Objective and Subjective Intraindividual Variability in Sleep: Predisposing Factors and Health Consequences

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Objective: We investigated the factors that predispose or precipitate greater intraindividual variability (IIV) in sleep. We further examined the potential consequences of IIV on overall sleep quality and health outcomes, including whether these relationships were found in both self-reported and actigraphy-measured sleep IIV.

Methods: In Study 1, 699 US adults completed a Sleep Intra-Individual Variability Questionnaire and self-reported psychosocial, sleep quality, and health outcomes. In Study 2, 100 university students wore actigraphy and completed psychosocial, sleep, and health surveys at multiple timepoints.

Results: In cross-sectional analyses that controlled for mean sleep duration, predisposing/precipitating factors to greater IIV were being an underrepresented racial/ethnic minority (Study 1: $F = 13.95$, $p < .001$; Study 2: $F = 7.03$, $p = .009$), having greater stress (Study 2: r values ≥ 0.32, p values ≤ .002) or trait vulnerability to stress (Study 1: r values ≥ 0.15, p values < .001), and showing poorer time management (Study 1: r values ≤ −0.12, p values ≤ .004; Study 2: r values ≤ −0.23, p values ≤ .028). In addition, both studies showed that greater sleep IIV was associated with decreased overall sleep quality, independent of mean sleep duration (Study 1: r values ≥ 0.20, p values < .001; Study 2: r values ≥ 0.33, p values ≤ .001). Concordance across subjective and objective IIV measures was modest (r values = 0.09–0.35) and similar to concordance observed for subjective-objective mean sleep duration measures.

Conclusion: Risk for irregular sleep patterns is increased in specific demographic groups and may be precipitated by, or contribute to, higher stress and time management inefficiencies. Irregular sleep may lead to poor sleep quality and adverse health outcomes, independent of mean sleep duration, underscoring the importance of addressing sleep consistency.

Key words: sleep regularity, Actigraphy, stress, work efficiency, procrastination, psychosocial determinants

Abbreviations: ANCOVA = analysis of covariance, **COVID-19** = coronavirus disease 2019, **FIRST** = Ford Insomnia Response to Stress Test, **IIV** = intraindividual variability, **ISD** = individual standard deviation, **PSQI** = Pittsburgh Sleep Quality Index, **SIIV** = Sleep Intra-Individual Variability Questionnaire, **SSS** = Stanford Sleepiness Scale, **TST** = total sleep time, **URM** = underrepresented minorities, **VAS** = visual analog scale

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INTRODUCTION

It is well documented that sleep is associated with physical and mental health. For example, short sleep duration is associated with worse metabolic function (1), cardiovascular disease (2), worse immune function (3), and mood and stress dysregulation (4). The causal direction of each of these associations has been an area of interest in psychosomatic research, with relationships often appearing to be bidirectional. For example, exposure to stressors shortens sleep duration and worsens sleep quality (5), but the converse is also true: reducing sleep causes mood disturbance and stress reactivity (6).

Most previous sleep research has investigated sleep through averaged/mean measures, potentially overlooking dynamic dimensions of sleep patterns including fluctuations in sleep within an individual over time (7–9). As such, a participant who sleeps 7 hours every night will often be treated the same as a participant who oscillates between restriction (5 hours) and recovery (9 hours) sleep every night because both participants averaged 7 hours. There is growing evidence, however, that irregular sleep habits are common in the population and that intraindividual variability in sleep (IIV) could be a key dimension of overall sleep health (8,10). Greater IIV (i.e., irregular sleep patterns) has been associated with adverse health consequences such as risk for cardiovascular disease (11,12), poor metabolic health (13,14), depression (15–17), worse stress regulation (18), worse cognitive functioning (13), greater daytime sleepiness (19), poorer academic performance (20), and greater mortality (21).

Keeping consistent sleep habits could be important to health and functioning, but there are some limitations in the existing literature that necessitate consideration. For example, most studies that connected sleep IIV to health outcomes did not adjust for mean sleep duration (8). Therefore, it is not always clear whether individuals with greater IIV are also the individuals who have short (mean) sleep, thereby muddying interpretations of whether sleep IIV uniquely contributes to health and functioning. In the present work, all analyses controlled for mean sleep duration. Another potential limitation of the existing literature is that many of the studies were not originally designed to investigate sleep IIV, but instead conducted retrospective exploratory analyses. Although this approach could lend greater credence to IIV-health associations because the association is existing in a wide range of studies, retrospective exploratory analyses come at the risk of potential reporting/publication biases (e.g., datasets that have been

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explored but produced no significant IIV outcomes may be less likely to be reported/published) (22). The present work was designed to test sleep IIV as the primary outcome, as our overarching goal was to develop the Sleep Intra-Individual Variability Questionnaire (SIIV) and investigate the predisposing/precipitating factors and health consequences associated with subjective and objective sleep IIV.

