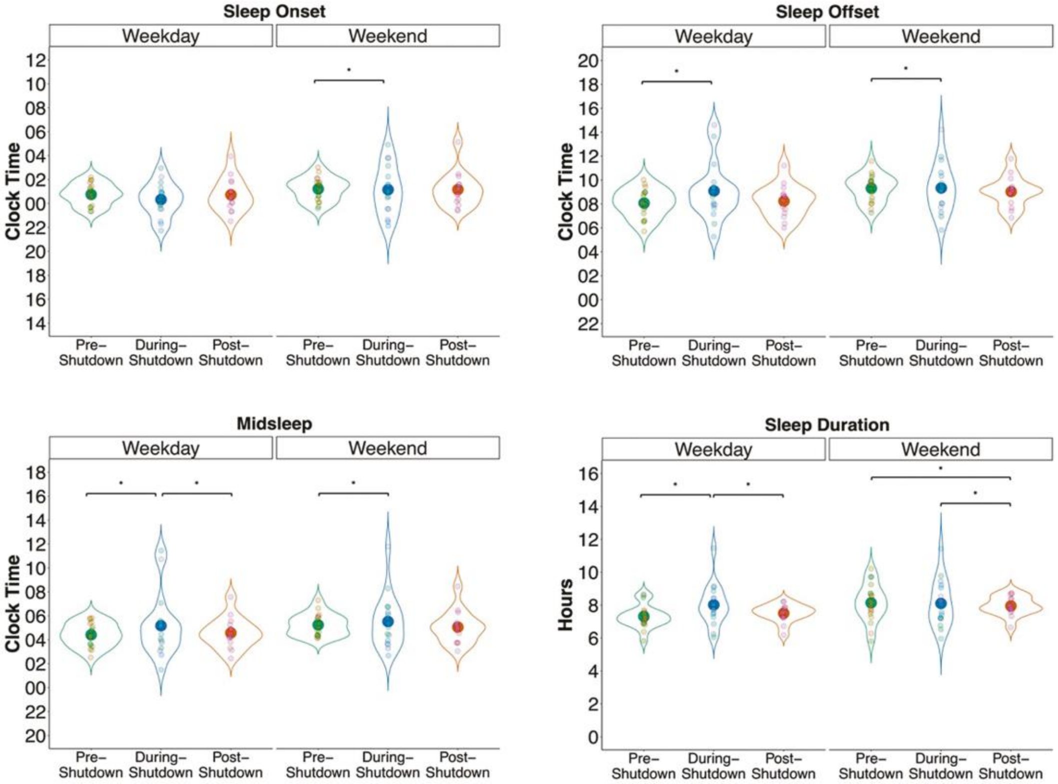

Figure 2.3 Violin plots of sleep onset, sleep offset, midsleep, and sleep duration pre, during, and post-shutdown restrictions. Large points in the middle of the plots represent the overall average for each sleep parameter. Smaller points in the middle of the plots represent individual student values, each color corresponding to a different student. Asterisks represent the results of Bartletts tests: *$p < 0.025$. See Table 2.2 and Table 2.3 for Bartletts test statistical results.

During weekends (Table 2.3), variability between students increased during-shutdown compared to pre-shutdown for all parameters except sleep duration. Sleep duration variability was lower post-shutdown compared to both pre- and during-shutdown conditions.

Table 2.3 Interindividual variability in weekend sleep parameters under different restrictions. Effect sizes and *p*-values are presented as in Table 2.2.

Sleep Onset	Pre-COVID	During-COVID	Post-COVID	**Sleep Offset**	Pre-COVID	During-COVID	Post-COVID
Pre-COVID				Pre-COVID			
During-COVID	**3.52x10^{-3} (-)**			During-COVID	**1.38x10^{-2} (-)**		
Post-COVID	0.0955	0.2543		Post-COVID	0.5999	0.08152	
Midsleep	Pre-COVID	During-COVID	Post-COVID	**Sleep Duration**	Pre-COVID	During-COVID	Post-COVID
Pre-COVID				Pre-COVID			
During-COVID	**4.13x10^{-4} (-)**			During-COVID	0.4062		
Post-COVID	0.0977	0.0813		Post-COVID	**1.56x10^{-2} (+)**	**2.62x10^{-3} (+)**	

As an estimate of the intraindividual variability in sleep timing, we calculated the standard deviation of the mean of each sleep parameter for each individual throughout all recorded days. Comparison of the intraindividual variance did not show differences between COVID restrictions (Figure 2.4, Table 2.4). This result indicates that although students differed more from each other in their sleep timing under the COVID stay-at-home mandate the social isolation did not make the sleep of each individual more variable from day to day. Of note, visual inspection of Figure 2.3 reveals there were two students with highly variable sleep patterns during-shutdown.

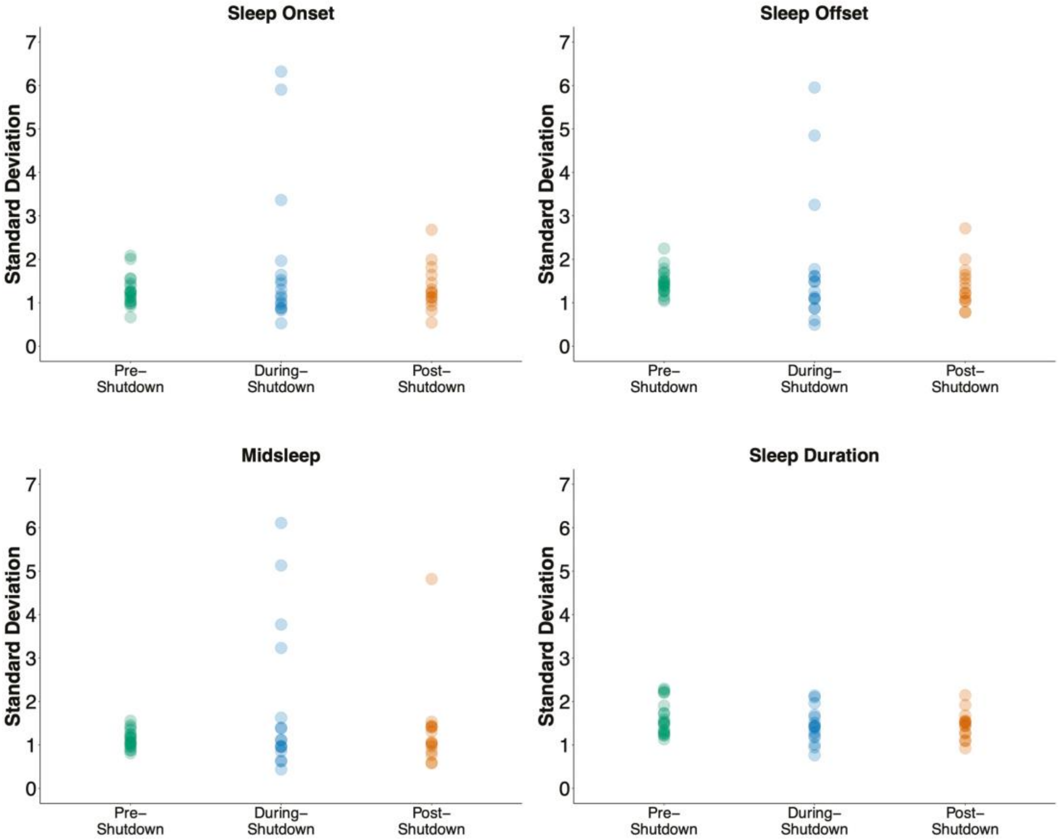

Figure 2.4 Interindividual variation of sleep onset, sleep offset, midsleep, and duration. Each point represents individual student standard deviation (school day and weekend values combined) for each sleep parameter. See Table 2.4 for Kruskal–Wallis and ANOVA statistical results.

