Sleep Health 8 (2022) 311–321

Contents lists available at ScienceDirect

Sleep Health

Journal of the National Sleep Foundation

journal homepage: sleephealthjournal.org

Prior sleep-wake behaviors are associated with mental health outcomes during the COVID-19 pandemic among adult users of a wearable device in the United States

Mark É. Czeisler, AB[a,b,c,d*], Emily R. Capodilupo, MA[e], Matthew D. Weaver, PhD[a,f,g], Charles A. Czeisler, PhD, MD[a,f,g], Mark E. Howard, MBBS, PhD[a,b,h], Shantha M.W. Rajaratnam, PhD[a,b,f,g]

[a] *Turner Institute for Brain and Mental Health and School of Psychological Sciences, Monash University, Melbourne, VIC, Australia*
[b] *Institute for Breathing and Sleep, Austin Health, Melbourne, VIC, Australia*
[c] *Department of Psychiatry, Brigham & Women's Hospital, Boston, MA, USA*
[d] *Francis Weld Peabody Society, Harvard Medical School, Boston, MA, USA*
[e] *WHOOP, Inc., Department of Data Science and Research, Boston, MA, USA*
[f] *Division of Sleep Medicine, Harvard Medical School, Boston, MA, USA*
[g] *Division of Sleep and Circadian Disorders, Departments of Medicine and Neurology, Brigham & Women's Hospital, Boston, MA, USA*
[h] *Division of Medicine, University of Melbourne, Melbourne, VIC, Australia*

ARTICLE INFO

Article History:
Received 26 July 2021
Revised 3 March 2022
Accepted 3 March 2022

Keywords:
Coronavirus
Anxiety
Depression
Substance use
Wearable
Epidemiology

ABSTRACT

Objectives: To characterize objective sleep patterns among U.S. adults before and during the COVID-19 pandemic, and to assess for associations between adverse mental health symptoms and (1) sleep duration and (2) the consistency of sleep timing before and during the pandemic.
Design: Longitudinal objective sleep-wake data during January-June 2020 were linked with mental health and substance use assessments conducted during June 2020 for The COVID-19 Outbreak Public Evaluation (COPE) Initiative.
Setting: Adult users of WHOOP—a commercial, digital sleep wearable.
Participants: Adults residing in the U.S. and actively using WHOOP wearable devices, recruited by WHOOP, Inc.
Intervention: The COVID-19 pandemic and its mitigation.
Measurements: Anxiety or depression symptoms, burnout symptoms, and new or increased substance use to cope with stress or emotions.
Results: Of 4912 participants in the primary analytic sample (response rate, 14.9%), we observed acutely increased sleep duration (0.25 h or 15 m) and sleep consistency (3.51 points out of 100) and delayed sleep timing (onset, 18.7 m; offset, 36.6 m) during mid-March through mid-April 2020. Adjusting for demographic and lifestyle variables, participants with persistently insufficient sleep duration and inconsistent sleep timing had higher odds of adverse mental health symptoms and substance use in June 2020.
Conclusions: U.S. adult wearable users displayed increased sleep duration, more consistent sleep timing, and delayed sleep onset and offset times after the COVID-19 pandemic onset, with subsample heterogeneity. Associations between adverse mental health symptoms and pre- and mid-pandemic short sleep duration and inconsistent sleep timing suggest that these characteristics warrant further investigation as potential modifiable mental health and substance use risk factors.

Introduction

Absent widespread testing or safe and effective coronavirus disease 2019 (COVID-19) vaccines in early 2020, stringent mitigation policies (eg, stay-at-home orders, business closures) were implemented in the United States and globally to contain severe acute respiratory syndrome coronavirus 2 (SARS-CoV-2), the virus that causes COVID-19. Among the consequences of these measures were enhanced opportunities for the self-selection of sleep habits, resulting from work-at-home directives, reduced travel and commutes, school closures, and stay-at-home orders. Recognizing this opportunity, and the value of sleep health during an interval of profound

*Corresponding author: Mark É Czeisler, AB, Francis Weld Peabody Society, Harvard Medical School, 25 Shattuck St, Boston, Massachusetts, 02115.
E-mail address: mark.czeisler@fulbrightmail.org (M.É. Czeisler).

https://doi.org/10.1016/j.sleh.2022.03.001
2352-7218/

disruption, the National Sleep Foundation published a Position Statement urging the public to follow healthy sleep habits and maintain regular sleep-wake schedules during the pandemic.[1]

Survey data[2-6] and longitudinal wearable or mobile application data[7-12] have been used to report increased sleep duration and delayed sleep timing during the pandemic in the U.S. and other countries. More than half of 6882 participants from 59 countries who completed online surveys conducted during mid-April to early May 2020 reported that they had delayed their sleep timing, according to a study published by Yuksel et al. in *Sleep Health*.[2] Similarly, among approximately 1000 survey respondents in Argentina, Leone et al. found that participants slept longer and later on weekdays during the initial phase of Argentinian COVID-19 lockdowns compared with before the pandemic, and exhibited lower levels of social jetlag.[3] Using wearable data, a *Sleep Health* publication by Rezaei and Grandner revealed similar changes to the trajectories of sleep duration and timing among 163,524 active Fitbit users from 6 major U.S. cities.[7] Additionally, analysis of objective smartphone application users from 5 major metropolitan areas across 4 countries by Robbins et al. found that estimated sleep duration increased across regions. The authors observed a 14-minute increase in estimated sleep duration in March 2020 as compared with March 2019, and a 22-minute increase when comparing April 2020 with April 2019.[8]

Simultaneously, population-level surveillance studies revealed considerably elevated levels of adverse mental health symptoms and substance use among U.S. adults, including 3-4 times the prevalence of anxiety and depression symptoms and twice the prevalence of suicidal ideation in the second quarter of 2020 as compared to that of 2019.[13-15] Adverse mental health symptoms were disproportionately reported by younger adults, unpaid caregivers, essential workers, and persons with psychiatric or substance use conditions.[16]

Associations between mental health and multiple dimensions of impaired or insufficient sleep have been well-established,[17-19] underscoring the importance of examining different sleep characteristics to inform strategies and interventions to improve population-level sleep health and patient-level clinical care. For example, evidence from the 2018 Behavioral Risk Factor Surveillance System data including 273,695 U.S. adults aged 18-64 years found that participants with an average sleep duration ≤6 h nightly had 2.5 times (95% CI, 2.3-2.7) the odds of frequent mental distress compared with individuals who slept >6 h nightly.[20] Separately, adjusting for sleep duration, a study of 451,025 individuals using multiple Mendelian Randomization techniques found robust evidence supporting early diurnal preference as protective for depression and wellbeing.[21] Poor sleep quality, including sleep disorders and sleep disturbances, commonly co-occurs with mental health conditions.[22] Finally, relationships between inconsistent sleep timing and adverse mental health are increasingly recognized, including with mood disorders, depression, wellbeing, and cognitive function.[23-26]

Indeed, during the initial phase of the COVID-19 pandemic, links between poor sleep and adverse mental health symptoms have been reported based on survey data,[2,4,27-29] with poor sleep associated with anxiety and depression symptoms.[2] However, most surveys have limited resolution of sleep-wake measurement (eg, daily logs or cross-sectional surveys vs 30-second epochs) and lack prepandemic data. Moreover, sleep health has several dimensions (duration, timing, quality, regularity) linked with mental health,[19] and published studies during the pandemic have not included measures of variability in sleep timing, which has been associated with depressed mood[23,25] and other adverse health outcomes.[30,31]

To address these knowledge gaps, we examined objective sleep and mental health among U.S. users of a sleep wearable (WHOOP, Inc., Boston, Massachusetts) before and during the COVID-19 pandemic using comprehensive sets of mental health (symptoms of anxiety or depression, burnout, and substance use to cope with stress or emotions) and sleep variables (duration, sleep onset, sleep offset, consistency of sleep timing, and wakefulness during time in bed). We characterized multiple dimensions of sleep before and during the pandemic and explored associations between mental health and (1) sleep duration and (2) consistency of sleep timing. Regarding sleep patterns overall, given prior survey and wearable data on various samples during the pandemic, we hypothesized that during as compared with before the pandemic, participants would exhibit acutely increased sleep duration, delayed sleep timing, and increased sleep consistency, without reduced sleep efficiency. Regarding sleep and mental health, we hypothesized that reduced sleep duration and lesser sleep consistency would each be associated with anxiety or depression symptoms, new or increased substance use, and burnout symptoms.