We tested three aims/hypotheses in the current work. Hypothesis 1 was that greater sleep IIV would be observed in populations that have greater irregularity in their daytime schedules including shift workers, younger individuals, individuals who have greater stress, and individuals with poorer time management (i.e., factors hypothesized to predispose/precipitate greater IIV) (18,23,24). Hypothesis 2 was that greater sleep IIV would be associated with poorer sleep quality and subjective health, independent of mean total sleep time (TST; i.e., hypothesized health consequences of greater sleep IIV). Aim 3 was to compare different measures of subjective and objective sleep IIV and explore whether they would produce convergent outcomes with predisposing factors and health consequences (Study 2). Like the relationship between self-reported mean TST and actigraphy mean TST, we expected that concordance rates across measures would probably be modest, but that they would demonstrate similar associations with the same psychosocial, sleep quality, and health outcomes.

STUDY 1

Participants

Participants consisted of 699 US residents from two online samples that were recruited in 2020 (for full details, see (25–27)). The first group of $n = 199$ participants were recruited in mid-February 2020, before COVID-19 was declared as a global pandemic and prior to shelter-in-place policies in the US. A second group of $n = 500$ participants were recruited between March 25 and March 27, 2020, approximately 1 week after shelter-in-place policies were enacted in the US. COVID-19–related changes in sleep were described in detail previously (25,27). The Baylor University Institutional Review Board approved this study, and participants provided informed consent.

Materials

Participants completed surveys on demographic information, chronotype (1–4 scale; from "definitely a morning type" to "definitely an evening type"), overall subjective health (1–5 scale; from "poor" to "excellent"), subjective sleep quality (Pittsburgh Sleep Quality Index [PSQI]) (28), vulnerability to stress-related sleep disturbances (Ford Insomnia Response to Stress Test [FIRST]) (29), and daytime sleepiness (Stanford Sleepiness Scale [SSS]) (30). In addition, they responded how well they managed their time (0 = not well, 100 = very well), how efficiently they worked during the day (0 = not efficiently, 100 = very efficiently), and how often they procrastinated (0 = not often, 100 = very often) on visual analog scales (VAS). We reverse-coded the procrastination scores and averaged the three VAS scores to form a composite score of time management (higher = better time management).

Participants also completed the SIIV, which we developed to investigate subjective IIV in sleep. Prior to Study 1, we pilot tested a beta version of the SIIV in 126 participants to inform feasibility, usability, and identify areas of confusion. In this early version, participants were instructed to draw lines across the week to indicate their sleep consistency (flatter lines indicated greater consistency). Based on this pilot testing, we improved the SIIV by clarifying instructions, providing response choices instead of free response boxes (to avoid impossible data responses), and changing the layout of items to ensure that participants gave a response for each of the 7 days of the week (drawing lines often led to >7 data points in the pilot study). In the current version of the SIIV (Supplemental Material 1 section, Supplemental Digital Content, http://links.lww.com/PSYMED/B22), participants first reported their usual sleep patterns for each day of the week, from Monday through Sunday. Rated measures included bedtimes, waketimes, sleep onset latencies, daytime naps, and sleep durations. The current work focused on IIV in sleep duration rather than other possible measures to constrain analyses and determine whether IIV in TSTs was conceptually distinguishable from mean TST. To estimate IIV, we computed the individual standard deviation (ISD) of the seven TSTs (10,31). To determine if a simpler VAS approach produced comparable outcomes, we also had participants rate from 0 to 100 the consistency of their overall sleep patterns across weekdays as well as rate their consistency between weekdays and weekends. We averaged the scores on the two VAS items and reverse-coded them to quantify variability of overall sleep patterns (higher = more variable).

Statistical Analyses

For Hypothesis 1, we conducted partial Pearson correlations and analyses of covariance (ANCOVAs) to test which factors may predispose one to having greater IIV in TST, after adjusting for mean TST. For Hypothesis 2, we conducted partial Pearson correlations to test whether greater IIV in TST was associated with poorer sleep quality and subjective health, independent of mean TST. For all analyses, we used both the ISD of TST approach and VAS of sleep pattern consistency approach to measure self-reported IIV. For Aim 3, we conducted Pearson correlations to examine the associations between ISD of TST and VAS of sleep patterns, as well as the item-total and inter-item correlations of VAS items. Cronbach's α was used to assess the internal consistency of the VAS items. Outliers with values greater than 3 standard deviations from the mean in sleep IIV or mean TST were not included in statistical analyses (32). Pairwise deletion was used to handle missing data. Data and study materials are publicly available at Open Science Framework (https://osf.io/u4bcp/).

Results

Of the 699 respondents, 13 participants were excluded for reporting conflicting information on the questionnaires (e.g., conflicting demographics, which was interpreted as low effort of participation). Participant characteristics are shown in Table S1, Supplemental Digital Content, http://links.lww.com/PSYMED/B22. The two groups of participants were similar in gender and race/ethnicity distributions, and differed in age by only 3 years ($t(683) = 2.89$, $p = .004$). The two groups also reported similar sleep IIV (ISD of TST: $t(536) = 0.33$, $p = .746$; VAS of sleep patterns: $t(682) = 1.14$, $p = .257$). Therefore, we combined the two samples for all analyses.

Participants included in the analyses were 37.90 years old (SD = 11.65) on average, 45.34% were female, 73.03% were White, 89.65% were employed, and 26.09% held a shift-work job. There was considerable interindividual variability in participants' SIIV responses (ISD approach: M = 0.54, SD = 0.78; VAS approach: M = 30.35, SD = 25.44). Only 26.09% of participants reported no IIV in TST (i.e., ISD for the seven TSTs was 0), indicating that most individuals recognized nightly fluctuations in their sleep on the SIIV. The ISD of TST measure correlated weakly with the VAS measure of IIV (r = 0.10, p = .025), suggesting that one's overall perception of the consistency of their sleep patterns may not be strongly aligned to their fluctuations in sleep durations. The VAS items showed excellent internal consistency among the six sleep domains (Cronbach's α = .90). Item-total and inter-item correlations are listed in Table S2, http://links.lww.com/PSYMED/B22.