Table 2.4 Statistical analyses (Kruskal–Wallis or One-Way ANOVA) for intraindividual variability of sleep parameters.

	Fixed effect	Df	F-Value	p-value
Sleep Onset (Kruskal – Wallis)	Year	2	1.87	0.166
Sleep Offset (Kruskal – Wallis)	Year	2	0.972	0.386
Midsleep (Kruskal – Wallis)	Year	2	2.034	0.142
Duration (ANOVA)	Year	2	1.15	0.326

2.3.3 *Covid stay-at home restrictions and differences in light exposure between school days and weekends*

To determine the time course of light exposure during the day we measured students' first time and last time of exposure to light above 50-lux (Figure 2.5). The 50-lux threshold was chosen as an arbitrary threshold for circadian responses, but similar results were obtained with higher (500 lux) or lower (5 lux) thresholds (data not shown). The LMEM for first exposure to 50-lux light showed an effect of type of day ($F = 18.76$, $p = 7.96 \times 10^{-5}$) and the interaction between type of day and COVID restrictions ($F = 5.07$, $p = 1.03 \times 10^{-2}$). Pre-shutdown, students were exposed to a 50-lux light intensity one hour and 5 min earlier on school days (9:24 ± 15 min) than weekends (10:29 ± 12 min; $p \leq 1 \times 10^{-4}$). The time of the first exposure to 50-lux light did not differ between school days (9:22 ± 23 min) and weekends (9:23 ± 24 min; $p = 1.0$) during-shutdown restrictions, but a 50-min difference reappeared post-shutdown (9:49 ± 1 h 27 min on school days, 10:39 ± 1 h 56 min on weekends; $p = 2.05 \times 10^{-2}$).

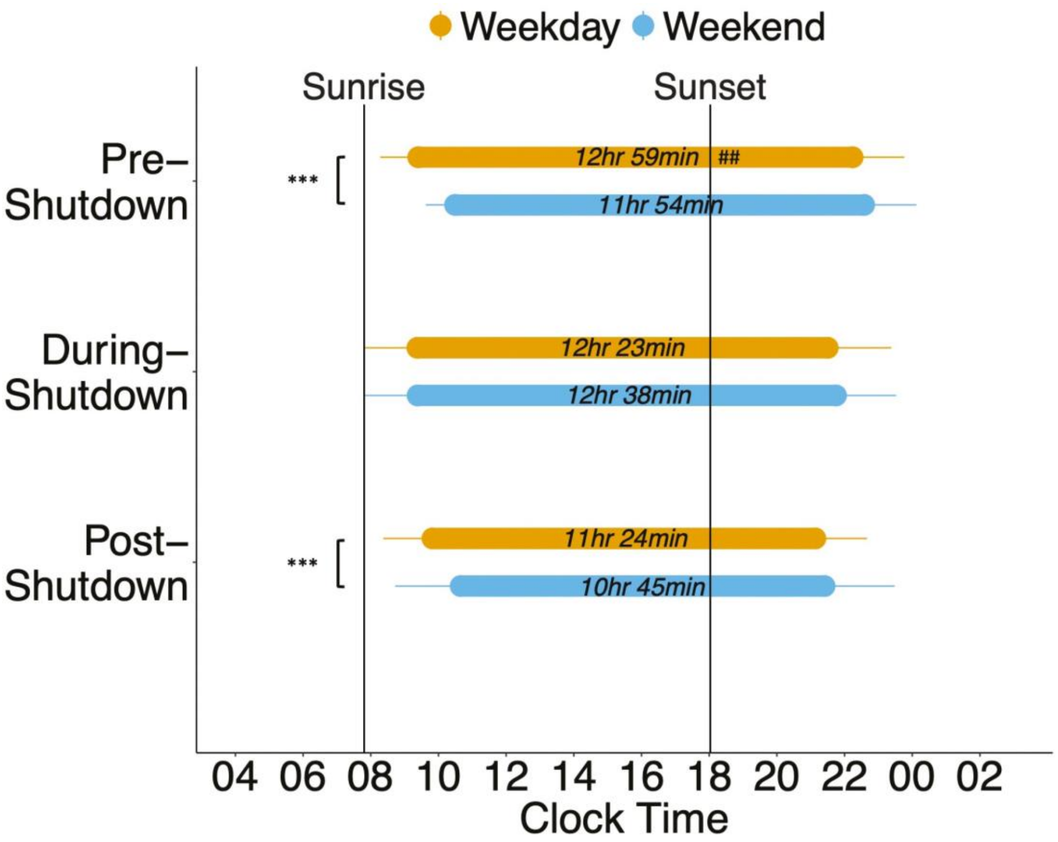

Figure 2.5 Light exposure before and during COVID restrictions. Bar plots of the average time of first exposure to 50 lux, last exposure to 50-lux, and light exposure duration. Years are split (top = pre-shutdown [2019], middle = during-shutdown [2020], bottom = post-shutdown [2021]) with school days and weekends split within each year. n = 19 (pre), n = 16 (during), n = 14 (post). Error bars represent the standard deviation.

The last exposure to 50-lux light showed no significance effect for any factors or the interaction. On the other hand, the daily duration of exposure to at least 50-lux light showed a significant effect of type of day and of the interaction. Pre-shutdown, students were exposed to 50 lux light intensity for about one hour longer on school days than weekends (12 h 59 min ± 1 h 51 min and 11 h 54 min ± 1 h 50 min, $p = 4.09 \times 10^{-3}$). In contrast, exposure duration during-shutdown (12 h 23 min ± 42 min on school days, 12 h 38 min ± 48 min on weekends; p =

0.9620) and post-shutdown (11 h 24 min ± 26 min on school days and 10 h 45 min ± 37 min on weekends; p = 0.3563) did not differ between school days and weekends.

Our waveform analysis of light exposure further confirmed more consistent timing of light exposure between school days and weekends under COVID restrictions (Figure 2.6A). The day of the week did not influence light exposure except under pre-shutdown conditions when students were exposed to lower levels of light during the weekend than during school days (Figure 2.6A). Interestingly, the comparison between school day and weekend waveforms revealed a difference pre- and post-shutdown conditions but not during-shutdown. Pre- and post-shutdown, students were exposed to brighter light during school days than during weekends, both during the morning and evening (Figure 2.6A). These results indicate that the 24-hour profile of light exposure was similar between school days and weekends only for students under strict COVID restrictions.

The waveform analysis comparing different COVID restrictions revealed the expected effect of time of day, and no effect of COVID restrictions except for a trend for exposure to brighter light intensity during school days pre-shutdown compared to the other two conditions (Figure 2.6B). There was an effect of the interaction between time of day and COVID restrictions both during school days and weekends. Further analysis showed that during the weekend mornings, students were exposed to higher light intensities pre- than during-shutdown ($F_{(2,46)} = 4.39$, $p = 0.0179$; $p = 0.0192$ post hoc Tukey comparison).