Participants and methods

Study design and participant details

U.S. WHOOP users aged ≥18 years who had recorded 7 consecutive nocturnal sleep episodes prior to a prospective invitation were invited to participate in Internet-based surveys during June 24-30, 2020. The week was selected to align with a similar largescale, national survey administered through The COVID-19 Public Evaluation (COPE) Initiative to a demographically representative sample of U.S. adults.[15] Participants provided informed electronic consent prior to enrollment and agreed to allow their deidentified wearable data to be used for research purposes, as outlined in the WHOOP, Inc. Terms and Conditions. Investigators received anonymized survey responses, which were linked with wearable data using unique identifiers. The Monash University Human Research Ethics Committee reviewed and approved the study (#25280).

WHOOP measures

For this analysis, objective WHOOP variables included sleep duration in hours over 24 h intervals (calculated as the sum of nocturnal sleep episodes plus nap sleep episodes, detected automatically or manually[32]), sleep consistency (a proprietary metric of the WHOOP platform adapted from the Sleep Regularity Index [SRI][31,33] for daily use by accounting for recency in weighting of comparator sleep-wake episodes), sleep onset and offset, and wakefulness during time in bed (calculated as the difference between time in bed and time asleep, which is equivalent to sleep latency plus wake after sleep onset [WASO]). The WHOOP sleep consistency measure, like the SRI developed by Phillips et al.,[33] calculates the percentage of concordance of individuals being in the same state (asleep vs. awake) at different timepoints. Whereas the SRI compares 2 timepoints 24 h apart, WHOOP sleep consistency compares 24 h timepoints over a 4-day interval (eg, timepoint 1 [T1], T1 + 24 h, T1 + 48 h, T1 + 72 h), with comparisons of intervals further apart assigned progressively lower weights in calculating sleep consistency scores for a given timepoint.[34] Scores are converted to a 0%-100% scale, with higher consistency scores reflecting lower sleep timing variability.

Naps were included within 24 h sleep measures to avoid erroneously categorizing individuals with comparatively more nap sleep duration during versus before the pandemic as having slept less on the basis of relatively decreased nocturnal sleep duration, especially given evidence of increased frequency of napping during the pandemic.[6]

Three performance evaluations of objective measurement of sleep by WHOOP wearables have been published.[32,35,36] Among 6 young, healthy participants, compared with polysomnography, both autodetected and manually entered WHOOP sleep measurements demonstrated high levels of agreement for 2-stage (sleep vs. wake) categorization, at 86% and 90%, respectively.[31] Among 12 young, healthy adults, compared with polysomnography, total sleep time recorded by WHOOP did not differ significantly (WHOOP mean, 358.7 ± 98.5 m, polysomnography mean, 350.4 ± 105.2 m, mean difference, 8.2 ± 32.9 m, P = .54). For 2-stage categorization, WHOOP demonstrated high levels of agreement with polysomnography and sensitivity to sleep (89% and 95%, respectively), and moderate specificity for wake and Cohen's kappa for chance-adjusted agreement (51% and 0.49, respectively).[35] Finally, among 32 young, healthy participants, WHOOP demonstrated low bias and precision errors (13.8 m and 17.8 m, respectively) for measuring sleep duration compared with polysomnography, and recorded a moderate intraclass correlation coefficient (0.67 ± 0.15).[36]

Survey instrument

The survey instrument was developed for The COPE Initiative (www.thecopeinitiative.org). Similar versions of the survey have been administered to adults in the U.S. and Australia to assess public attitudes, behaviors, and beliefs about the COVID-19 pandemic and its mitigation,[14] and to assess mental and behavioral health.[15,28]

Demographic variables included in this analysis were age, sex, combined race and ethnicity, U.S. Census region, 2019 household income, highest education attainment, employment status, unpaid caregiver role, and political ideology. Age and sex were input upon WHOOP user registration. Age was categorized for the analysis as 18-29, 30-44, 45-64, or 65-plus years. Sex options were female or male. Within the survey, demographic variables included race and ethnicity (assessed separately and analyzed in the combined categories of non-Hispanic White, non-Hispanic Black, non-Hispanic Asian, non-Hispanic other race or multiple races, Hispanic or Latino of any race, or unknown), U.S. Census region (Northeast, Midwest, South, or West), 2019 household income in USD (categorized as <25,000, 25,000-49,999, 50,000-99,999, 100,000-199,999, ≥200,000, or unknown), highest education attainment (categorized as high school diploma or less, college or some college, bachelor's degree, professional degree, or unknown), employment status (categorized as employed as an essential worker, employed as a nonessential worker, unemployed, retired, or student only), unpaid caregiver role (categorized as yes, no, or unknown), and political ideology (categorized as very liberal, slightly liberal, neither liberal nor conservative, slightly conservative, very conservative, or either apolitical or unknown).

Additional measures included weekly days with ≥30 m of physical activity and with alcoholic beverage consumption, plus diurnal preference. Physical activity was assessed using a validated single-item physical activity measure.[37] Weekly alcoholic beverage consumption was analyzed by multiplying 7 by the answer to the following question: "How many alcoholic beverages did you consume on a typical day in the past week?" Diurnal preference was assessed using Item 19 of the Horne & Östberg Morningness-Eveningness questionnaire.[38]

Mental health and substance use variables included anxiety and depression symptoms assessed using the 4-item Patient Health Questionnaire (PHQ-4),[39] burnout symptoms assessed using the single-item Mini-Z burnout measure,[40] and past-month new or increased substance use to cope with stress or emotions. For the PHQ-4, participants who scored ≥3 out of 6 on the Generalized Anxiety Disorder (GAD-2) and Patient Health Questionnaire (PHQ-2) subscales were considered symptomatic for anxiety or depression, respectively.[39,41] For the Mini-Z, participants who scored ≥3 out of 5 were considered symptomatic for the emotional exhaustion dimension of burnout symptoms.[40] Substance use was defined as use of "alcohol, legal or illegal drugs, or prescriptions drugs that are taken in a way not recommended by your doctor." Participants were asked, "Have you started or increased using substances to help you cope with stress or emotions during the COVID-19 pandemic?"

Statistical Analysis

Study intervals were set as prepandemic (January1-March 12, 2020) and pandemic (March 13-June 30, 2020). For the sleep analysis, the pandemic interval was subdivided into the acute pandemic onset (March 13-April 12, 2020), and mid-pandemic (April 13-June 30, 2020) intervals. Participants with WHOOP data for ≥70% of nocturnal sleep episodes during the pre-pandemic, acute pandemic onset, and mid-pandemic intervals were included in the primary analytic sample. Participants in the primary analytic sample who completed the PHQ-4 were included in the mental health analytic subsample. Chi-square tests were used to assess for demographic differences between participants who did versus did not complete the PHQ-4, with statistical significance set at 2-sided $P \times 9 < .05$ to account for nine comparisons (Bonferroni adjustment).

Means and standard deviations were calculated for each WHOOP variable for participants, overall and during each study interval. Paired t-tests were used to test for differences in mean values for sleep measures between the prepandemic and acute pandemic onset intervals, and between the prepandemic and mid-pandemic intervals. Statistical significance was set at 2-sided $P \times 10 < .05$ and 95% confidence intervals were estimated at the 99.5% confidence level to account for 10 comparisons (Bonferroni adjustment). Continuous sleep measures were used to maximize resolution of the data.

Means and standard deviations were also calculated for each WHOOP variable for deciles of participants (n, 491) with the highest-magnitude changes in sleep measures comparing the prepandemic and pandemic intervals (ie, combined acute pandemic onset and mid-pandemic intervals). Among each decile, paired t-tests were used to test for differences in mean values between these intervals. Statistical significance was set at 2-sided $P \times 10 < .05$ and 95% confidence intervals were estimated at the 99.5% confidence level to account for 10 comparisons (Bonferroni adjustment).

Finally, multivariable logistic regression models were used to estimate adjusted odds ratios (aORs) and 95% confidence intervals (CIs) for each of the assessed adverse mental health symptoms (anxiety or depression symptoms, new or increased substance use, burnout symptoms) based on prepandemic and mid-pandemic WHOOP measures for sleep duration and sleep consistency. The mid-pandemic interval was chosen rather than the acute pandemic onset interval both because it was a more stable interval (following acute pandemic-related disruptions) and because it captured sleep more temporally proximate to the measurement of mental health.

Mean sleep duration during these intervals was categorized as <6 h, 6-7 h, or >7 h, with >7 h as the reference group reflecting optimal healthy sleep duration based on the Joint Consensus Statement of the American Academy of Sleep Medicine and Sleep Research Society,[42] and based on a 13% higher all-cause mortality risk among individuals sleeping <6 h as compared with those sleeping 7-9 h.[43] While a standard based on sleep consistency has not yet been established, more consistent sleep timing is generally associated with better health outcomes.[23-25] Given the distribution of sleep consistency scores in the mental health sample (percentiles: 25th = 71.5; 50th = 76.3; 75th = 80.5), mean sleep consistency was categorized as <70, 70-80, or >80 out of 100, with >80 as the reference group reflecting optimal sleep consistency.