Table 1 shows the significant predisposing/precipitating factors for sleep IIV (Hypothesis 1; for the full correlational matrix, see Table S3, http://links.lww.com/PSYMED/B22). After adjusting for mean TST, younger individuals, participants with greater vulnerability to stress, and participants with poorer time management showed greater sleep IIV on both ISD and VAS measures. Shift workers and underrepresented racial/ethnic minorities showed greater ISD values. The primary consequences of greater sleep IIV (Hypothesis 2), when controlling for mean TST, were worse overall sleep quality and greater sleepiness (Table 1).

Discussion

Study 1 suggested that a single timepoint questionnaire can give a "snapshot" of whether a person perceives that they have higher or lower Sleep IIV. Despite the SIIV being a self-reported single timepoint measure, our findings converged with prior diary and actigraphy-based work that being younger and being more vulnerable to stress predisposed or precipitated irregular sleep patterns (Hypothesis 1) (18,23); adding to this literature, we also observed that individuals with higher self-reported IIV reported greater difficulties with time management. In addition, SIIV-based responses showed that not only mean sleep duration but also maintaining regular/consistent sleep was associated with better sleep quality and lower sleepiness (Hypothesis 2) (19,33).

Within the SIIV, we compared an ISD approach (based on seven individual sleep durations separated by days of week) to a simple VAS approach (0–100 in consistency of sleep patterns; Aim 3). Though these two approaches were weakly associated, they generally yielded similar results suggesting that they may capture distinct aspects of sleep IIV.

In Study 2, we investigated which of the Study 1 findings would be reproducible (Hypotheses 1 and 2). In addition, because either or both of the self-report measures of IIV may have been influenced by social desirability, memory distortions, or other psychological biases, we compared their outcomes to actigraphy-derived outcomes at two timepoints (Aim 3). Although it is widely recognized that most self-reported and actigraphy-derived sleep estimates are weakly correlated, both approaches have been viewed as beneficial to the sleep field because they often predict similar outcomes. Therefore, we not only examined direct concordance between the SIIV and actigraphy-derived IIV but also investigated whether they were associated with similar predisposing factors and health consequences.

TABLE 1. Demographic and Sleep-Related Correlates of Mean and IIV of TST (Study 1; N = 686)

Variables	Mean TST	IIV in TST (ISD Approach of 7 TSTs)[a]	IIV in Sleep Patterns (VAS Approach)
IIV in TST (ISD approach of 7 TSTs)[a]	$r(532) = -0.15, p < .001$***	—	—
IIV in sleep patterns (VAS approach)	$r(675) = -0.17, p < .001$***	$r(536) = 0.10, p = .025$*	—
Age	$r(676) = -0.09, p = .016$*	$r_p(530) = -0.17, p < .001$***	$r_p(673) = -0.13, p = .001$**
Gender	$t(677) = 0.27, p = .785$	$F(1, 531) = 0.18, p = .676$	$F(1,674) = 0.62, p = .430$
Race/Ethnicity (URM/non-URM)	$t(664) = 1.38, p = .169$	$F(1, 521) = 13.95, p < .001$***	$F(1,661) = 0.03, p = .874$
Shift worker	$t(677) = 0.59, p = .559$	$F(1, 531) = 7.57, p = .006$**	$F(1,674) = 0.03, p = .855$
Chronotype	$r(677) = -0.01, p = .727$	$r_p(531) = 0.03, p = .543$	$r_p(674) = 0.03, p = .402$
Vulnerability to stress-related sleep disturbances (FIRST)	$r(677) = -0.10, p = .012$*	$r_p(531) = 0.15, p < .001$***	$r_p(674) = 0.19, p < .001$***
Time management	$r(675) = 0.08, p = .041$*	$r_p(531) = -0.12, p = .004$**	$r_p(674) = -0.27, p < .001$***
Subjective health	$r(675) = 0.19, p < .001$***	$r_p(531) = -0.01, p = .773$	$r_p(672) = -0.03, p = .402$
Sleep quality (PSQI)	$r(663) = -0.45, p < .001$***	$r_p(521) = 0.26, p < .001$***	$r_p(660) = 0.20, p < .001$***
Sleepiness (SSS)	$r(677) = -0.12, p = .002$**	$r_p(531) = 0.17, p < .001$***	$r_p(674) = 0.12, p = .002$**

IIV = intraindividual variability; TST = total sleep time; ISD = individual standard deviation; VAS = visual analog scale; URM = underrepresented minorities; including American Indian or Native Alaskan, Hispanic, and African American; FIRST = Ford Insomnia Response to Stress Test; PSQI = Pittsburgh Sleep Quality Index; SSS = Stanford Sleepiness Scale.

Bivariate or partial Pearson correlations were conducted for continuous variables. Independent-samples t tests or analyses of covariance were conducted for dichotomous variables. Analyses on sleep IIV adjusted for mean TST.