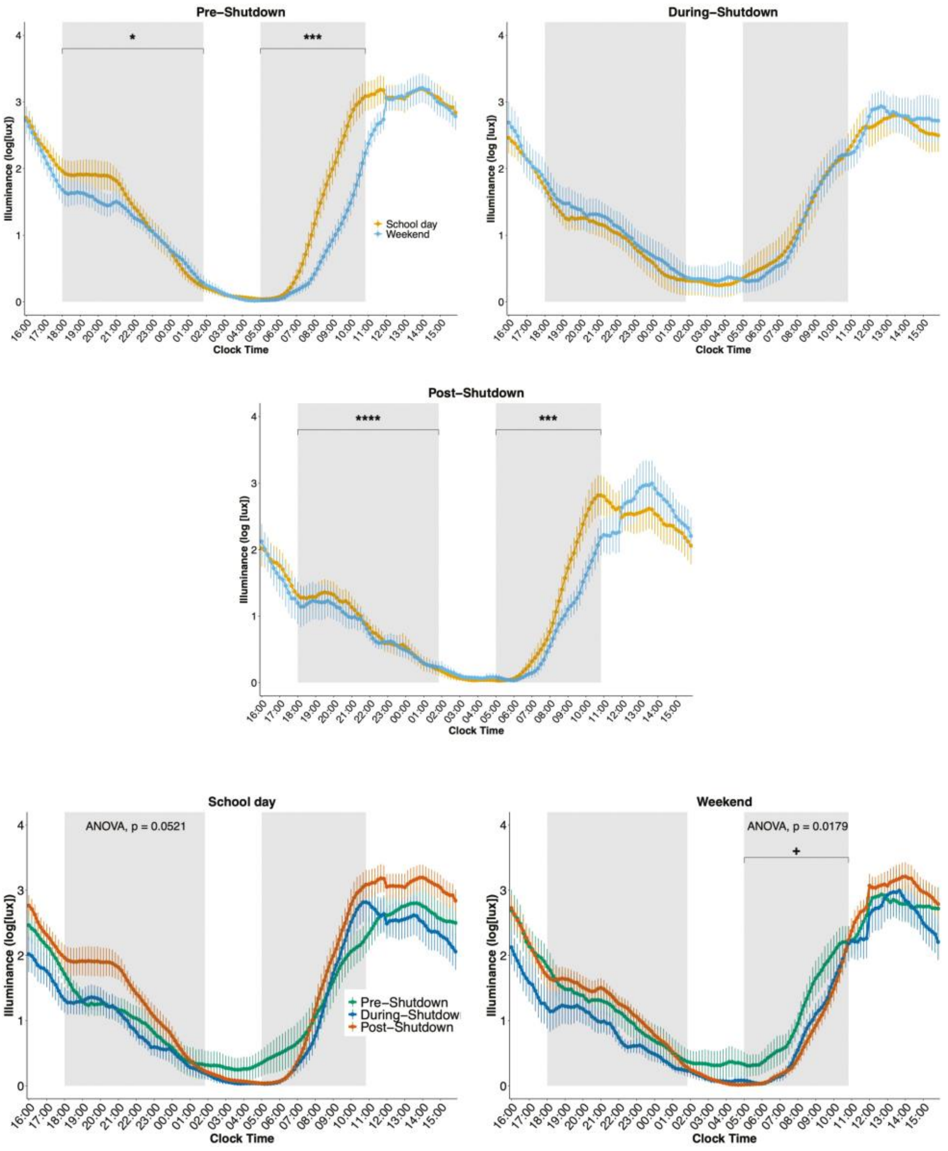

Figure 2.6 Light waveforms compared between (A) days and (B) COVID restrictions. Dots represent average illuminance level of students for each time point, split either between days or COVID restrictions, and SEM for error bars on points. Grey shaded areas represent morning and evening time windows in which cumulative light exposure was compared between groups. *$p < 0.05$, ***$p < 0.001$, paired t-test analysis. +$p < 0.05$ Tukey between pre- and during-shutdown conditions.

2.4 DISCUSSION

In this natural experiment, we observed increased consistency between school day and weekend sleep timing among university students in Seattle, WA learning under remote and hybrid conditions during the 2020 and 2021 fall quarters of the COVID-19 pandemic, as compared to students observed in the fall of 2019. Students pre-shutdown showed differences in timing of all sleep parameters between school days and weekends, while only sleep onset and offset differed during- and post-shutdown, respectively (Figure 2.1). These findings are consistent with the notion that school closures during the COVID-19 shutdown ended the need to commute to campus and allowed university students more freedom to choose their bed and wakeup times. Although some studies reported poorer sleep quality in students during the COVID shutdown [50], [86][88], our actimetry results are consistent with our previously published results, which showed decreased SJL and increased sleep duration in university students during the shutdown [55] through self-reported surveys. This latter result was supported in the current study when the school day sleep duration during the COVID shutdown was compared to pre-shutdown conditions.

Increased SJL is associated with physical and mental health problems [56] [57]. In students, this difference in sleep timing between school days and weekends likely reflects the fact that during school days they are pressed to sleep out of phase with their circadian clock to meet their class schedule, a mismatch that is magnified by the delaying effect that the weekend has on circadian phase [80]. Our finding that the interindividual variability in sleep times increased under the COVID-19 shutdown supports this idea, suggesting that more sleep timing freedom for students led them to consistently sleep at a preferred time, which is likely determined by circadian phase and differs between students. Importantly, the intraindividual variance in sleep timing did not increase during the shutdown, indicating that the increased freedom for bedtime choices did not necessarily result in more erratic sleep patterns, and supporting previous findings indicating that young adults present a stable circadian phase [78], [93]. Together these findings suggest that sleep among teenager and young adult university students may benefit from later school start times or flexible schedules that allow them to choose specific times of instruction and reduce commute time. Alternatively, if earlier bedtimes and waketimes are desired, then adopting and maintaining a consistent wake-sleep/light-dark schedule with exposure to bright light in the morning and dim light in the evening in the home will facilitate earlier sleep times.

Observations of students' light exposures during school days vs. weekends agreed with those of sleep timing results. Pre- and post-shutdown, students showed delayed weekend light exposure in the morning compared to school days, while this wasn't the case during-shutdown (Figure 2.5). This further suggests the COVID-19 shutdown minimized early wakings for classes on school days, so students were able to expose themselves to light with the same timing as on weekends. Because light exposure timing affects sleep–wake timing [94] and a single weekend of changed light exposure is sufficient to change circadian phase [80], [95] the delayed light exposure on weekends pre- and post-shutdown likely exacerbated students' SJL by delaying their sleep timing further. The impact of reduced morning light exposure during the weekend mornings may be particularly detrimental during the short photoperiod and overcast skies of Seattle during the fall quarter [22].

Some studies have found that during the COVID-19 school closures, students reported living more sedentary lifestyles with less interactions [96] [97]. When comparing the daily activity levels of pre-, during, and post-shutdown (Figure 2.2B), we surprisingly found no difference on school days or weekends. Similarly, daily light exposure levels between the COVID conditions did not differ, except for a trend to brighter light exposure on school days pre-shutdown, which can be explained by the fact that students were forced to attend all classes in person.

Some limitations in our study should be noted. First, each condition was measured in different cohorts of students across each year of observation, though students were observed during the same fall course. Our pre-shutdown recordings were concluded before the COVID-19 pandemic and the pandemic could not have been predicted at the time. Second, we did not include gender as a factor in our LMEM, as a majority of participants in all cohorts identified as women, and we had no statistical power to detect gender differences. Third, although SJL has been correlated with reduced academic performance [47] this was not analyzed in our study because expectations and evaluations of course assessments were handled differently during remote learning. Finally, our post-shutdown condition did not represent a return to the pre-shutdown conditions, which may explain why some of the sleep parameters did not return to the values recorded in 2019.

In summary, we found that the COVID-19 shutdown led to better consistency in the phase of sleep and light exposure between school days and weekends, and a longer duration of sleep during school days. As these changes are associated with better health and behavioral outcomes such as decreased obesity, better academic performance, and less depression, our findings support the importance of alignment between circadian/sleep and social timing in adolescents and young adults.

Chapter 3. SLEEP IN PEOPLE EXPERIENCING HOMELESSNESS

3.1 INTRODUCTION

The amount of people experiencing homelessness has reached alarming numbers throughout the world, including highly developed economies like the United States of America (USA). In King County, where the city of Seattle is located, the number of unhoused people has been increasing steadily in the last two decades, and the 2022 Point in Time Count led to the astonishing number of 13,368 unsheltered people [98]. The high incidence of homelessness reveals a crisis in human rights, social justice, and public health, which local governments are trying to alleviate with interventions to reduce the impact of homelessness on each individual's health as well as on the local economy. These interventions include permanent and overnight shelters, tiny houses, and tent cities.