As there were 2 intervals and 3 categories for each variable, there were 9 possible combinations per variable (eg, sleep duration <6 h during both intervals, sleep duration <6 hours during the prepandemic interval, 6-7 h during the mid-pandemic interval, etc.). For these models, the reference groups were having recorded the longest mean duration (ie, >7 h) and highest sleep consistency (ie, >80) during both intervals. Assessment of wakefulness during time in bed, sleep onset, and sleep offset for associations with adverse mental health symptoms was outside the scope of this paper and therefore not included in multivariable analyses.

Standard demographic covariates included sex, age, combined race and ethnicity, highest education attainment, and employment status. Additional covariates included Census region to adjust for potential regional confounding related to COVID-19 prevalence and associated government-imposed movement restrictions, as well as characteristics associated with mental health disparities—unpaid caregiver role,[44,45] diurnal preference,[46] alcohol consumption,[47] and physical activity.[48] Variables were identified *a priori* based on biologic plausibility and relevance to the study hypotheses. Statistical significance was set at 2-sided $P \times 2 < .05$ and 95% confidence intervals were estimated at the 97.5% confidence level to account for 2 comparisons (Bonferroni adjustment).

All calculations were performed in Python version 3.7.8 (Python Software Foundation) and R version 4.0.2 (The R Project for Statistical Computing) using the R survey package version 3.29. Detailed methods are in the Supplement.

Results

Sample characteristics

During June 24-30, 2020, 20,717 of 139,237 eligible invited U.S. WHOOP users aged 18 years or older completed Internet-based surveys (response rate, 14.9%). Overall, 4912 (23.7%) participants recorded ≥70% nocturnal sleep episodes throughout all 3 study intervals (prepandemic, acute pandemic onset, mid-pandemic) and were included in the primary analytic sample. Of these, 3845 (78.3%) completed the PHQ-4 to screen for symptoms of anxiety and depression and were included in the mental health subsample. The sample comprised 3471 (70.7%) male and 3802 (77.2%) non-Hispanic White (White) adults. Most participants were highly educated (4105 [83.6%] college-educated), employed (4417 [89.9%]), and reported high household income (eg, ≥USD$100,000, 3126 [65.5%]). Mean age was 39.7 ± 11.24 years. See eFigure for the survey flow and Table 1 for detailed participant characteristics.

Sleep before and during the pandemic

Overall, compared to the 6.95 ± 0.687 h or 416.9 ± 41.2 m mean sleep duration in the pre-pandemic interval, mean sleep duration was 0.25 h (95% CI, 0.237-0.270, $P < .0001$) or 15.2 m (95% CI, 14.2-16.2) longer in the acute pandemic interval, and 0.09 h (95% CI, 0.076-0.107, $P < .0001$) or 5.5m (95% CI, 4.5-6.4) longer in the mid-pandemic interval (Fig. 1A, eTable 1). In the overall sample, mean sleep duration remained significantly longer on weekend nights compared with weeknights (except for holidays), though the magnitude of difference dampened with time (Fig. 1A). Sleep consistency (0-100), which was generally lower on weekend nights compared to weeknights, increased during both COVID-19 intervals compared to the prepandemic interval, by 3.51 points (95% CI, 3.295-3.728 $P < .0001$) in the acute pandemic interval, and by 4.06 points (95% CI, 3.856-4.267, $P < .0001$) in the mid-pandemic interval (Fig. 1B, eTable 1). Wakefulness during time in bed increased by 0.05 h (95% CI, 0.031-0.074, $P < .0001$) or 3.2 m (95% CI, 0.03-4.4) in the acute pandemic interval compared to the prepandemic interval but did not between the mid-pandemic and prepandemic intervals (difference, 0.01 h, 95% CI, −0.020 to 0.0393, $P > .99$ or 0.6 m, 95% CI, −1.2 to 2.4) (Fig. 1C, eTable 1). Finally, sleep timing abruptly shifted to a later time (ie, delayed) immediately following the declaration of the pandemic by the World Health Organization on March 12, 2020, which preceded subsequent government-imposed movement restrictions in many U.S. states.[49] Over the next 4 weeks, mean sleep onset was 18.7 m later (95% CI, 17.4-20.0, $P < .0001$) and sleep offset was 36.6 m later (95% CI, 35.1-38.1, $P < .0001$) than during the prepandemic interval (Fig. 1D, eTable 1). The delay in sleep onset was sustained throughout the mid-pandemic interval (17.9 m [95% CI, 16.5-19.3, $P < .0001$]), while the delay in sleep offset attenuated to 25.2 m (95% CI, 23.6-26.7, $P < .0001$).

Participants with high-magnitude changes to sleep

While in the overall sample we observed longer sleep duration, increased consistency of sleep timing, relatively stable wakefulness during time in bed, and delayed sleep timing during the COVID-19 pandemic intervals, a subset of participants experienced marked changes in the opposite directions (Fig. 2). We therefore examined deciles of participants with the highest-magnitude changes in sleep variables. The deciles with the highest-magnitude changes in sleep duration were lengthened and shortened by 0.77 h (95% CI, 0.742-0.794, $P < .0001$) or 46.1 m (95% CI, 44.5-47.7) and 0.50 h (95% CI, 0.522-0.470, $P < .0001$) or 29.8 m (95% CI, 31.3-28.2), respectively, while the deciles with the highest-magnitude changes in sleep consistency were increased and decreased by 12.85 points (95% CI, 12.480-13.214, $P < .0001$) and 4.41 points (95% CI, 4.720-4.099, $P < .0001$), respectively (eTable 2). Regarding sleep timing, the deciles with the largest delays in sleep onset and offset shifted later by 1.35 h (22:57 to 00:18, 95% CI, 1.288-1.414, $P < .0001$) or 81.1 m (95% CI, 77.3-84.9) and 1.65 h (06:40 to 08:19, 95% CI, 1.591-1.714, $P < .0001$) or 99.1 m (95% CI, 95.5-102.8), respectively. The deciles with the largest advances in sleep onset and offset shifted earlier by 0.56 h (07:12 to 06:43, 95% CI, 0.516-0.606, $P < .0001$) or 33.7 m (95% CI, 30.9-36.4) and 0.48 h (23:29 to 22:55, 95% CI, 0.434-0.523, $P < .0001$) or 28.7 m (95% CI, 26.0-31.4), respectively.

Mental and behavioral health

Of 3845 participants who completed the PHQ-4, 755 (19.6%) screened positive for anxiety or depression symptoms, 1208 (32.4%) screened positive for burnout symptoms, and 856 (22.4%) reported new or increased substance use to cope with stress or emotions (Table 1). Multivariable analysis including demographic variables, sleep, physical activity, and alcohol use revealed that sleep duration and consistency were associated with differences in mental health outcomes (Table 2).

Compared with participants who slept >7 h in the prepandemic and pandemic intervals, participants who slept <6 h in both intervals had higher odds of anxiety or depression symptoms (aOR, 1.75 [95% CI, 1.14-2.69] $P = .007$) and burnout symptoms (aOR, 1.57 [95% CI, 1.07-2.29] $P = .016$), as did those who slept 6-7 h and those who experienced a decrease in sleep duration to <6 h during the pandemic from 6-7 h in the prepandemic interval (eg, burnout symptoms, aOR, 2.22 [95% CI, 1.32-3.71] $P = .001$).

Compared with participants with sleep consistency >80 in both intervals, participants with sleep consistency <70 in both intervals had higher odds of all assessed adverse mental and behavioral health symptoms (eg, new or increased substance use, aOR, 2.17 [95% CI, 1.48-3.19] $P < .0001$). Odds of new or increased substance use were also higher among participants with sleep consistency of 70-80 during both intervals (aOR, 1.46 [95% CI, 1.06-2.01] $P = .016$), and odds of anxiety or depression symptoms were higher among participants whose sleep consistency decreased from 70-80 in the prepandemic interval to <70 in the pandemic interval (aOR, 2.07 [95% CI, 1.17-3.67] $P = .0009$). Odds of adverse mental or behavioral health symptoms were not higher for participants with decreases in sleep duration or sleep consistency who had optimal duration (>7 h) or consistency (>80) in the prepandemic interval.

Table 1
Participant characteristics.