[a] Degrees of freedom differed across tests due to missing data.

* $p < .05$.

** $p < .01$.

*** $p < .001$.

STUDY 2

Participants

Participants were 100 adult undergraduate students (M_{age} = 19.08, SD_{age} = 1.26, 50% females, 50% underrepresented minorities) recruited via campus flyers, classroom announcements, and email lists. To ensure representativeness of gender and racial/ethnic groups, participants were continuously enrolled until four gender-race/ethnicity demographic intersection groups each reached $n = 25$ (female minority, male minority, female nonminority, male nonminority). Underrepresented minorities in higher education were defined as identifying as Hispanic/Latinx, Black/African American, and/or American Indian/Alaskan Native (34). The fall academic semester started in person in late August and concluded in mid-December. To avoid the potential confounding effect of acclimation to the new semester and final exam-related stress, session 1 was conducted between September 18 and October 21, 2020. Session 2 was conducted between October 23 and November 25, 2020. This study was approved by the Baylor University Institutional Review Board, and all participants provided written informed consent.

Materials

Participants wore wristband actigraphy during two, 1-week monitoring sessions (1 month apart). They also completed surveys on demographic information, sleep, health, and psychosocial outcomes. Sleep assessments included sleep quality (PSQI) (28), daytime sleepiness (nine-point Likert scale; higher = sleepier), chronotype (four-point Likert scale; higher = evening), and insomnia symptoms (Insomnia Severity Index) (35). Furthermore, at each session, participants completed the SIIV (both ISD and VAS approaches).

Health measures included a 5-point Likert scale rating of overall health from "very poor" to "very good." Psychosocial assessments included perceived stress (Perceived Stress Scale) (36), depression (Center for Epidemiologic Studies Depression scale) (37), and VAS items on time management, work/study efficiency, and procrastination (formed a composite measure of time management; higher = better management).

We used Philips Respironics Actiwatch 2 Spectrum Plus devices (Bend, Oregon) to objectively measure sleep/wake state. We used the medium sensitivity setting (i.e., 40 activity counts) for nocturnal sleep intervals and the high sensitivity setting (i.e., 20 activity counts) for daytime naps (38). Actigraphy data were scored by trained research personnel based on established guidelines (39). Participants also completed daily diaries during actigraphy-monitoring sessions (40).

Procedures

Participants completed all survey assessments online via Qualtrics (baseline). Then, they wore actigraphy and completed daily diaries for 1 week (session 1). Upon completion of session 1 monitoring, participants completed a second set of survey assessments. Four weeks after session 1, participants wore actigraphy and completed daily diaries again for 1 week (session 2). Upon completion of session 2 monitoring, participants completed a third set of survey assessments.

Statistical Analyses

We computed ISD in TST for both subjective (SIIV) and objective sleep (actigraphy) for each monitoring session. For Hypothesis 1, we conducted partial Pearson correlations and ANCOVAs to investigate whether predisposing factors at baseline (i.e., age, sex, chronotype, race/ethnicity) and precipitating factors at session 1 (i.e., perceived stress, depression, time management) were associated with sleep IIV at session 1 or longitudinal changes in sleep IIV from session 1 to session 2, after adjusting for mean actigraphy TST at the corresponding session. For Hypothesis 2, we conducted partial Pearson correlations to investigate whether sleep IIV at session 1 was associated with sleep/health outcomes at session 1 or changes in sleep/health outcomes from session 1 to session 2, after adjusting for mean actigraphy TST at session 1. For Aim 3, we conducted Pearson correlations to examine the correspondence between objective and subjective sleep IIV, between ISD and VAS subjective measures, and among VAS items. Intraclass correlations and paired-sample t tests were conducted to compare sleep IIV during sessions 1 and 2. We additionally examined whether self-reported and objectively measured sleep IIV correlated with similar variables in Hypotheses 1 and 2. Participants with mean TST or IIV sleep metrics lower than −3 standard deviations or greater than +3 standard deviations of the mean were excluded from analyses. Pairwise deletion was used to handle missing data. All data and study materials are publicly available at Open Science Framework (https://osf.io/u4bcp/).

Results

Participants were 19.08 (SD = 1.26) years old, 50% female, and 50% URM. As in Study 1, the SIIV measure showed considerable interindividual variability at session 1 (ISD approach: $M = 0.84$, SD = 0.65; VAS approach: $M = 48.62$, SD = 23.49) and session 2 (ISD approach: $M = 0.81$, SD = 0.65; VAS approach: $M = 45.57$, SD = 22.53). Only 11% and 12% of participants at session 1 and 2, respectively, reported no IIV in TST (i.e., ISD = 0 h). The correspondence between ISD and VAS subjective SIIV measures was moderate at both session 1 ($r = 0.35$, $p < .001$) and session 2 ($r = 0.27$, $p = .008$). The VAS scores showed acceptable internal consistency at both sessions (Cronbach's $\alpha = .71$; Cronbach's $\alpha = .77$). Item-total and inter-item correlations of the VAS items are presented in Table S4, Supplemental Digital Content, http://links.lww.com/PSYMED/B22.