Arguably the biggest challenge that people experiencing homeless (PEH) face is the lack of a proper sleep environment. Indeed, several survey-based studies have shown that PEH report poor sleep quality and quantity, that this disturbed sleep is associated with negative health outcomes, and that specific factors may causally mediate the link between poor sleep and poor physical and mental health [59] [60] [61] [63] [64] [99] [69] [70]. Insufficient and low-quality sleep has a bidirectional relationship with physical and mental disease: poor sleep worsens core symptoms of virtually every physical and mental disorder, and these symptoms decrease sleep quality. Thus, PEH are caught in a vicious circle that is extremely hard to break. A critical goal of any intervention to cope with homelessness should be to improve sleep, which in turn should improve health outcomes. On the other hand, improved sleep should represent a highly reliable metric of success for any intervention. Several studies have specifically used this framework for sleep in PEH. However, they all have two important limitations: 1) they are based on a selfassessment of sleep quality and quantity, and 2) this assessment takes place as a single questionnaire that asks for a retrospective analysis of sleep. Although these methods are sensitive enough to detect rough sleep deficiencies associated with homelessness, they likely lack the resolution to detect smaller differences in sleep timing and quality that may be present between PEH in, for instance, permanent vs. overnight shelters. Furthermore, for PEH in high-latitudes, seasons could potentially have impacts that are obscured in a single-time survey.

In the present study, we sought to address these limitations in what it is, to our knowledge, the first study to use wrist actimetry to objectively measure sleep in PEH. Wrist actimetry represents the gold standard to measure sleep under field conditions, as it is the most objective and quantitative measure of both sleep timing and quality. We report the results from PEH in four different types of homeless settings in the city of Seattle: permanent shelter, overnight shelter, tiny houses, and tent city. Furthermore, because of the large seasonal variation on the influence of the elements at the Seattle latitude, we also compared sleep parameters in the same communities between the summer and the winter.

3.2 METHODS

3.2.1 *Participants*

We recorded from participants living in housed and different unhoused communities all within Seattle, WA. Unhoused community participants were recruited through Seattle based organizations ROOTS and SHARE/WHEEL and housed community participants were recruited through the University of Washington (Seattle, WA) Biology Department. Participant information is included in Table 3.1.

During recruitment, participants signed informed consent forms and each participant was compensated with gift cards weekly based on completion of their daily sleep diaries and wearing wrist actimeters.

All studies were approved by the Human Subjects Division at UW (IRB study number 00005293).

3.2.2 *Data Collection*

All activity and light exposure data was recorded using Actiwatch Spectrum Plus (Phillips, Respironics, Bend, OR) loggers programmed to collect 1-min epochs (except for summer permanent shelter recordings that collected 15-sec epochs). Participants also completed a demographic form in person and daily sleep logs through online forms asking their bedtime, wake time, nap time (if taken), etc. Recording dates for each community are noted in Table 3.1.

Data in two different tiny home locations were collected, but data was pooled for analysis since a preliminary t-test showed no difference in sleep parameter values between locations (midsleep: $p = 0.2444$).

All preparation, analysis (including statistical analysis), and plotting of data were performed using R studio version 2023.06.1 + 524, unless otherwise indicated. A p-value of <0.05 was considered statistically significant.

Table 3.1 Participant Characteristics

	Tiny House (Central District & Northlake)		**Tent**		**Overnight Shelter**		**Permanent Shelter**		**Housed**	
	Winter n = 14	Summer n = 10	Winter n = 9	Summer n = 12	Winter n = 9	Summer n = 10	Winter n = 7	Summer n = 7	Winter n = 14	Summer n = 6
Recording dates	1/23/2023-2/22/2023	9/5/2022-10/17/2022	1/23/2023-2/22/2023	9/5/2022-10/17/2022	2/7/2019-3/6/2019	9/5/2018-10/4/2018	1/23/2023-2/22/2023	9/5/2022-10/17/2022	2/15/2021-4/7/2021	9/26/2023-10/14/2023
Self-Reported Gender (%)										
Female	36	30	33	33	22	10	0	14	43	67
Male	50	70	67	58	67	80	86	71	50	33
Non-binary or transgender	14	0	0	0	11	10	14	14	0	0
Other or missing	0	0	11	8	0	0	0	0	7	0
Self-Reported Race (%)*										
Caucasian	57	60	78	67	0	0	86	86	36	67
Black	35	20	0	56	0	0	14	14	14	0
Asian	0	10	0	0	0	0	0	0	7	17
Hispanic	0	0	0	0	0	0	0	0	35	17
American Indian	14	20	11	14	0	0	14	0	0	0
Other or missing	0	0	11	0	100	100	14	0	7	0
Age (years):	43 [28-60]	48 [31-63]	44 [35-55]	44 [24-65]	22 [19-26]	23 [18-26]	43 [32-58]	44 [26-58]	38 [24-68]	30 [22-58]

mean [range]										
Excluded participants (n)	2	3	3	7	1	0	1	0	0	1

*Participants may have reported more than one race, so total percent could be greater than 100%

3.2.3 *Inclusion Criteria*

Individual actograms were inspected with Philips Actiware (version 6.09) software to check for watch malfunction and that watches were worn for an appropriate number of days during recording. Individual sleep diaries were also inspected and compared to actiwatch recordings. Any dates with more than 3-hour discrepancy in watch determined sleep or wake timing compared to self-reported sleep dairy sleep or wake timing were excluded.

In our final statistical analyses, participants with less than half of the days they were recorded and participants with overnight shift jobs were excluded. The number of excluded participants is included in Table 3.1.

3.2.4 *Sleep Parameters*

Actiwatch recordings were downloaded and exported using the Philips Actiware software. The software estimates sleep parameters including onset, offset, and duration from activity measurements.

3.2.4.1 Statistical analysis

Each participant's daily sleep parameters (sleep onset, sleep offset, sleep duration, and midsleep timing) were averaged for all days, generating one value per participant. Data was analyzed using a linear model on each season (winter or summer) and sleep parameter separately considering gender (female, male, non-binary, and transgender) and sleeping community as factors. The linear model coefficient values were used to compare housed sleep parameter values to all other unhoused (tent, tiny home, permanent shelter, overnight shelter) values.

To assess differences in intraindividual variance of sleep parameters between communities we calculated the standard deviation of each sleep parameter across all days recorded for each participant. Then, we used a one-way ANOVA with community as the factor to compare intraindividual variances between communities. Lastly, a Dunnett's test using the Desctools package was run to compare intraindividual variances of unhoused communities to housed variance [100] .

3.2.5 *Light Exposure*

All light exposure data was analyzed using the Actiwatch white-light lux reading. The first, last, and duration of daily exposure times to a specific light intensity were determined using the 1-minute epoch raw light data for each individual. We analyzed the mean time of the first, last, and duration of. exposure to a 50-lux light intensity for each participant. Importantly, 50 lux is not necessarily a circadian threshold for non-visual responses [8],[92], but instead it was chosen as an arbitrary value that would likely be above the threshold for circadian photic stimulation for most of the participants as previously described [69, 72, [101]].

3.2.5.1 Statistical analysis

Differences in light exposure times between participants in all communities and seasons were analyzed using a linear mixed effects model (LMEM) using the lme4 package [91]. QQ plots for every LMEM fit were first analyzed to check normality. The model was run on each light timing variable (first 50-lux time, last 50-lux time and total duration under 50-lux) separately considering environment (housed, tiny home, permanent shelter, overnight shelter, tent), season (summer or winter), and gender as factors. Tukey post hoc comparisons were used to determine differences in the timing of light exposure between communities and seasons.