	All participants unweighted n (%)		Did complete the PHQ-4 unweighted n (%)		Did not complete PHQ-4 unweighted n (%)		Chi-square test for difference between samples *P*
Total Participants	4912	(100)	3845	(78.0)	1067	(22.0)	-
Sex							
Female	1441	(29.3)	1187	(30.9)	254	(23.8)	0.0001
Male	3471	(70.7)	2658	(69.1)	813	(76.2)	
Age group in years							
18-29	981	(20.0)	692	(18.0)	289	(27.1)	<0.0001
30-44	2357	(48.0)	1827	(47.5)	530	(49.7)	
45-64	1460	(29.7)	1221	(31.8)	239	(22.4)	
≥65	113	(2.3)	105	(2.7)	8	(0.7)	
Race and ethnicity							
White, non-Hispanic	3802	(77.4)	3062	(79.6)	740	(69.4)	<0.0001
Black, non-Hispanic	93	(1.9)	72	(1.9)	21	(2.0)	
Asian, non-Hispanic	174	(3.5)	122	(3.2)	52	(4.9)	
Other race or races, non-Hispanic	147	(3.0)	115	(3.0)	32	(3.0)	
Hispanic or Latino, any race or races	375	(7.6)	271	(7.0)	104	(9.7)	
Unknown	321	(6.5)	203	(5.3)	118	(11.1)	
U.S. Census region							
Northeast	1211	(24.7)	942	(24.5)	269	(25.2)	>0.99
Midwest	780	(15.9)	601	(15.6)	179	(16.8)	
South	1588	(32.3)	1244	(32.4)	344	(32.2)	
West	1333	(27.1)	1058	(27.5)	275	(25.8)	
2019 household income (USD)							
<25,000	114	(2.3)	79	(2.1)	35	(3.3)	<0.0001
25,000-49,999	286	(5.8)	203	(5.3)	83	(7.8)	
50,000-99,999	876	(17.8)	681	(17.7)	195	(18.3)	
100,000-199,999	1503	(30.6)	1211	(31.5)	292	(27.4)	
≥200,000	1713	(34.9)	1374	(35.7)	339	(31.8)	
Unknown	420	(8.6)	297	(7.7)	123	(11.5)	
Education							
High school or less	118	(2.4)	82	(2.1)	36	(3.4)	0.029
Some college	663	(13.5)	498	(13.0)	165	(15.5)	
Bachelor's degree	2353	(47.9)	1836	(47.8)	517	(48.5)	
Professional degree	1752	(35.7)	1411	(36.7)	341	(32.0)	
Unknown	26	(0.5)	18	(0.5)	8	(0.7)	
Employment status							
Employed nonessential	2441	(49.7)	1910	(49.7)	531	(49.8)	0.0004
Employed essential	1976	(40.2)	1551	(40.3)	425	(39.8)	
Retired	151	(3.1)	135	(3.5)	16	(1.5)	
Unemployed	203	(4.1)	157	(4.1)	46	(4.3)	
Student only	141	(2.9)	92	(2.4)	49	(4.6)	
Unpaid caregiver of adults							
Yes	417	(8.5)	414	(10.8)	3	(0.3)	>0.99
No	3061	(62.3)	3046	(79.2)	15	(1.4)	
Missing or unknown	1434	(29.2)	385	(10.0)	1049	(98.3)	
Political ideology							
Very liberal	669	(13.6)	555	(14.4)	114	(10.7)	<0.0001
Slightly liberal	1121	(22.8)	905	(23.5)	216	(20.2)	
Neither liberal nor conservative	1223	(24.9)	941	(24.5)	282	(26.4)	
Slightly conservative	999	(20.3)	803	(20.9)	196	(18.4)	
Very conservative	348	(7.1)	263	(6.8)	85	(8.0)	
Unknown or apolitical	552	(11.2)	378	(9.8)	174	(16.3)	

Note. As caregiving status was assessed in the third phase of the survey, along with the PHQ-4, most participants who did not complete the PHQ-4 did not complete the question regarding caregiving status. The "missing or unknown" group was therefore excluded from the prevalence comparison between groups.

Discussion

Among nearly 5000 active users of an objective sleep wearable with data preceding the COVID-19 pandemic, we found acutely increased sleep duration and delayed sleep timing in the first month during which stringent mitigation policies were implemented widely across the U.S., consistent with national and global literature.[2-12] Using a novel metric to quantify the consistency of sleep timing adapted from the SRI,[31,33] we also found abrupt and sustained increases in sleep consistency during the pandemic. Across the sample, the magnitude of the increase in mean sleep duration decreased gradually in the subsequent 2 months, as mean sleep offset returned to near prepandemic times, while delayed sleep onset persisted.

Adverse mental and behavioral health symptoms, including anxiety or depression symptoms, new or increased substance use to cope with stress or emotions, and burnout symptoms were associated with prepandemic sleep deficiency and inconsistent sleep, but not acute decreases in sleep duration or sleep consistency experienced during the pandemic. Recent past sleep-wake behavior was therefore associated with comparatively better mental health during the pandemic interval with profound lifestyle changes, such as the stringent social and behavioral interventions (eg, stay-at-home orders, work-from-home directives). Alternatively, given bidirectional relationships between sleep and mental health,[17] persistently unhealthy sleep patterns in some individuals might have been associated with existing mental health conditions. Independent of the directionality, these

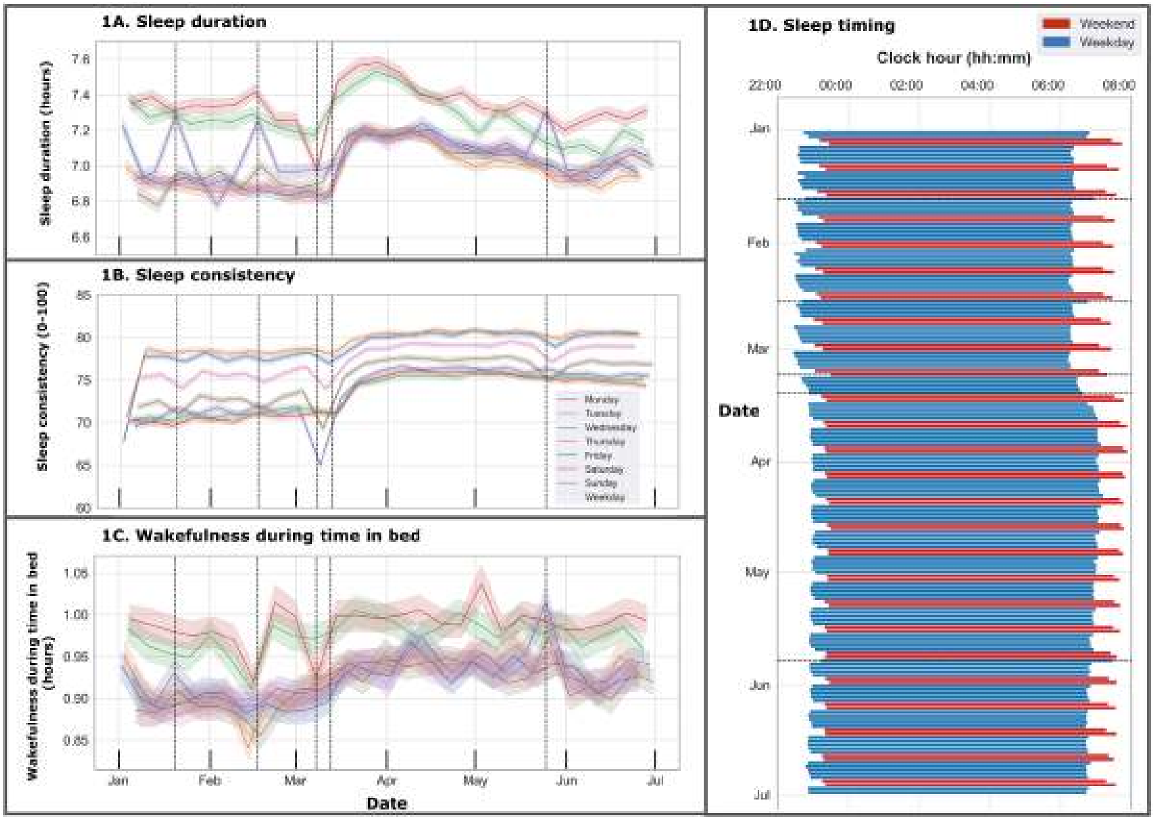

Fig. 1. Sleep duration, consistency, wakefulness during time in bed, and timing, January 1, 2020-June 30, 2020. The vertical (A-C) or horizontal (D) dashed lines represent major public holidays (L to R) Martin Luther King Jr. Day, President's Day, Daylight Saving Time (March), the declaration of COVID-19 as a national emergency in the United States, and Memorial Day.

findings provide further evidence of the important role of sleep during the pandemic as outlined in the National Sleep Foundation Position Statement,[1] and support continued investigation of behavioral interventions to improve sleep duration and the consistency of sleep timing as modifiable risk factors[5] to enhance mental health.