Actigraphy-derived ISD values also showed some intraindividual variability at sessions 1 and 2 ($M = 1.25$, SD = 0.56; $M = 1.57$, $SD = 0.80$; change between sessions: $t(92) = 4.37$, $p < .001$), and all participants showed actigraphy ISD values greater than 0 (range: 0.32–3.20 hours at session 1 and 0.40– 4.14 hours at session 2). There were modest levels of test-retest consistency in IIV when measured by either the SIIV (ISD: ICC = 0.69, $p < .001$; VAS: ICC = 0.60, $p < .001$) or actigraphy (ICC = 0.56, $p < .001$), suggesting that levels of sleep variability are a combination of individual traits and precipitating factors. Figure 1 shows the correspondence between objective and subjective mean TST as well as objective and subjective sleep IIV; as expected, correlations ranged from medium- to weak-sized effects. At both sessions, participants underestimated the level of their sleep IIV ($t(92) = 6.46$,

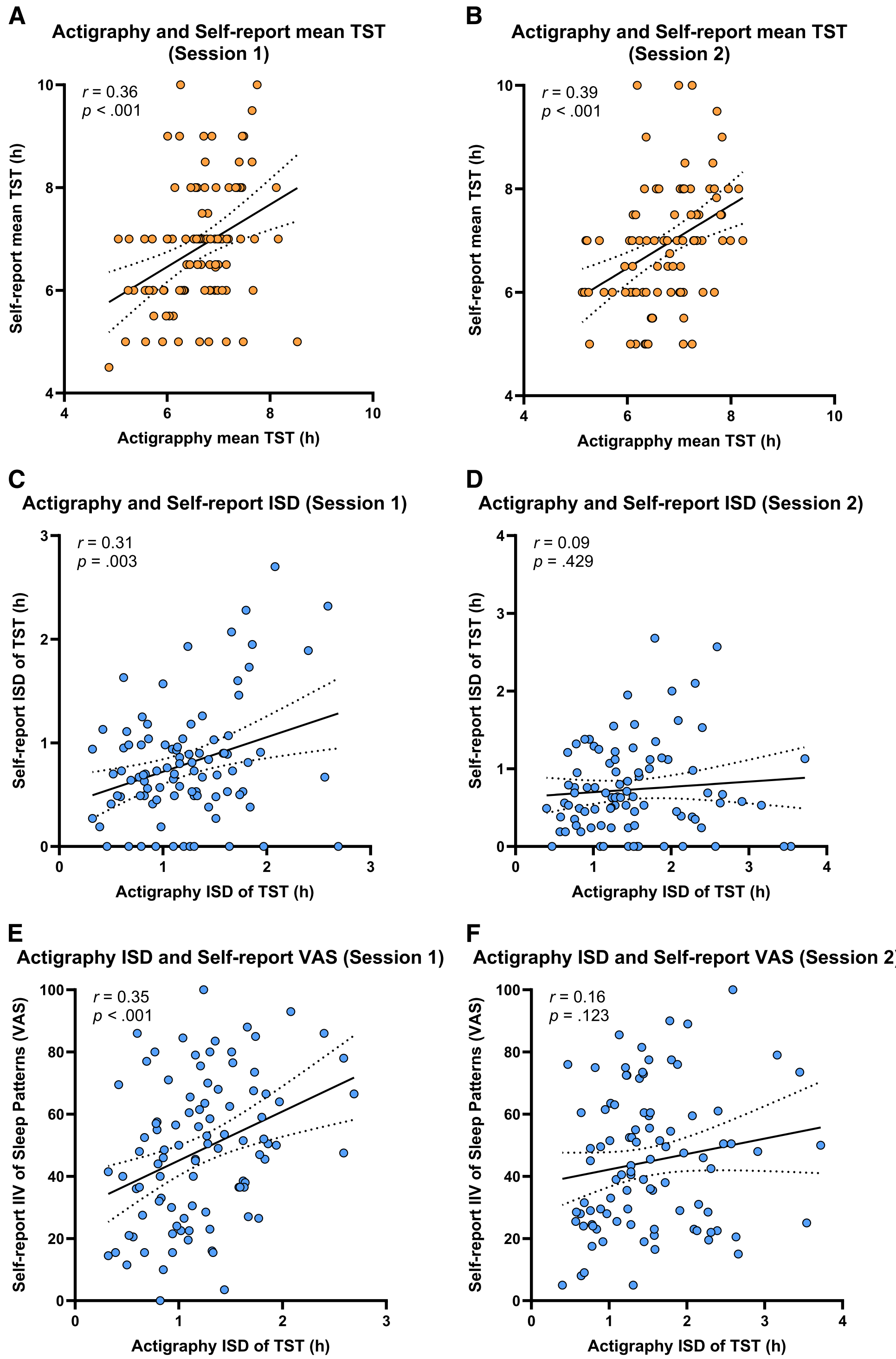

FIGURE 1. Associations between corresponding actigraphy and self-report measures for sessions 1 and 2, split by mean total sleep time measures (A, B), SIIV ISD measures (C, D), and SIIV VAS ratings (E, F). The solid lines represent the regression lines, with dotted lines illustrating the 95% confidence interval of regression lines. SIIV = Sleep Intra-Individual Variability Questionnaire; ISD = individual standard deviation. Color figure is available online only at the journal's website.

$p < .001$; $t(88) = 8.37$, $p < .001$). Other participant characteristics are presented in Table S5 and correlates of mean TST are presented in Table S6, http://links.lww.com/PSYMED/B22.