3.2.6 *Waveforms*

To evaluate differences in overall activity, raw 1-minute activity data for each participant was binned into means of 30-min intervals. After 30-min data were log-transformed, activity was smoothed by a one- hour running average. The resulting data were used to generate individual 24-hour activity waveforms for each participant. Individual waveforms were in turn used to generate mean waveforms, leading to two activity waveforms per community (one for each season).

3.2.6.1 Statistical analysis

Analysis of summer and winter waveforms between sleeping communities was done using a two-way mixed ANOVA with community as a between-participants factor and time of day as a within-participants factor. We compared community activity during specific time windows during the morning (summer = 7:00-10:00; winter = 7:00-9:00) or evening (summer = 19:00-21:30; winter = 20:00 – 22:00). For these time window analyses, we added cumulative activity counts for each participant and used a one-way ANOVA with community as the factor to compare values between communities. Time windows for morning and evening analysis were chosen based on visual inspection and the slope of the waveforms.

3.2.7 *Sleep Regularity Index*

In order to determine the sleep regularity of participants, we calculated their sleep regularity index (SRI). SRI calculates the percentage probability of an individual being in the same state (asleep vs. awake) at any two time-points 24-hours apart [103] [104] . An individual who falls asleep and wakes up at the same time every day will score a 100 and an individual who is never asleep or awake at the same time every day will score a 0.

3.2.7.1 Statistical analysis

Full recordings of the raw 1-minute activity data for each participant were used to calculate SRI values. SRI data was analysed using a one-way ANOVA with community as the factor and Dunnett's test similarly to the analysis done with the interindividual variance analysis. The ANOVA and Dunnett's tests were run on each season (summer or winter) separately, with the housed community as the control for Dunnett's test.

3.3 RESULTS

3.3.1 *Sleep Timing Between Unhoused and Housed Communities During Summer and Winter*

We compared sleep parameters in each homeless community to sleep parameters in housed individuals during the either the winter or summer. We used a linear model for each season, where coefficient estimates (Table 3.2) with the housed community values were compared to each unhoused community. Figure 3.1 shows the sleep timing of unhoused and housed communities during the summer and winter. During the summer, sleep onset, offset, midsleep, or duration did not show a significant difference between housed and unhoused communities.

During the winter, sleep onset and offset did not show a significant difference of unhoused sleeping communities to the housed winter values. In contrast, midsleep time during the winter did yield a significant difference between housed and the tent community (p=0.0353), with midsleep of participants in tents (5:09 ± 2:11 min) being 1:39 min later than midsleep of housed participants (3:30 ± 48 min). Sleep duration during the winter also showed a difference between housed and several unhoused communities. On average, housed participants slept (8:22 ± 59 min) 1:20 min longer than participants in the permanent shelter (7:02 ± 38 min, p = 0.0420), 1:24 min longer than the overnight shelter (7:02 ± 49 min, p = 0.0006), and 1:10 min longer than participants in tiny houses (7:12 ± 55 min, p = 0.0011).

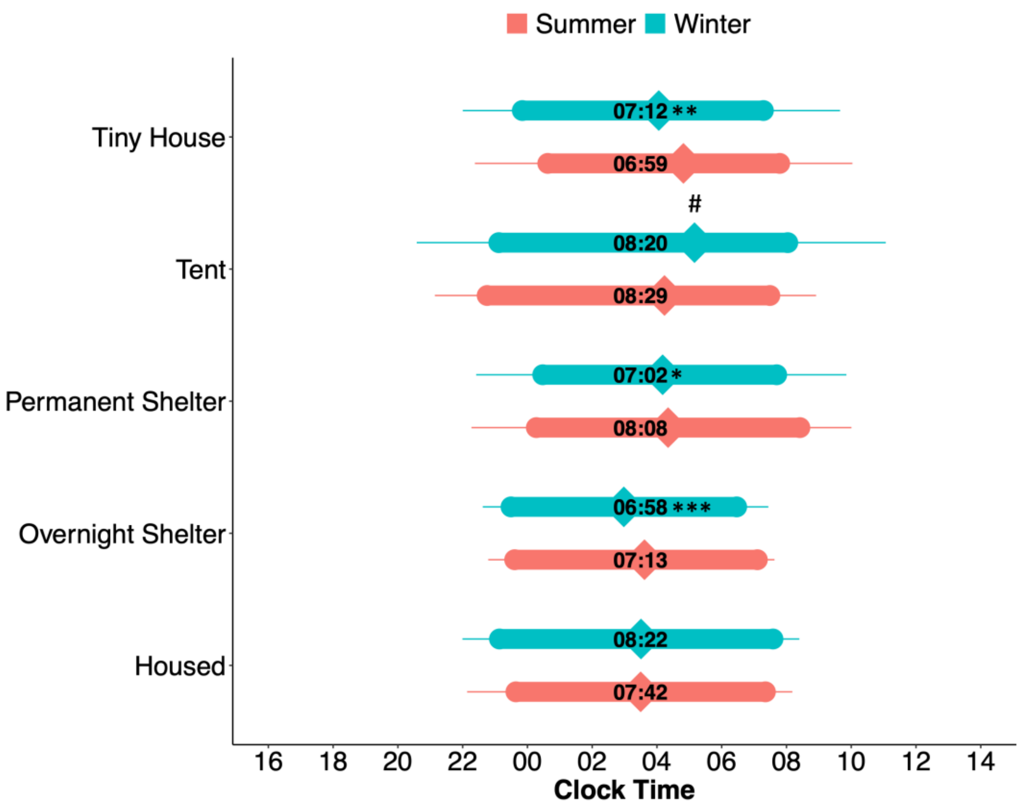

Figure 3.1 Sleep timing in housed and unhoused communities. Bar plots of average sleep onset, offset, and sleep duration. The diamond shapes within the colored bars represent the midpoint of sleep. Sleep plots for each community are split between seasons (summer or winter). Error bars represent standard deviation. Symbols represent linear model coefficient values comparing all unhoused communities to the housed (seasons compared separately): *p < 0.05; **p < 0.01, ***p < 0.001, difference in sleep duration; $^{\#}p < 0.05$, difference in midsleep. Note that the lengths of the bars do not necessarily reflect the duration indicated in hours and minutes because the average duration is not calculated as the difference between average onset and average offset. See Table 3.2 for linear model coefficient results.

Table 3.2 Results of linear model coefficients for each sleep parameter and season

Winter					
	Community (vs. Housed)	**Estimate**	**Std. Error**	**T-Value**	**P-Value**

Sleep Onset	Overnight Shelter	0.2301	0.67861	0.339	0.7365
	Permanent Shelter	1.1268	0.8342	1.351	0.1850
	Tent	0.0364	0.7995	0.046	0.9639
	Tiny House	0.7165	0.6173	1.161	0.2532
Sleep Offset	Overnight Shelter	-1.3287	0.8175	-1.625	0.113
	Permanent Shelter	0.1664	1.0051	0.166	0.869
	Tent	0.4891	0.9632	0.508	0.615
	Tiny House	-0.3844	0.7437	-0.517	0.608
Midsleep	Overnight Shelter	-0.8257	0.6438	-1.283	0.2076
	Permanent Shelter	0.3822	0.7915	0.483	0.6319
	Tent	1.6570	0.7585	2.185	**0.0353**
	Tiny House	0.4346	0.5856	0.742	0.4627
Sleep Duration	Overnight Shelter	-1.4547	0.3891	-3.739	**0.0006**
	Permanent Shelter	-1.0075	0.4784	-2.106	**0.0420**
	Tent	-0.0358	0.4584	-0.078	0.9382
	Tiny House	-1.2549	0.3539	-3.546	**0.0011**
Summer					
Sleep Onset	Overnight Shelter	-0.2114	1.0922	-0.194	0.848
	Permanent Shelter	0.4363	1.1350	0.384	0.704
	Tent	-0.7018	1.1308	-0.621	0.540
	Tiny House	0.9715	1.1274	0.862	0.397
Sleep Offset	Overnight Shelter	-0.7331	0.9398	-0.780	0.442
	Permanent Shelter	0.5857	0.9767	0.600	0.554
	Tent	0.0333	0.9730	0.034	0.973
	Tiny House	0.0833	0.9702	0.086	0.932
Midsleep	Overnight Shelter	0.0945	0.8918	0.106	0.9164
	Permanent Shelter	0.8006	0.9268	0.864	0.3956
	Tent	0.9367	0.9233	1.015	0.3197
	Tiny House	1.41263 0.92055	0.9206	1.535	0.1369