With the prevalence of adverse mental and behavioral health symptoms among U.S. adults having increased several-fold during the pandemic,[13-15] modifiable mental health risk factors are of critical importance. Insufficient sleep duration and inconsistent sleep timing are highly prevalent in modern society.[50] Alongside many undesirable changes during the COVID-19 pandemic has been a unique opportunity for some to improve sleep behaviors.[2-12] Our unique dataset linking mental health and objective, high-resolution prepandemic sleep-wake data enhances our understanding of relationships between sleep and mental health.[43,51] Importantly, there is evidence supporting the efficacy of cognitive and behavioral interventions to improve sleep in adults without sleep disorders,[52] providing a precedent for effective measures, including for improvement of sleep to enhance mental health.[53] Furthermore, improving sleep may have benefits for other elements of health, including general health, cardiovascular and immune function, and metabolic performance.[51]

Analysis of participants with high-magnitude changes to sleep measures revealed disparate changes to sleep-wake behavior during the pandemic, which could be explored through trajectory analyses in future work.

Strengths and limitations

Strengths of this study include the use of objective sleep measures, inclusion of prepandemic comparator sleep data, recruitment of a large sample, use of psychometrically validated mental health screening instruments, and inclusion of demographic and lifestyle-related variables (ie, physical activity, alcohol consumption) in multivariable models assessing for associations with a comprehensive set of sleep variables (ie, duration, timing, consistency).[19,54]

Limitations of this study include the 14.9% response rate, a lack of prepandemic comparator mental health data, nonrandom recruitment methods, uncertainties about objective measurement of sleep in this population and setting, and potential seasonal influences on sleep and mood.

Regarding the relatively low response rate, nonresponse could give rise to sampling bias if nonresponse were unequal among participants with respect to sleep and mental health measures.

Regarding reliance upon cross-sectional mental health measures, doing so precludes a causal interpretation of mental health findings, especially given evidence of bidirectional relationships with sleep.[17,55] Additional studies are warranted to elucidate the directionality of these relationships. Moreover, some stressors might not have been captured, including employment disruptions, health declines, and SARS-CoV-2 infection or COVID-19 illness.

Regarding nonrandom recruitment, most sample participants were male, highly educated, employed, and reported higher-than-national-average household income. Given that income was highly predictive of changes in mobility during the pandemic, with wealthy areas exhibiting larger mobility reductions,[56] this sample may over-represent effects on sleep of stay-at-home orders. Moreover, there is evidence that social determinants of mental and sleep health include more assets, such as income and employment requirements (eg, remote-work options, essential-worker responsibilities).[57,58] Sample-level prevalence estimates for anxiety or depression symptoms were considerably lower in this sample (19.6%) than in a largescale, demographically representative sample evaluated using the same screening instrument during the same time interval (30.9%),[15] which might reflect demographic and socioeconomic differences in sample composition. However,

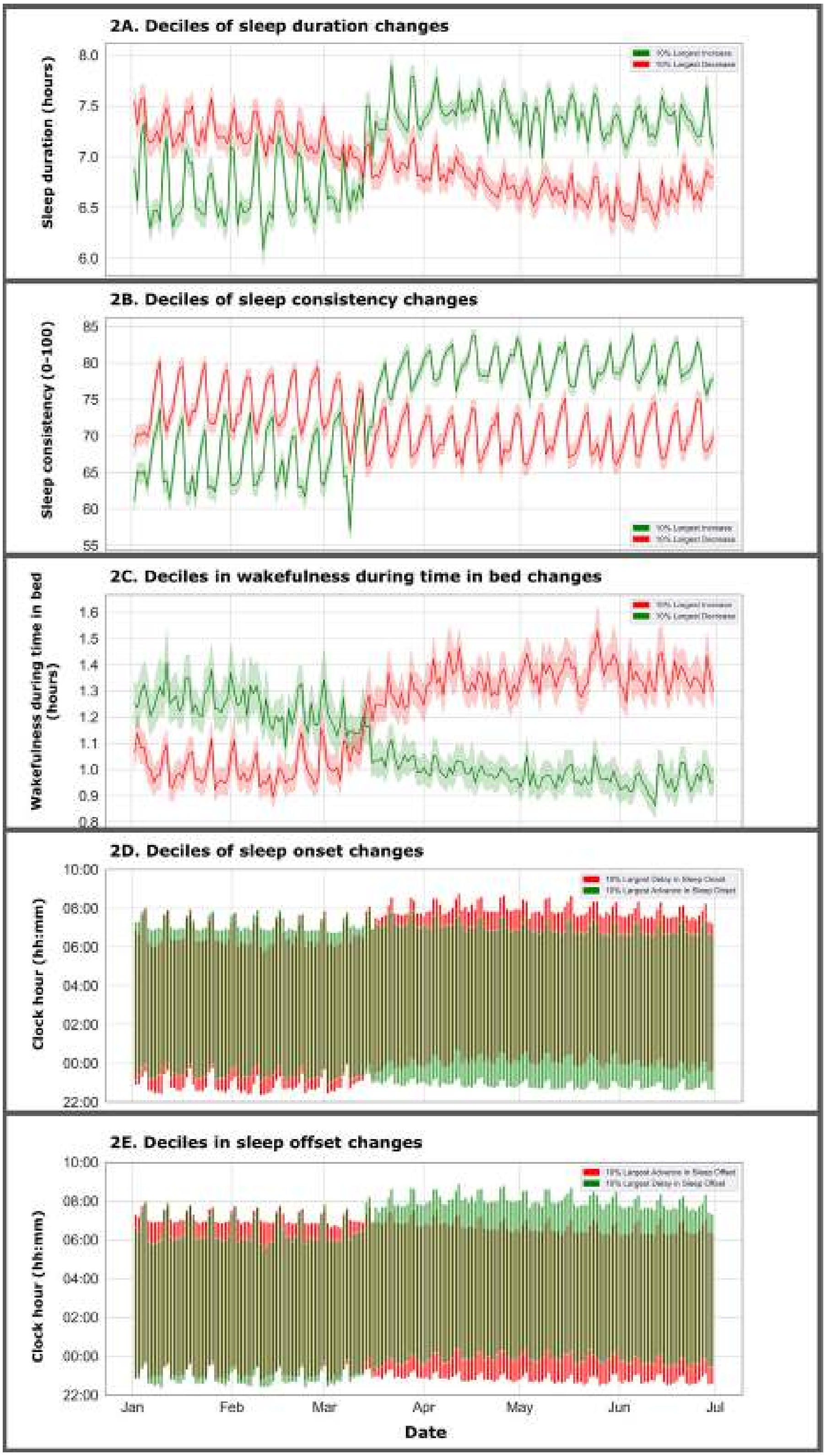

Fig. 2. Heterogeneity in changes to sleep duration, consistency, wakefulness during time in bed, sleep onset, and sleep offset.

multivariable analysis odds ratio estimates (not shown) suggest that most of the relative demographic differences in adverse mental health symptoms (eg, by sex, age, and diurnal preference) were consistent with those of the general population.[13-15,27]

Regarding objective sleep-wake measurement, although WHOOP has demonstrated high levels of agreement for sleep-wake with gold-standard polysomnography among young, healthy adults in laboratory assessments,[32,35,36] its performance in free-living conditions within a more heterogeneous sample is less known, and participants did not complete daily sleep diaries to support sleep onset and offset measurements. Furthermore, the performance of WHOOP relative to polysomnography on some variables (sleep onset, sleep offset,

Table 2
Adjusted odds ratios (aORs) for adverse mental health symptoms by pre-pandemic and pandemic sleep characteristics.