We next examined whether subjective and objective sleep IIV measures converged in correlating with similar psychosocial and health outcome variables. A key point of convergence was that, in session 1 cross-sectional analyses, both subjective and objective sleep IIVs were greater in those with worse perceived stress and poorer time management, after adjusting for mean TST (Table 2). Both subjective and objective IIV measures were

TABLE 2. Cross-Sectional and Longitudinal Relationship Between Sleep IIV, Predisposing/Precipitating Factors, and Sleep/Health Outcomes (Study 2; $N = 100$)

	Self-Report IIV in TST (ISD; Session 1)	IIV in Sleep Patterns (VAS; Session 1)	Actigraphy IIV in TST (ISD; Session 1)
Age (baseline)	$r_p(89) = -0.06$, $p = .585$	$r_p(93) = 0.14$, $p = .180$	$r_p(94) = 0.05$, $p = .607$
Gender (female; baseline)	$F(1,90) = 2.95$, $p = .089$	$F(1,93) = 0.27$, $p = .607$	$F(1,95) = 0.46$, $p = .499$
Race/ethnicity (URM; baseline)	$F(1,90) = 0.15$, $p = .698$	$F(1,93) = 1.55$, $p = .216$	$F(1,95) = 7.03$, $p = .009$**
Chronotype (baseline)	$r_p(90) = 0.15$, $p = .160$	$r_p(93) = 0.29$, $p = .004$**	$r_p(95) = 0.16$, $p = .114$
Perceived stress (PSS; session 1)	$r_p(90) = 0.09$, $p = .397$	$r_p(93) = 0.32$, $p = .002$**	$r_p(95) = 0.33$, $p < .001$***
Depression (CESD; session 1)	$r_p(90) = 0.15$, $p = .163$	$r_p(93) = 0.22$, $p = .036$*	$r_p(95) = 0.12$, $p = .225$
Time management (session 1)	$r_p(90) = -0.23$, $p = .028$*	$r_p(93) = -0.31$, $p = .002$**	$r_p(94) = -0.38$, $p < .001$***
	Self-Report IIV in TST (ISD; Longitudinal Change)	**IIV in Sleep Patterns (VAS; Longitudinal Change)**	**Actigraphy IIV in TST (ISD; Longitudinal Change)**
Age (baseline)	$r_p(79) = -0.03$, $p = .818$	$r_p(86) = 0.14$, $p = .197$	$r_p(87) = 0.09$, $p = .417$
Gender (female; baseline)	$F(1,80) = 1.07$, $p = .305$	$F(1,86) = 1.85$, $p = .178$	$F(1,88) = 0.29$, $p = .593$
Race/ethnicity (URM; baseline)	$F(1,80) = 5.68$, $p = .020$*	$F(1,86) < 0.001$, $p = .987$	$F(1,88) = 0.51$, $p = .476$
Chronotype (baseline)	$r_p(80) = 0.05$, $p = .676$	$r_p(86) = 0.08$, $p = .439$	$r_p(88) = 0.26$, $p = .014$*
Perceived stress (PSS; session 1)	$r_p(80) = 0.16$, $p = .156$	$r_p(86) < 0.001$, $p = .997$	$r_p(88) = 0.02$, $p = .877$
Depression (CESD; session 1)	$r_p(80) = -0.07$, $p = .540$	$r_p(86) = -0.08$, $p = .466$	$r_p(88) = -0.10$, $p = .360$
Time management (session 1)	$r_p(80) = -0.27$, $p = .016$*	$r_p(86) = -0.15$, $p = .172$	$r_p(87) = -0.01$, $p = .944$
	Self-Report IIV in TST (ISD; Session 1)	**IIV in Sleep Patterns (VAS; Session 1)**	**Actigraphy IIV in TST (ISD; Session 1)**
Subjective health (session 1)	$r_p(89) = -0.16$, $p = .140$	$r_p(92) = -0.26$, $p = .013$*	$r_p(94) = -0.18$, $p = .078$
Sleep quality (PSQI) (session 1)	$r_p(90) = 0.04$, $p = .678$	$r_p(92) = 0.33$, $p = .001$**	$r_p(95) = 0.38$, $p < .001$***
Sleepiness (session 1)	$r_p(90) = 0.12$, $p = .244$	$r_p(93) = 0.05$, $p = .661$	$r_p(95) = 0.001$, $p = .989$
Insomnia symptoms (ISI) (session 1)	$r_p(90) = 0.28$, $p = .007$**	$r_p(93) = 0.46$, $p < .001$***	$r_p(95) = 0.41$, $p < .001$***
Subjective health (longitudinal change)	$r_p(88) = 0.06$, $p = .568$	$r_p(91) = 0.05$, $p = .613$	$r_p(93) = -0.01$, $p = .961$
Sleep quality (PSQI) (longitudinal change)	$r_p(89) = -0.05$, $p = .673$	$r_p(91) = 0.10$, $p = .327$	$r_p(94) = 0.17$, $p = .101$
Sleepiness (longitudinal change)	$r_p(89) = 0.05$, $p = .656$	$r_p(92) = 0.07$, $p = .510$	$r_p(94) = 0.09$, $p = .381$
Insomnia symptoms (ISI) (longitudinal change)	$r_p(89) = 0.05$, $p = .667$	$r_p(92) = 0.17$, $p = .112$	$r_p(94) = 0.08$, $p = .458$

IIV = intraindividual variability; TST = total sleep time; ISD = individual standard deviation; VAS = visual analog scale; URM = underrepresented minorities; including American Indian or Native Alaskan, Hispanic, and African American; PSS = Perceived Stress Scale; CESD = Center for Epidemiological Studies Depression; PSQI = Pittsburgh Sleep Quality Index; ISI = Insomnia Severity Index.