Sleep Duration	Overnight Shelter	-0.8022	0.8809	-0.911	0.371
	Permanent Shelter	0.1321	0.9155	0.144	0.886
	Tent	0.4978	0.9121	0.546	0.590
	Tiny House	-1.0548	0.9094	-1.160	0.257

We also compared the intraindividual variability of sleep parameters across days for each community using a one-way ANOVA with community as a factor followed by a Dunnett's test (Figure 3.2). During the summer, the variability in sleep parameters (Table 3.3) did not show a significant effect of community. During the winter, variability in sleep onset, offset, midsleep, and duration showed a significant effect of community. However, post-hoc comparisons (Table 3.4) did not reveal differences in variability in sleep onset between housed and any of the unhoused communities. On the other hand, the intraindividual variability of sleep offset and midsleep in the tent participants was larger than in the housed participants. Furthermore, sleep duration variability was higher for participants in the permanent shelter, tents, and tiny houses than for housed participants.

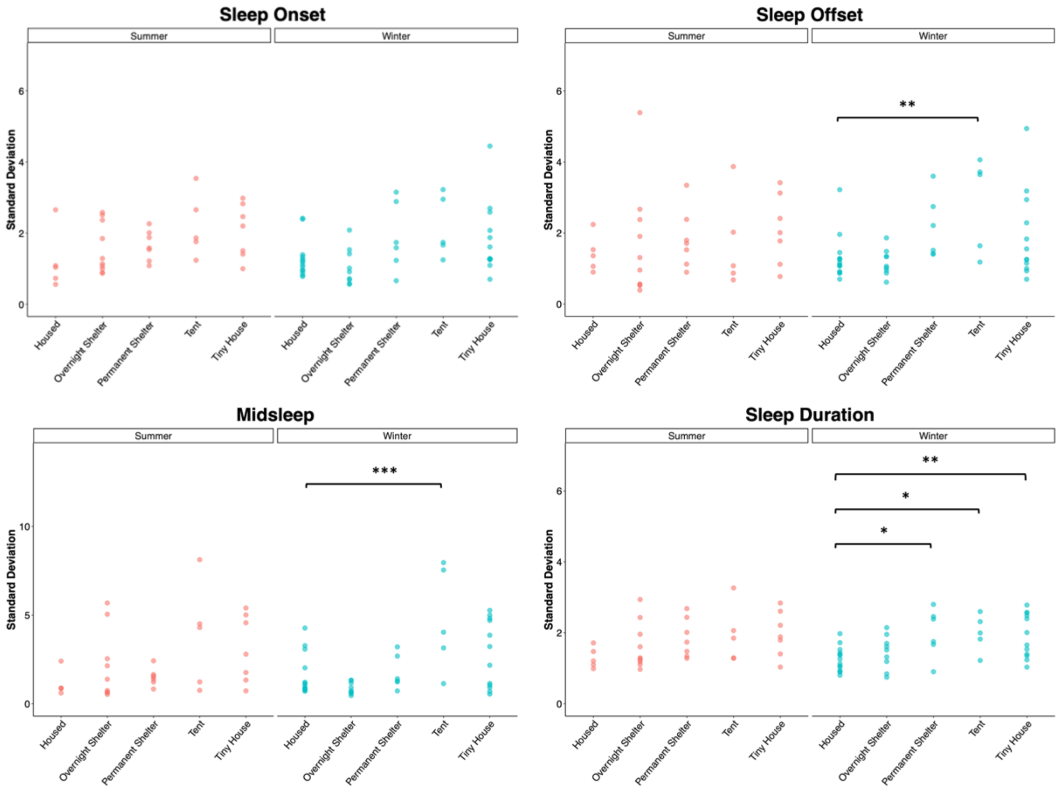

Figure 3.2 Intraindividual variation of sleep onset, offset, midsleep, and duration. Each point represents an individual participants' standard deviation (all days combined) for each sleep parameter. Asterisks represent the results of Dunnett's test: *p < 0.05, **p < 0.01, ***p < 0.001. See supplemental table 1 for ANOVA results and supplemental table 2 for Dunnett's test results.

Table 3.3 One-way ANOVA for intraindividual variability of sleep parameters and seasons

Winter				
	Fixed Effect	**Df**	**F-value**	**P-value**
Sleep Onset	Community	4	2.861	**0.0352**
Sleep Offset	Community	4	3.93	**0.0086**
Midsleep	Community	4	6.344	**0.0005**
Sleep Duration	Community	4	4.482	**0.0043**
Summer				
Sleep Onset	Community	4	1.727	0.171
Sleep Offset	Community	4	0.275	0.892
Midsleep	Community	4	2.131	0.102
Sleep Duration	Community	4	1.221	0.323

Table 3.4 Dunnett's test analysis for intraindividual variability of sleep parameters in winter

Winter		
	Community (vs. Housed)	**P-value**
Sleep Onset	Overnight Shelter	0.9313
	Permanent Shelter	0.3536
	Tent	0.1118
	Tiny House	0.2133
Sleep Offset	Overnight Shelter	0.9933
	Permanent Shelter	0.2105
	Tent	0.0087
	Tiny House	0.2927
Midsleep	Overnight Shelter	0.7095
	Permanent Shelter	0.9974
	Tent	**0.0009**
	Tiny House	0.1646
Sleep Duration	Overnight Shelter	0.8055
	Permanent Shelter	**0.0188**
	Tent	**0.0318**
	Tiny House	**0.0076**

3.3.2 *24-hour Activity Patterns*

Our waveform analysis allowed us to visually inspect activity patterns of each community throughout the 24-hour day (**Error! Reference source not found.**). A two-way ANOVA revealed an effect of time of day ($p = 5.71 \text{ x}10^{-26}$) and the interaction between community and time ($p = 7.66 \text{ x}10^{-17}$) during the summer. Morning and evening comparisons of activity revealed differences in morning activity between communities. Similarly, comparison of activity during the winter yielded an effect of time ($p = 3.96 \text{ x}10^{-21}$) and the interaction of community and time ($p = 4.18 \text{ x}10^{-05}$). Differences in activity levels were found during the morning time window. Visual inspection of the waveforms clearly shows that most of the differences during the morning and evening arise from the high activity levels of participants in the overnight shelter. This morning and evening activity is preceded and followed by rest, respectively, which is a consequence of the strict schedule of the overnight shelter.