	Anxiety or depression symptoms				New or increased substance use				Burnout symptoms			
	Total N	N (%) positive screen	aOR (95% CI)	*P*	Total N	N (%) positive screen	aOR (95% CI)	*P*	Total N	N (%) positive screen	aOR (95% CI)	*P*
Sleep duration—mean over prepandemic and pandemic intervals												
Both >7 h (reference group)	1464	323 (22.1)	1.00 (Reference)		1720	376 (21.9)	1.00 (Reference)		1677	502 (29.9)	1.00 (Reference)	
Both <6 h	180	44 (24.4)	1.75 (1.14, 2.69)	0.007	179	37 (20.7)	1.11 (0.69, 1.78)	>0.99	177	64 (36.2)	1.57 (1.07, 2.29)	0.016
<6 h to 6-7 h	122	23 (18.9)	1.12 (0.64, 1.98)	>0.99	121	29 (24.0)	1.21 (0.71, 2.04)	0.845	120	40 (33.3)	1.22 (0.77, 1.93)	0.663
<6 h to >7 h	4	0 (0.0)	NO ESTIMATE		4	1 (25.0)	NO ESTIMATE		4	1 (25.0)	NO ESTIMATE	
Both 6-7 h	1058	212 (20.0)	1.30 (1.03, 1.65)	0.025	1052	249 (23.7)	1.21 (0.96, 1.52)	0.126	1033	358 (34.7)	1.39 (1.13, 1.70)	0.001
6-7 h to <6 h	90	24 (26.7)	1.96 (1.09, 3.54)	0.021	90	21 (23.3)	1.19 (0.65, 2.17)	>0.99	90	40 (44.4)	2.22 (1.32, 3.71)	0.001
6-7 h to >7 h	435	92 (21.1)	1.23 (0.90, 1.67)	0.265	435	90 (20.7)	0.96 (0.70, 1.31)	>0.99	421	143 (34.0)	1.22 (0.93, 1.6)	0.191
>7 h to <6 h	6	1 (16.7)	NO ESTIMATE	>0.99	6	3 (50.0)	NO ESTIMATE		6	6 (100)	NO ESTIMATE	
>7 h to 6-7 h	216	36 (16.7)	0.94 (0.60, 1.46)	>0.99	213	50 (23.5)	1.08 (0.72, 1.64)	>0.99	206	54 (26.2)	0.86 (0.59, 1.26)	0.750
Sleep consistency—mean over pre-pandemic and pandemic intervals												
Both >80 out of 100 (reference group)	595	87 (14.6)	1.00 (Reference)		588	92 (15.6)	1.00 (Reference)		570	153 (26.8)	1.00 (Reference)	
Both <70	427	110 (25.8)	1.74 (1.19, 2.55)	0.002	421	131 (31.1)	2.17 (1.48, 3.19)	<0.001	415	180 (43.4)	1.77 (1.28, 2.45)	<0.001
<70 to 70-80	540	117 (21.7)	1.38 (0.95, 1.99)	0.101	537	128 (23.8)	1.38 (0.95, 1.99)	0.103	525	186 (35.4)	1.27 (0.94, 1.73)	0.158
<70 to >80	84	17 (20.2)	1.13 (0.57, 2.25)	>0.99	84	20 (23.8)	1.35 (0.69, 2.65)	0.643	79	22 (27.8)	0.88 (0.48, 1.62)	>0.99
Both 70-80	1106	223 (20.2)	1.34 (0.97, 1.85)	0.088	1102	259 (23.5)	1.46 (1.06, 2.01)	0.016	1080	363 (33.6)	1.22 (0.93, 1.60)	0.191
70-80 to <70	104	31 (29.8)	2.07 (1.17, 3.67)	0.009	104	29 (27.9)	1.66 (0.91, 3.03)	0.119	103	34 (33.0)	1.08 (0.63, 1.84)	>0.99
70-80 to >80	909	154 (16.9)	1.11 (0.79, 1.56)	0.954	906	177 (19.5)	1.17 (0.84, 1.63)	0.598	888	246 (27.7)	0.99 (0.75, 1.31)	>0.99
>80 to <70	2	1 (50.0)	NO ESTIMATE		2	1 (50.0)	NO ESTIMATE		2	0 (0.0)	NO ESTIMATE	
>80 to 70-80	78	15 (19.2)	1.35 (0.66, 2.75)	0.700	76	19 (25.0)	1.62 (0.80, 3.30)	0.253	72	24 (33.3)	1.31 (0.71, 2.42)	0.649

Note. Scores ≥3 out of 6 on either the PHQ-2 or GAD-2 subscales of the PHQ-4 were considered positive screens for anxiety or depression symptoms. Affirmative answers to a question about having past-month new or increased substance use to cope with stress or emotions was considered positive screens for new or increased substance use. Scores ≥3 out of 5 on the single-item Mini-Z burnout measure were considered positive screens for burnout symptoms. Multivariable logistic regression models used to estimate odds ratios included the following covariates: sex, age, race and ethnicity, education attainment, employment status, Census region, unpaid caregiver status, diurnal preference, alcohol consumption, and physical activity. Estimates are not provided for outcomes with Total N <10 respondents. Bolded values are significant at 2-sided $P \times 2 < 0.05$ and 95% confidence intervals were estimated at the 97.5% confidence level to account for 2 comparisons (Bonferroni adjustment).

wakefulness during time in bed) has not been reported. Given that WHOOP is a subscription tracker of sleep and fitness, participants may have been more knowledgeable about and motivated to pursue optimal sleep health and fitness than the U.S. adult population, which could limit the generalizability of findings.

Finally, it is possible that sleep and mental health responses to the onset of a pandemic may vary with season and be influenced by daylight savings time changes; however, 2019 and 2020 data on time in bed and sleep timing from both Ong et al. based on data from 20 countries (with variable daylight savings time presence and timing)[11] and Capodilupo and Miller in the U.S.[12] indicate that the magnitude of changes to sleep-wake behavior observed in the months after the COVID-19 pandemic were not observed the year before. For example, in 2019, time in bed was slightly shorter during March 10 through May 15 compared to January 1 through March 9, 2019 (by 0.05 ± 0.003 h), and sleep offset time did not differ significantly between the intervals. Comparing the same intervals in 2020, time in bed was considerably longer during March 10 through May 15 (by 0.24 ± 0.003 h), and sleep offset was significantly later (by 29 ± 1 m).

Conclusions

As policymakers grapple with decisions about stringent mitigation measures during future waves of SARS-CoV-2 or other pathogens, community institutions, healthcare providers, and public health agencies should consider the potential roles of sleep and circadian rhythms in mitigating potential mental health consequences. Findings from this study of U.S. adult users of a wearable device support sleep duration and consistency of sleep timing as potential modifiable risk factors for adverse mental health during stressful life events. Future research should (1) explore the directionality and impact of prolonged physiological and behavioral changes observed following SARS-CoV-2 infection on mental health (2) determine predictors of counter-sample sleep patterns (eg, reduced sleep duration, less consistent sleep timing) and (3) evaluate public health programs with elements informed by sleep and circadian principles as primary prevention strategies for adverse mental health outcomes.

Funding

There was no specific funding for survey data collection. Mr Czeisler was supported in part by a 2020 Australian-American Fulbright Scholarship funded by The Kinghorn Foundation, and by a grant from WHOOP, Inc., to Monash University acting through its Faculty of Medicine, Nursing and Health Sciences. Dr Czeisler is the incumbent of an endowed professorship provided to Harvard University by Cephalon, Inc.

Declaration of conflict of interest

Mr Czeisler and Drs Weaver, Czeisler, Howard, and Rajaratnam reported receiving a grant from the CDC Foundation with funding from BNY Mellon, a grant from WHOOP, Inc., and a gift from Hopelab, Inc. Mr Czeisler reported having received a grant from the Australian-American Fulbright Commission administered through a 2020 to 2021 Fulbright Scholarship funded by The Kinghorn Foundation and having received personal fees from Vanda Pharmaceuticals. Ms Capodilupo is a paid employee of and has equity interest in WHOOP, Inc., and has equity interest in ARCHANGELS. Dr Weaver reported consulting fees from National Sleep Foundation and the University of Pittsburgh. Dr Czeisler reported receiving grants to support The COVID-19 Outbreak Public Evaluation (COPE) Initiative and grants from Brigham and Women's Physician's Organization during the conduct of the study; being a paid consultant to or speaker for Ganésco, Institute of Digital Media and Child Development, Klarman Family Foundation, M. Davis and Co, Physician's Seal, Samsung Group, State of Washington Board of Pilotage Commissioners, Tencent Holdings, Teva Pharma Australia, and Vanda Pharmaceuticals, in which Dr Czeisler holds an equity interest; receiving travel support from Aspen Brain Institute, Bloomage International Investment Group, UK Biotechnology and Biological Sciences Research Council, Bouley Botanical, Dr Stanley Ho Medical Development Foundation, Illuminating Engineering Society, National Safety Council, Tencent Holdings, and The Wonderful Co; receiving institutional research and/or education support from Cephalon, Mary Ann and Stanley Snider via Combined Jewish Philanthropies, Harmony Biosciences, Jazz Pharmaceuticals PLC, Johnson and Johnson, Neurocare, Peter Brown and Margaret Hamburg, Philips Respironics, Regeneron Pharmaceuticals, Regional Home Care, Teva Pharmaceuticals Industries, Sanofi S.A., Optum, ResMed, San Francisco Bar Pilots, Schneider National, Serta, Simmons Betting, Sysco, Vanda Pharmaceuticals; being or having been an expert witness in legal cases, including those involving Advanced Power Technologies; Aegis Chemical Solutions; Amtrak; Casper Sleep; C and J Energy Services; Complete General Construction; Dallas Police Association; Enterprise Rent-A-Car; Steel Warehouse Co; FedEx; Greyhound Lines; Palomar Health District; PAR Electrical, Product, and Logistics Services; Puckett Emergency Medical Services; South Carolina Central Railroad Co; Union Pacific Railroad; UPS; and Vanda Pharmaceuticals; serving as the incumbent of an endowed professorship provided to Harvard University by Cephalon; and receiving royalties from McGraw Hill and Philips Respironics for the Actiwatch-2 and Actiwatch Spectrum devices. Dr Czeisler's interests were reviewed and are managed by the Brigham and Women's Hospital and Mass General Brigham in accordance with their conflict-of-interest policies. Dr Rajaratnam reported receiving institutional consulting fees from CRC for Alertness, Safety, and Productivity; Teva Pharmaceuticals; Vanda Pharmaceuticals; Circadian Therapeutics; BHP Billiton; and Herbert Smith Freehills; receiving grants from Teva Pharmaceuticals and Vanda Pharmaceuticals; and serving as chair for the Sleep Health Foundation outside the submitted work. Dr Howard reports receiving institutional consulting fees from Teva Pharmaceuticals, Biogen and Sanofi; and equipment to support research from Optalert and Philips Respironics outside the submitted work. No other potential conflicts of interest were reported.