Partial Pearson correlations (for continuous variables) and analysis of covariance (for dichotomous variables) were conducted to examine correlates of IIV in TST and sleep patterns, while adjusting for mean TST.

* $p < .05$.

** $p < .01$.

*** $p < .001$.

also greater in underrepresented minority students and those with later chronotypes, with subtle differences in cross-sectional versus longitudinal timepoints (Table 2). Furthermore, with regard to health correlates of greater IIV, greater subjective and objective IIV measures were both associated with poorer sleep quality and worse insomnia symptoms in cross-sectional analyses. Poorer subjective health and sleepiness were not consistently associated with sleep IIV measures after controlling for mean TST (Table 2).

Discussion

For Hypothesis 1, we identified the same predisposing/precipitating factors as in Study 1 (e.g., stress, time management, underrepresented minority status). Interestingly, in this population of college students that has a high proportion of evening types, we found that a later chronotype was also associated with greater sleep IIV. For Hypothesis 2, we also replicated the Study 1 finding that greater sleep IIV was associated with poorer sleep quality (and greater insomnia symptoms), independent of mean sleep duration. For Aim 3, we found that subjective and objective measures of IIV showed weak- to medium-sized correlations, just as has been documented for the correspondence between objective and subjective mean sleep duration (41,42). Though objective and subjective sleep IIV measures correlated modestly, they showed overlap in correlational outcomes related to stress, time management, underrepresented minority status, chronotype, sleep quality, and insomnia symptoms. Therefore, single timepoint questionnaires may provide a quick snapshot of a person's sleep IIV, even though actigraphy-derived metrics are likely to remain the gold standard for measuring IIV in sleep patterns.

GENERAL DISCUSSION

Irregular sleep patterns are common. Among college students (Study 2), actigraphy-defined sleep duration on a *typical* individual day deviated from the mean by 1.2–1.6 hours. Though IIV in sleep appears relatively lower in the general adult population (Study 1), participants still reported sleep durations on typical days that varied by 0.54 hours from their typical means. Our findings are consistent with Dillon and colleagues' observations that sleep variability within an individual is so common that it even exceeds sleep variability between individuals (23). In the following paragraphs, we will interpret the reproducibility of findings across the two studies, followed by consideration of the limitations, strengths, and future directions of this line of work.

The goals of this work were to identify predisposing and precipitating factors for sleep IIV (Hypothesis 1), investigate whether sleep IIV was associated with sleep/health outcomes (Hypothesis 2), and evaluate different approaches to subjective and objective IIV measurement (Aim 3). With regard to *predisposing* factors, both studies indicated that underrepresented minority status increased risk for greater sleep IIV. This finding was consistent with prior research on racial/ethnic disparities in sleep health (43,44). Three other possible predisposing factors—age, chronotype, and being a shift worker—were observed only in a single study, possibly due to sample characteristics. For example, Study 1 included a large age range and showed that sleep IIV improved with age (Study 2 was age restricted to young college students and therefore showed a null effect). This age-IIV association has been reported elsewhere in the literature (23) and is interesting because most aspects of sleep worsen with aging (45). Another sample-dependent finding was that individuals with later chronotypes reported greater sleep IIV only in Study 2, possibly due to the heightened rate of late chronotypes among college students who may also have early morning classes or irregular daily habits, both of which could increase sleep IIV (46). The analog for Study 1 (broader sample) was that individuals with variable work schedules (i.e., shift workers) were those who reported greater sleep IIV. By identifying possible predisposing factors to sleep IIV, future interventions in such groups should emphasize the importance of maintaining regular sleep-wake schedules (47,48).

In addition to predisposing factors, Studies 1 and 2 provided convergent evidence for factors that could potentially *precipitate* the increase of sleep IIV. We consistently observed that greater stress, trait vulnerability to stress, and poorer time management were associated with greater IIV (for similar outcomes, see (18,49)). It is possible that stressors prevent individuals from maintaining regular sleep schedules; for example, an upcoming exam/deadline may necessitate staying up late. Vulnerability to stressors may also elicit emotional responses and compromise sleep quality on one night, followed by a rebound in sleep duration the next night to restore homeostasis, thereby causing variability in sleep across days.

A relatively novel finding was that poor time management may precipitate greater sleep IIV, an outcome that we observed both in the general adult population (Study 1) and in college students (Study 2). Multiple interpretations for this association are possible, such as both sleep and work performance being associated with personality traits. For example, people who are more conscientious have been found to maintain more regular sleep habits and higher work performance (50,51). Another possibility is that poorer time management per se precipitates irregular sleep habits (20). By this view, someone with poor time management is more likely to need to "cram" to meet work or class deadlines, and such cramming can result in sleep restriction prior to the deadline and sleep recovery following the deadline (52). With both stress and time management correlations, reverse-causality is also possible, such as irregular sleep causing greater reactivity to stressors through modulation of hypothalamo-pituitary-adrenal axis functions and the depletion of resources for self-regulation and alertness, which would lead to reduced work efficiency (53,54). Future research will be needed to clarify the mechanisms underlying the associations between sleep IIV and stress and time management.