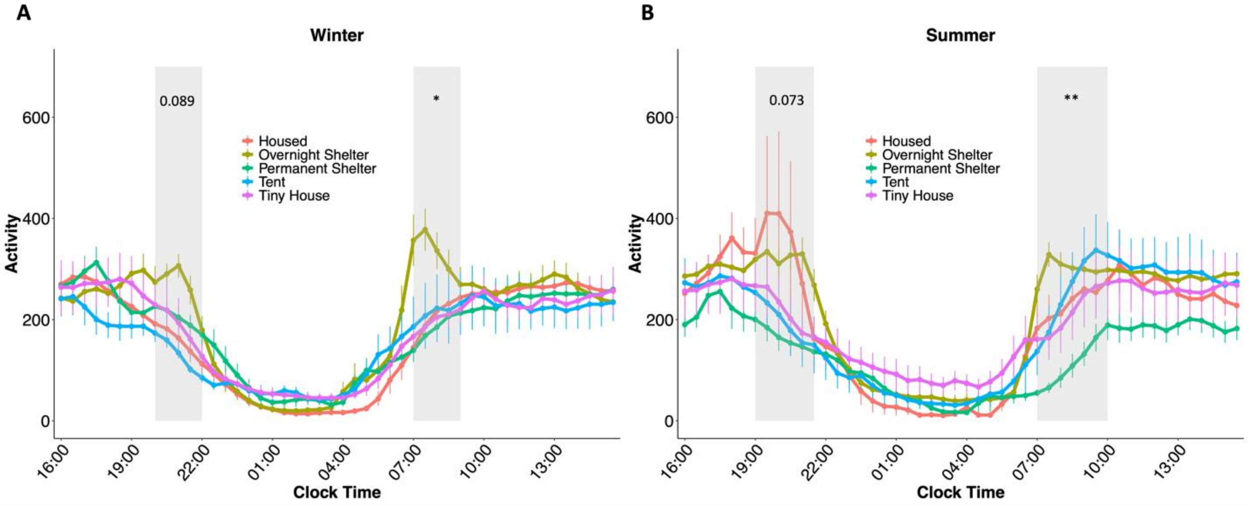

Figure 3.3 Activity Waveforms between unhoused communities in (A) summer and (B) winter. Points represent average activity level of participants for each time point, split between season, and SEM for error bars on points. Grey shaded areas represent morning and evening time windows in which summation of activity was compared between communities. *p < 0.05, **p < 0.01, one-way ANOVA analysis.

3.3.3 *Sleep Quality*

To estimate nocturnal sleep quality, we measured sleep regularity index (SRI) (**Error! Reference source not found.**). We compared SRI between housed and unhoused participants in each season through a one-way ANOVA (Table 3.5) followed by Dunnett's test (Table 3.6). During the summer, there was a significant effect of community; however, Dunnett's tests revealed no differences in SRI between the housed and any of the unhoused groups. Similarly, during the winter, there was a significant effect of community, with housed participants displaying higher SRI (75.86 ± 6.39) than participants in the permanent shelter (58.48 ± 15.09), tent city (50.21 ± 9.83), and tiny houses (59.77 ± 9.91). Although the overnight shelter (73.37 ± 5.92) had a similar SRI value to the housed community, this is most likely an artifact of the strict bedtime schedule of the overnight shelter as opposed to a measurement of sleep quality.

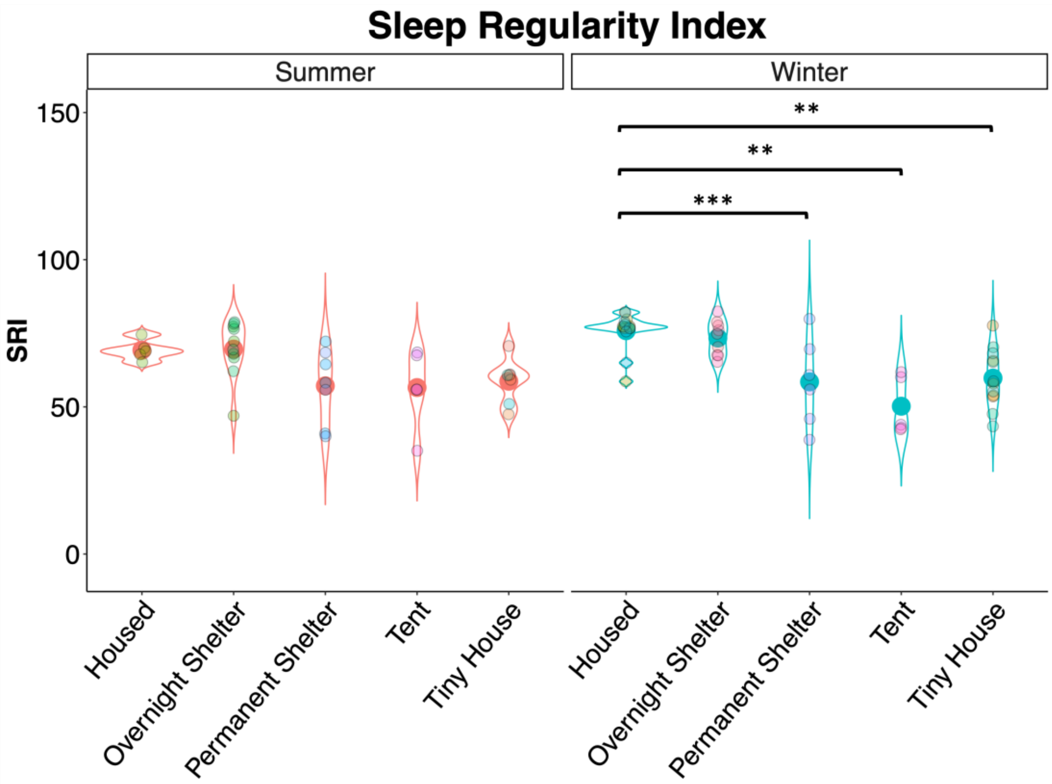

Figure 3.4 Violin plot of SRI with housed and unhoused communities during summer and winter. Large points in the middle of plots represent the overall average SRI. Smaller points in the middle of plots represent individual participant values, each color corresponding to a different participant. Asterisks represent the results of Dunnett's test: **p < 0.01, ***p < 0.001. See table 3 for ANOVA results and table 4 for Dunnett's test results.

Table 3.5 One-Way Anova for SRI in summer and winter

	Fixed Effect	**Df**	**F-value**	**P-value**
Summer	Community	4	2.999	**0.0346**
Winter	Community	4	11.71	**1.97×10^{-6}**

Table 3.6 Results of Dunnett's test for SRI in summer and winter

	Community (vs. Housed)	**P-value**
Summer	Overnight Shelter	1.0000
	Permanent Shelter	0.1387
	Tent	0.1554
	Tiny House	0.2247
Winter	Overnight Shelter	0.9338
	Permanent Shelter	**0.0013**

	Tent	**1.4×10^{-5}**
	Tiny House	**0.0002**

3.3.4 *Light exposure*

To determine the timing of light exposure during the day we measured participants first (morning) and last (evening) time of exposure to light above 50-lux (Figure 3.5). The 50-lux threshold was chosen as an arbitrary threshold for circadian responses. A linear model with mixed effects for first 50-lux light exposure showed an effect of season (p = 0.019), community ($p = 9.83 \times 10^{-05}$), and gender (p = 0.0057). Tent city participants were first exposed to 50-lux light 2 hours and 10 minutes earlier in the summer versus the winter (8:44 ± 1 hour 7 min during summer, 10:54 ± 1 hour 27 min during winter, p = 0.038). The last 50-lux exposure had an effect of season (p = 0.0003) and community ($p = 1.58 \times 10^{-08}$), however pairwise comparisons did not show differences between the seasons for the same communities. The daily duration of exposure to at least 50-lux light showed a significant effect of season ($p=4.729 \times 10^{-05}$), community ($p = 3.904 \times 10^{-09}$), and gender (p = 0.049). The tent community was exposed to 50 lux light 4 hours and 41 minutes more daily during the summer versus winter (10:44 ± 2 hours 13 min during summer, 6:03 ± 3-hours 38 min during winter; p = 0.027). These results reveal that participants in tent city were less isolated from natural photoperiod changes than participants in other communities.