Acknowledgments

The authors thank Thomas Rand (WHOOP, Inc.) for coding the survey onto the WHOOP interface, as well as Rebecca Robbins, PhD (Brigham and Women's Hospital, Harvard Medical School), Laura K Barger, PhD (Brigham and Women's Hospital, Harvard Medical School), and Elise R Facer-Childs, PhD (Monash University) for their contributions to the initial survey instrument for The COPE Initiative. MÉC gratefully acknowledges funding by The Kinghorn Foundation through a 2020 to 2021 Australian-American Fulbright Scholarship.

Supplementary materials

Supplementary material associated with this article can be found in the online version at doi:10.1016/j.sleh.2022.03.001.

References

1. Barber I. Sleep in a time of pandemic - a position statement from the national sleep foundation. *Sleep Health*. 2020;6(3):431. https://doi.org/10.1016/j.sleh.2020.05.003.
2. Yuksel D, McKee GB, Perrin PB, et al. Sleeping when the world locks down: correlates of sleep health during the COVID-19 pandemic across 59 countries. *Sleep Health*. 2021;7(2):134–142. https://doi.org/10.1016/j.sleh.2020.12.008.
3. Leone MJ, Sigman M, Golombek DA. Effects of lockdown on human sleep and chronotype during the COVID-19 pandemic. *Curr Biol*. 2020;30(16):R930–R931. https://doi.org/10.1016/j.cub.2020.07.015.
4. Facer-Childs ER, Hoffman D, Tran JN, Drummond SPA, Rajaratnam SMW. Sleep and mental health in athletes during COVID-19 lockdown. *Sleep*. 2021;44(5):zsaa261. https://doi.org/10.1093/sleep/zsaa261.