The two studies also showed convergent evidence for the health consequences of sleep IIV (Hypothesis 2). In both studies, we found a negative association between sleep IIV and sleep quality that was independent of mean sleep duration. These findings were consistent with past reports that showed greater actigraphy and diary-reported sleep IIV among individuals with insomnia symptoms compared to healthy controls (33,55,56). Although the current studies were correlational in nature, other work indicates that IIV could be causing worse sleep quality outcomes. For example, Van Dyk et al. (19) manipulated sleep IIV by assigning 20 adolescents to regular sleep or irregular sleep for 1 week, and the adolescents reported greater overall sleepiness during the irregular sleep week. In addition, cognitive behavioral therapies, exercise interventions, and motivational interventions that effectively reduced sleep IIV were also associated with improved sleep quality, reduced sleep complaints, and improved academic outcomes (20,57–61). The next goal for the field should be attempting larger-sample randomized controlled designs that manipulate IIV while ensuring that mean TST remains stable.

Because monitoring sleep over days can be costly and practically challenging, our Aim 3 was to compare one-time assessments of IIV with weeklong actigraphy metrics. The SIIV questionnaire and actigraphy metrics only showed small- to medium-sized correlations (indicating that they are not identical constructs), which was expected because discrepancies between self-reported and objectively measured sleep are common. For example, in the study by Jackson et al. of $N = 1920$ adults, participants overestimated sleep duration by approximately 1 hour, compared to actigraphy or polysomnography with spearman correlations between $\rho = 0.28$ and $\rho = 0.38$ (similar subjective-objective average sleep duration discordance was observed in Study 2) (41). Though it is common for total sleep time to be overestimated in self-report measures, in the current work, we found that participants were self-reporting *lower* IIV values relative to actigraphy. Therefore, many people may be unaware of the degree to which their sleep fluctuates night to night.

At first glance, the relatively low levels of subjective-objective concordance might indicate that subjective IIV is too influenced by memory distortions or other psychological biases to be of benefit. It is important, however, to note that, in Study 1, the subjective IIV measures showed the same sensitivity to behavioral and health correlates (e.g., stressors, sleep quality), as have been reported in previous diary-based IIV studies. Furthermore, in Study 2, the subjective IIV and objective IIV measures showed similar correlations to outcome variables. Therefore, questionnaire-derived IIV values appear to be complementary to objective measures in study designs that allow for both. Although actigraphy monitoring should remain the preferred method for IIV, including a questionnaire-based IIV measure in a cross-sectional study in which actigraphy is not feasible is better than having no IIV measure at all, so long as the subjective IIV data are interpreted with the appropriate caveats (i.e., subjective IIV is not identical to objectively measured IIV). For such studies, we recommend using both ISD and VAS approaches as we observed in both Study 1 and Study 2 that these metrics provided complementary information about one's subjective IIV. In addition, future research should continue to examine the psychosocial or other causes of discordance across different subjective approaches as well as between subjective and objective sleep IIV measures (42,62).

Limitations of the current studies included correlational designs that limit implications for understanding causality and an absence of measures of sleep physiology that are needed to understand homeostatic regulation. Future studies, therefore, can build on the existing literature by using prospective and experimental study designs (e.g., (63)). In addition, the current work did not include detailed information on existing health conditions, medication use, lifestyle factors, and mental health disorders that may moderate or mediate the associations between sleep IIV and health. Furthermore, there is currently no consensus on the analytical method for best representing sleep IIV. Although we used ISD of TSTs, others have employed different metrics, such as mean successive squared differences of TST and variability in TST between weekdays and weekends (social jetlag) (64,65). Additional research has examined variability in other sleep-related aspects, such as overall sleep patterns (sleep regularity index) (66), bedtime (67), and rest-activity rhythms (68,69). Future methodological advancements are anticipated to standardize approaches for studying IIV in sleep.

In conclusion, the two studies replicated and extended the literature in four ways. First, we demonstrated how a one-off assessment for sleep IIV (Supplemental Material 1 section, Supplemental Digital Content, http://links.lww.com/PSYMED/B22) can be incorporated into studies. Second, we found that a self-reported assessment of sleep IIV often captured the same relationships with age, race/ethnicity, shift work, stress, chronotype, sleep quality, and insomnia symptoms, as has been observed with sleep diaries and actigraphy measures. Third, the consistent finding that poorer time management co-occurs with greater sleep IIV informs how sleep IIV may impact industrial/organizational and educational settings. Fourth, we identified that people typically underestimate their degree of nightly sleep variability (relative to actigraphy), signaling an opportunity to highlight the importance of minimizing "yo-yo sleeping" in sleep interventional programs and cognitive behavioral therapy for insomnia clinical practice. Collectively, therefore, irregular sleep appears to be common, impactful, and a distinct dimension of sleep health.

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Data Availability Statement: Study data can be publicly accessed on Open Science Framework at https://osf.io/u4bcp/.

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