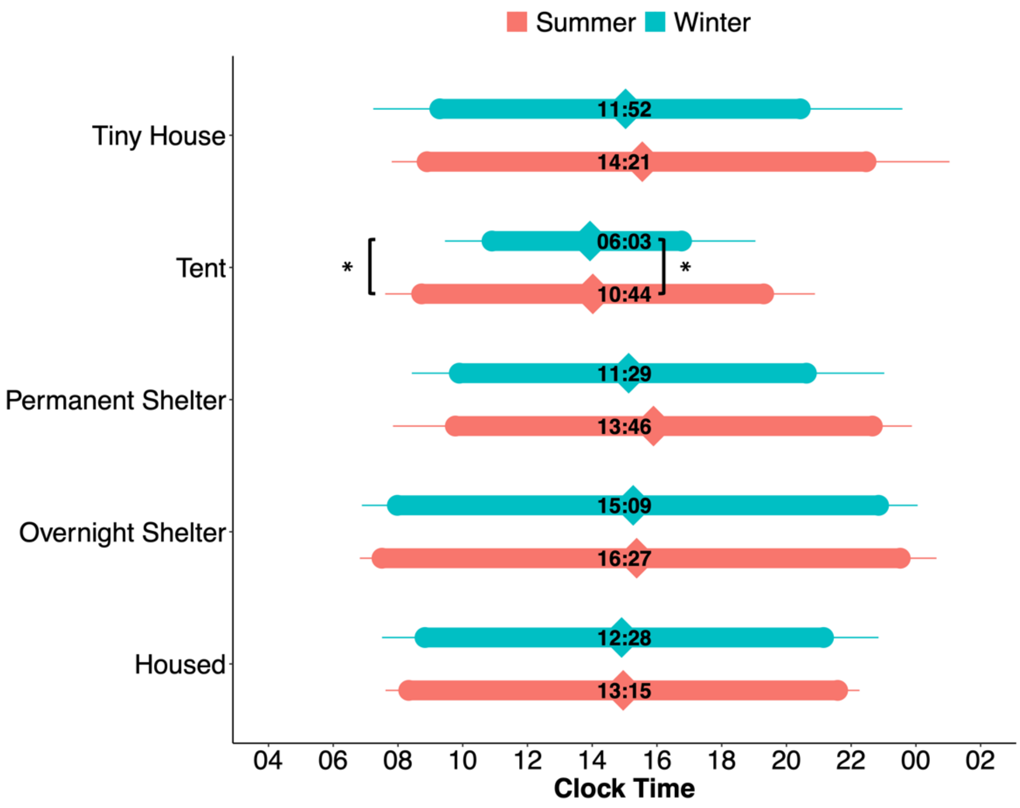

Figure 3.5 Timing of light exposure between communities and seasons. Bar plots of the average time of first exposure to 50 lux, last exposure to 50 lux, and light exposure duration. Communities (tiny house, tent, permanent shelter, overnight shelter, housed) and split with each season (winter and summer) spit within each community. Error bars represent standard deviation. Asterisks represent the results of post hoc Tukey comparisons between summer and winter: **$p < 0.01$

3.4 DISCUSSION

We show that actimetry-based sleep represents a sensitive method to detect differences in the timing and quality of sleep of PEH in different environments. For instance, our data shows that compared to housed individuals, the different homelessness environments have minimal effects on sleep duration during the summer, but large effects during the winter, when participants in some homelessness communities slept up to 1 hour and 20 min less daily than housed participants. These results show that recording actimetry-based sleep represents a non-invasive, objective quantitative method that can reliably assess the effectiveness of any intervention in improving sleep of PEH, which should in turn improve their health and wellbeing.

Although the goal for any community should be that all people experiencing homelessness eventually find stable housing, it is also important to assess the effectiveness of any transitional intervention. Individually recorded, objective sleep data is extremely powerful as a metric for overall wellbeing, but it is critical to place results for each sleep parameter in each environmental context. The recommended sleep duration for the age group in our study is 7-9 hours [102] and housed participants clearly met this recommendation. According to this metric, during the winter participants in overnight and permanent shelters, and in tiny houses met the 7-hour minimum but they all slept much less than housed individuals, although the impact was smaller in tiny houses. Interestingly, tent city participants did not sleep less than housed individuals in the winter, and this leads to the somehow counterintuitive impression that sleep in a tent in the Seattle winter is similar to sleep in a house. On the other hand, tent city participants displayed higher intraindividual variability in their sleep parameters. This result points to the lower day-to-day sleep consistency in tent city, which is consistent with the fact that participants sleeping in tents also had lower SRI. Thus, an apparently healthy sleep duration may not necessarily reveal adequate sleep.

Our analysis did not yield any differences between housed individuals and participants in the overnight shelter. Although this suggests sleep in overnight shelters could be as good as in stable housing, we think this is instead an artifact from the scheduling that permanent shelters have. Actimetry-based sleep has been used as a gold standard for field sleep studies, in which polysomnography is typically —as in the case of homeless communities— not feasible.

Nevertheless, actimetry-based sleep main limitation is that sleep parameters come from a proxy of sleep that is the lack of wrist activity. Even our sleep quality data (activity during sleep and SRI) are based on activity measures. Although actimetry-based sleep has been validated by polysomnography it is likely that the high accuracy that actimetry has in identifying sleep bouts is lost in an environment like an overnight shelter. This type of shelters has a very regimented scheduled for arrival and bedtime as well as for wakeup time and departure. This is clearly shown by our waveform analysis, which reveals peaks of evening and morning activity in overnight shelter participants. Thus, the apparent sleep hygiene that these participants have may simply reveal the fact that their inactivity is strictly enforced. Interviews of some of these participants by our laboratory clearly indicate that their sleep is highly disrupted.

Light exposure revealed large seasonal differences in tent city participants but not in other communities. Seattle has large photoperiod differences between the winter and summer not only due to its latitude that leads to a nearly 8-hour difference in the time between sunrise and sunset between summer and winter, but also because the sky is overcast during the winter. Importantly, at least in housed young adults living in Seattle, the amount of daylight hours is the main predictor for sleep phase [22], and is associated with delayed sleep phase during the winter. This relationship would predict a later sleep phase in tent city during the winter, which is clearly a trend in our results even when the LMEM did not yield a general effect of seasons. A later sleep phase in the winter in the Seattle area is particularly detrimental for people trying to maintain early morning schedules, which would put tent city individuals at a disadvantage relative to other communities.

Some limitations in our study should be noted. First, while the winter recordings clearly reveal a high negative impact of homelessness on sleep we are not able to assess what the major predictors —photoperiod, ambient temperature, precipitation— of poor sleep during the winter are. Second, our housed controls were recorded on the same seasons as PEH, the recordings were not simultaneous. Nevertheless, the differences encountered between housed and unhoused participants were clearly in line with the prespecified hypothesis that housed participants should sleep better. Third, our study does not present any health outcomes that could be accounted for by the differences in sleep between communities. Future, longitudinal studies could assess the predictive value of objectively recorded sleep parameters for health outcomes in PEH.

Sleep and health have bidirectional relationship in which disruption of one leads to disruption of the other. Similarly, improved sleep leads to better health, which is in turn associated with better sleep. Evidence for this relationship has been documented through surveys in people experiencing homelessness [59] [61]. Of note, sleep disparities have lately received attention as a critical factor that perpetuates health inequities. In this context, the current homelessness crisis represents a human societal crisis that is not only exposing people to the inhumane reality of not having stable housing but also to a tremendous sleep and health disparity. Our work shows that the objective measurement of sleep may represent a good instrument to quantify this disparity, to assess the effect of any intervention to reduce it, and to raise awareness about people who experience homelessness.

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