5. Wright KP, Linton SK, Withrow D, et al. Sleep in university students prior to and during COVID-19 Stay-at-Home orders. *Curr Biol*. 2020;30(14):R797–R798. https://doi.org/10.1016/j.cub.2020.06.022.
6. Petrov ME, Pituch KA, Kasraeian K, et al. Impact of the COVID-19 pandemic on change in sleep patterns in an exploratory, cross-sectional online sample of 79 countries. *Sleep Health*. 2021;7(4):451–458. https://doi.org/10.1016/j.sleh.2021.05.007.
7. Rezaei N, Grandner MA. Changes in sleep duration, timing, and variability during the COVID-19 pandemic: large-scale Fitbit data from 6 major US cities. *Sleep Health*. 2021;7(3):303–313. https://doi.org/10.1016/j.sleh.2021.02.008.
8. Robbins R, Affouf M, Weaver MD, et al. Estimated sleep duration before and during the COVID-19 pandemic in major metropolitan areas on different continents: observational study of smartphone app data. *J Med Internet Res*. 2021;23(2):e20546. https://doi.org/10.2196/20546.
9. Pépin JL, Bailly S, Mordret E, et al. Greatest changes in objective sleep architecture during COVID-19 lockdown in night-owls with increased REM sleep. *Sleep*. 2021:zsab075. https://doi.org/10.1093/sleep/zsab075. Published online.
10. Ong JL, Lau T, Massar SAA, et al. COVID-19-related mobility reduction: heterogenous effects on sleep and physical activity rhythms. *Sleep*. 2021;44(2):zsaa179. https://doi.org/10.1093/sleep/zsaa179.
11. Ong JL, Lau T, Karsikas M, Kinnunen H, Chee MWL. A longitudinal analysis of COVID-19 lockdown stringency on sleep and resting heart rate measures across 20 countries. *Sci Rep*. 2021;11(1):14413. https://doi.org/10.1038/s41598-021-93924-z.
12. Capodilupo ER, Miller DJ. Changes in health promoting behavior during COVID-19 physical distancing: utilizing wearable technology to examine trends in sleep, activity, and cardiovascular indicators of health. *PLoS One*. 2021;16:(8) e0256063. https://doi.org/10.1371/journal.pone.0256063.
13. Ettman CK, Abdalla SM, Cohen GH, Sampson L, Vivier PM, Galea S. Prevalence of depression symptoms in US adults before and during the COVID-19 pandemic. *JAMA Netw Open*. 2020;3:(9) e2019686. https://doi.org/10.1001/jamanetworkopen.2020.19686.
14. Czeisler MÉ, Howard ME, Robbins R, et al. Early public adherence with and support for stay-at-home COVID-19 mitigation strategies despite adverse life impact: a transnational cross-sectional survey study in the United States and Australia. *BMC Public Health*. 2021;21(1):503. https://doi.org/10.1186/s12889-021-10410-x.
15. Czeisler MÉ, Lane RI, Petrosky E, et al. Mental health, substance use, and suicidal ideation during the COVID-19 pandemic - United States, June 24-30, 2020. *MMWR Morb Mortal Wkly Rep*. 2020;69(32):1049–1057. https://doi.org/10.15585/mmwr.mm6932a1.
16. Czeisler MÉ, Howard ME, Rajaratnam SMW. Mental Health During the COVID-19 Pandemic: Challenges, Populations at Risk, Implications, and Opportunities. *Am J Health Promot*. 2021;35(2):301–311. https://doi.org/10.1177/0890117120983982b.
17. Alvaro PK, Roberts RM, Harris JK. A Systematic Review Assessing Bidirectionality between Sleep Disturbances, Anxiety, and Depression. *Sleep*. 2013;36(7):1059–1068. https://doi.org/10.5665/sleep.2810.
18. Kim JY, Ko I, Kim DK. Association of obstructive sleep apnea with the risk of affective disorders. *JAMA Otolaryngol Head Neck Surg*. 2019;145(11):1020–1026. https://doi.org/10.1001/jamaoto.2019.2435.
19. Buysse DJ. Sleep health: can we define it? Does it matter? *Sleep*. 2014;37(1):9–17. https://doi.org/10.5665/sleep.3298.
20. Blackwelder A, Hoskins M, Huber L. Effect of inadequate sleep on frequent mental distress. *Prev Chronic Dis*. 2021;18:E61. https://doi.org/10.5888/pcd18.200573.
21. O'Loughlin J, Casanova F, Jones SE, et al. Using Mendelian Randomisation methods to understand whether diurnal preference is causally related to mental health. *Mol Psychiatry*. 2021;26(11):6305–6316. https://doi.org/10.1038/s41380-021-01157-3.
22. Anderson KN, Bradley AJ. Sleep disturbance in mental health problems and neurodegenerative disease. *Nat Sci Sleep*. 2013;5:61–75. https://doi.org/10.2147/NSS.S34842.
23. Lyall LM, Wyse CA, Graham N, et al. Association of disrupted circadian rhythmicity with mood disorders, subjective wellbeing, and cognitive function: a cross-sectional study of 91 105 participants from the UK Biobank. *Lancet Psychiatry*. 2018;5(6):507–514. https://doi.org/10.1016/S2215-0366(18)30139-1.
24. Fang Y, Forger DB, Frank E, Sen S, Goldstein C. Day-to-day variability in sleep parameters and depression risk: a prospective cohort study of training physicians. *NPJ Digit Med*. 2021;4(1):28. https://doi.org/10.1038/s41746-021-00400-z.
25. Bei B, Manber R, Allen NB, Trinder J, Wiley JF. Too long, too short, or too variable? Sleep intraindividual variability and its associations with perceived sleep quality and mood in adolescents during naturalistically unconstrained sleep. *Sleep*. 2017;40(2). https://doi.org/10.1093/sleep/zsw067.
26. Bernert RA, Hom MA, Iwata NG, Joiner TE. Objectively assessed sleep variability as an acute warning sign of suicidal ideation in a longitudinal evaluation of young adults at high suicide risk. *J Clin Psychiatry*. 2017;78(6):e678–e687. https://doi.org/10.4088/JCP.16m11193.
27. Varma P, Junge M, Meaklim H, Jackson ML. Younger people are more vulnerable to stress, anxiety and depression during COVID-19 pandemic: A global cross-sectional survey. *Prog Neuropsychopharmacol Biol Psychiatry*. 2021;109: 110236. https://doi.org/10.1016/j.pnpbp.2020.110236.
28. Czeisler MÉ, Lane RI, Wiley JF, Czeisler CA, Howard ME, Rajaratnam SMW. Follow-up survey of US adult reports of mental health, substance use, and suicidal ideation during the COVID-19 pandemic, September 2020. *JAMA Netw Open*. 2021;4:(2) e2037665. https://doi.org/10.1001/jamanetworkopen.2020.37665.
29. Czeisler MÉ, Wiley JF, Facer-Childs ER, et al. Mental health, substance use, and suicidal ideation during a prolonged COVID-19–related lockdown in a region with low SARS-CoV-2 prevalence. *J Psychiatr Res*. 2021;140:533–544. https://doi.org/10.1016/j.jpsychires.2021.05.080.
30. Medic G, Wille M, Hemels ME. Short- and long-term health consequences of sleep disruption. *Nat Sci Sleep*. 2017;9:151–161. https://doi.org/10.2147/NSS.S134864.
31. Lunsford-Avery JR, Engelhard MM, Navar AM, Kollins SH. Validation of the sleep regularity index in older adults and associations with cardiometabolic risk. *Sci Rep*. 2018;8(1):14158. https://doi.org/10.1038/s41598-018-32402-5.
32. Miller DJ, Roach GD, Lastella M, et al. A validation study of a commercial wearable device to automatically detect and estimate sleep. *Biosensors (Basel)*. 2021;11(6):185. https://doi.org/10.3390/bios11060185.
33. Phillips AJK, Clerx WM, O'Brien CS, et al. Irregular sleep/wake patterns are associated with poorer academic performance and delayed circadian and sleep/wake timing. *Sci Rep*. 2017;7(1):3216. https://doi.org/10.1038/s41598-017-03171-4.
34. WHOOP Analytics Department. *Sleep Consistency: Why We Track it | The Locker*. WHOOP, Inc.; 2022. http://www.whoop.com/thelocker/new-feature-sleep-consistency-why-we-track-it/. Accessed January 31, 2022 .
35. Miller DJ, Lastella M, Scanlan AT, et al. A validation study of the WHOOP strap against polysomnography to assess sleep. *J Sports Sci*. 2020;38(22):2631–2636. https://doi.org/10.1080/02640414.2020.1797448.
36. Berryhill S, Morton CJ, Dean A, et al. Effect of wearables on sleep in healthy individuals: a randomized crossover trial and validation study. *J Clin Sleep Med*. 2020;16(5):775–783. https://doi.org/10.5664/jcsm.8356.
37. Milton K, Bull FC, Bauman A. Reliability and validity testing of a single-item physical activity measure. *Br J Sports Med*. 2011;45(3):203–208. https://doi.org/10.1136/bjsm.2009.068395.
38. Horne JA, Östberg O. A self-assessment questionnaire to determine morningness-eveningness in human circadian rhythms. *Int J Chronobiol*. 1976;4(2):97–110.
39. Löwe B, Wahl I, Rose M, et al. A 4-item measure of depression and anxiety: validation and standardization of the Patient Health Questionnaire-4 (PHQ-4) in the general population. *J Affect Disord*. 2010;122(1-2):86–95. https://doi.org/10.1016/j.jad.2009.06.019.
40. Dolan ED, Mohr D, Lempa M, et al. Using a single item to measure burnout in primary care staff: a psychometric evaluation. *J Gen Intern Med*. 2015;30(5):582–587. https://doi.org/10.1007/s11606-014-3112-6.
41. Löwe B, Kroenke K, Herzog W, Gräfe K. Measuring depression outcome with a brief self-report instrument: sensitivity to change of the Patient Health Questionnaire (PHQ-9). *J Affect Disord*. 2004;81(1):61–66. https://doi.org/10.1016/S0165-0327(03)00198-8.
42. Consensus Conference PanelWatson NF, Badr MS, et al. Joint Consensus Statement of the American Academy of Sleep Medicine and Sleep Research Society on the Recommended Amount of Sleep for a Healthy Adult: Methodology and Discussion. *J Clin Sleep Med*. 2015;11(8):931–952. https://doi.org/10.5664/jcsm.4950.
43. Hafner M, Stepanek M, Taylor J, Troxel WM, van Stolk C. Why Sleep Matters-The Economic Costs of Insufficient Sleep: A Cross-Country Comparative Analysis. *Rand Health Q*. 2017;6(4):11.
44. Czeisler MÉ, Drane A, Winnay SS, et al. Mental health, substance use, and suicidal ideation among unpaid caregivers of adults in the United States during the COVID-19 pandemic: Relationships to age, race/ethnicity, employment, and caregiver intensity. *J Affect Disord*. 2021;1(295):1259–1268. https://doi.org/10.1016/j.jad.2021.08.130.
45. Czeisler MÉ, Rohan EA, Mellilo S, et al. Mental Health Among Parents of Children Aged <18 Years and Unpaid Caregivers of Adults During the COVID-19 Pandemic - United States, December 2020 and February-March 2021. *MMWR Morb Mortal Wkly Rep*. 2021;70(24):879–887. https://doi.org/10.15585/mmwr.mm7024a3.
46. Daghlas I, Lane JM, Saxena R, Vetter C. Genetically proxied diurnal preference, sleep timing, and risk of major depressive disorder. *JAMA Psychiatry*. 2021;78(8):903–910. https://doi.org/10.1001/jamapsychiatry.2021.0959. Published online.
47. Volk RJ, Cantor SB, Steinbauer JR, Cass AR. Alcohol use disorders, consumption patterns, and health-related quality of life of primary care patients. *Alcohol Clin Exp Res*. 1997;21(5):899–905.
48. Chekroud SR, Gueorguieva R, Zheutlin AB, et al. Association between physical exercise and mental health in 1·2 million individuals in the USA between 2011 and 2015: a cross-sectional study. *Lancet Psychiatry*. 2018;5(9):739–746. https://doi.org/10.1016/S2215-0366(18)30227-X.
49. Moreland A, Herlihy C, Tynan MA, et al. Timing of state and territorial COVID-19 stay-at-home orders and changes in population movement - United States, March 1-May 31, 2020. *MMWR Morb Mortal Wkly Rep*. 2020;69(35):1198–1203. https://doi.org/10.15585/mmwr.mm6935a2.
50. Liu Y, Wheaton AG, Chapman DP, Cunningham TJ, Lu H, Croft JB. Prevalence of healthy sleep duration among adults—United States, 2014. *MMWR Morb Mortal Wkly Rep*. 2016;65(6):137–141. https://doi.org/10.15585/mmwr.mm6506a1.
51. Grandner MA. Sleep, Health, and Society. *Sleep Med Clin*. 2020;15(2):319–340. https://doi.org/10.1016/j.jsmc.2020.02.017.
52. Murawski B, Wade L, Plotnikoff RC, Lubans DR, Duncan MJ. A systematic review and meta-analysis of cognitive and behavioral interventions to improve sleep health in adults without sleep disorders. *Sleep Med Rev*. 2018;40:160–169. https://doi.org/10.1016/j.smrv.2017.12.003.
53. Christensen H, Batterham PJ, Gosling JA, et al. Effectiveness of an online insomnia program (SHUTi) for prevention of depressive episodes (the GoodNight Study): a randomised controlled trial. *Lancet Psychiatry*. 2016;3(4):333–341. https://doi.org/10.1016/S2215-0366(15)00536-2.
54. Dong L, Martinez AJ, Buysse DJ, Harvey AG. A composite measure of sleep health predicts concurrent mental and physical health outcomes in adolescents prone to eveningness. *Sleep Health*. 2019;5(2):166–174. https://doi.org/10.1016/j.sleh.2018.11.009.

55. Sun Y, Shi L, Bao Y, Sun Y, Shi J, Lu L. The bidirectional relationship between sleep duration and depression in community-dwelling middle-aged and elderly individuals: evidence from a longitudinal study. *Sleep Med*. 2018;52:221–229. https://doi.org/10.1016/j.sleep.2018.03.011.
56. Chang S, Pierson E, Koh PW, et al. Mobility network models of COVID-19 explain inequities and inform reopening. *Nature*. 2021;589(7840):82–87. https://doi.org/10.1038/s41586-020-2923-3.
57. Ettman CK, Cohen GH, Abdalla SM, et al. Persistent depressive symptoms during COVID-19: a national, population-representative, longitudinal study of U.S. adults. *Lancet Reg Health Am*. 2022;5: 100091. https://doi.org/10.1016/j.lana.2021.100091.
58. Yip T, Feng Y, Fowle J, Fisher CB. Sleep disparities during the COVID-19 pandemic: an investigation of AIAN, Asian, Black, Latinx, and White young adults. *Sleep Health*. 2021;7(4):459–467. https://doi.org/10.1016/j.sleh.2021.05.008.