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REGULAR ARTICLE

Emotional Vulnerability to Short Sleep Predicts Increases in Chronic Health Conditions Across 8 Years

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Abstract

Background Sleep is a robust determinant of next-day emotions, but people vary in the extent that their emotions fluctuate on days following short sleep duration. These individual differences in day-to-day sleep and emotion dynamics may have long-term health implications.

Purpose To evaluate emotional vulnerability to short sleep (within-person associations between sleep duration and next-day emotions) as a risk factor for future chronic conditions.

Methods Adults aged 33–84 (N = 1,426; 57% female) in the Midlife in the United States Study reported sleep duration and emotions by telephone for eight consecutive days. Chronic conditions were assessed via checklist at baseline and at a median follow-up of eight years (range: 5–10 years). Short sleep was examined in three ways: person-centered continuous variable, ≤6 hr, and <7 hr; long sleep was defined as ≥9 hr.

Results Multilevel structural equation models revealed that people with greater negative emotions following nights of sleep ≤6 hr (vs. their negative emotions after longer sleep) had increased chronic conditions at follow-up, compared to people who were less emotionally vulnerable to short sleep (Est. = 1.04, SE = .51, p < .028). Smaller declines in positive emotions following ≤6 hr of sleep were marginally predictive of lower risk for chronic conditions (Est. = –.77, SE = .44, p = .054). Emotional vulnerability to <7, ≥9, and continuous sleep hours were not associated with subsequent chronic conditions.

Conclusions Emotional vulnerability to short sleep is a unique risk factor for the development of chronic conditions, independent of mean-level sleep duration and emotions.

Keywords: Sleep · Negative emotions · Positive emotions · Chronic conditions · Daily diary · Longitudinal

Introduction

Adequate sleep is vital for health and well-being. Yet one in three Americans report sleeping an average of ≤6 hr per 24-hr period, and this population trend for short sleep duration has become more pronounced in recent years [1]. Short sleep duration—often defined as sleeping ≤6 or <7 hr per night [1, 2]—predicts poorer cognitive functioning, adverse health outcomes, and increased mortality risk [3–5]. Short sleep duration and sleep disorders (namely, insomnia) are also robustly linked with emotions [6, 7] and are associated with greater prospective risks for affective disorders [8, 9]. In their respective literatures, sleep and emotions have separately been implicated in the same pathophysiological mechanisms underlying the development of chronic diseases, including metabolic, cardiovascular, neuroendocrine, and immune pathways [10–13]. While past research has investigated the independent associations of sleep and emotions in mental and physical health, less work has focused on the dynamic, within-person process of sleep and emotions in determining long-term health.

Sleep and emotions are bidirectionally related [14], although sleep appears to be a stronger driver of next-day emotions than vice versa among healthy adults. Naturalistic studies using daily diaries or experience sampling have found more consistent evidence for shorter or

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poorer sleep (relative to one's typical sleep duration or quality) as predictors of increased negative emotions and decreased positive emotions on the following day, compared to the reversed direction of association [15–20]. In line with this, experimental studies have shown that a single night of partial or total sleep deprivation disrupts positive emotional functioning [21, 22], increases negative emotions in reaction to mild stressors [23], and amplifies impulsive responses towards negative stimuli [24].

The process model of emotion regulation [25] can be used as a conceptual framework for understanding the ways in which sleep contributes to emotion-related outcomes [26]. According to this framework, sleep may influence multiple stages of generating and regulating emotions, including encountering and modifying emotion-eliciting situations, deploying attention, changing one's thoughts, and attempts to alter the emotion itself [26]. For example, multiple studies have found that shorter-than-usual sleep duration predicted next-day emotion-eliciting situations (e.g., more stressors and fewer positive events) and altered emotional responses to these situations [18, 20, 27]. In addition, nights of greater wake after sleep onset were associated with increases in perceived stressor severity on the following day [28]. Emotion-related processes, in turn, are strongly implicated in physical health outcomes [29]. Emotion regulation strategies (such as suppression, i.e., inhibiting expression of emotion) are linked to greater cortisol activation in our current sample [30], as well as elevated inflammation and cardiovascular disease risk in other research [31, 32]. Further, individual differences in emotional reactivity to daily stressors are associated with biological risk factors (e.g., lower heart rate variability [33], higher inflammation [34]), development of chronic conditions across a decade [35], and heightened mortality risk [36, 37].

People significantly differ from one another in the extent to which sleep duration is related to their next-day positive and negative emotions [20]. Beyond their independent associations, the strength of the within-person relationship between sleep and daily psychological functioning uniquely contributes to downstream health and well-being. Notably, individual differences in stress-related sleep disruptions (i.e., sleep reactivity) is a risk factor for the development of insomnia and depression [38]. This pattern has also been observed when considering trait-like associations between sleep duration and next-day functioning. In particular, there are stable individual differences in vulnerability to neurobehavioral impairment (e.g., fatigue, sleepiness, cognitive performance, and moods such as vigor and happiness) following total and partial sleep loss [39–41]. To our knowledge, only one previous study has evaluated the within-person association of nightly sleep and next-day psychological well-being as a predictor of physical health. In a sample of middle-aged workers, the extent to which individuals reported stressors following shorter-than-usual sleep duration was cross-sectionally associated with higher body mass index [42]. Given the robust link between sleep duration and emotions, it is important to understand the health consequences of sleep-related fluctuations in daily emotions.

The purpose of this study was to examine whether individual differences in emotional vulnerability to short sleep—as indicated by greater fluctuations in emotions after nights of shorter sleep compared to nights of longer sleep—would predict long-term changes in chronic health conditions. In a large national U.S. sample of adults, the within-person relationship between sleep and next-day emotions was assessed via daily diaries, and chronic conditions were self-reported at baseline and approximately eight years later. We hypothesized that people with greater increases in negative emotions and decreases in positive emotions following shorter-than-usual sleep duration would have elevated risk for future chronic conditions, compared to people who were less emotionally vulnerable to short sleep.

Method

Participants and design

Our data came from the Midlife in the United States Study (MIDUS), a national study designed to examine the roles of psychosocial and behavioral factors in health and well-being. MIDUS currently has three waves of data. We used data from the second and third waves, as the first wave did not assess daily positive emotions. At Wave 2 (2004–2009), a sample of 2,022 community-dwelling, English-speaking adults ages 33–84 were asked to report their chronic conditions in a self-administered questionnaire and subsequently enrolled in a daily diary substudy called the National Study of Daily Experiences (NSDE). The NSDE consisted of telephone interviews for eight consecutive evenings about participants' daily experiences, including sleep and emotions. At Wave 3 (2013–2014), participants were asked again to report their chronic conditions via questionnaire. Wave 3 was conducted a median of 8 years after the daily diaries (SD = 1.2 years, range = 5–10). Of the 2,022 participants in NSDE Wave 2, data on chronic conditions were available for 1,945 participants at Wave 2 and 1,466 participants at Wave 3. Our final analytic sample was 1,426 because the analyses used data only from participants who reported chronic conditions at both waves and had complete data on covariates. Informed consent was obtained from all individual participants included in the study. Research procedures were approved by Institutional Review Boards at the study sites.

Measures

Chronic conditions

At Waves 2 and 3, participants reported their chronic health conditions from the past 12 months using a checklist of 30 possible health conditions (e.g., asthma, diabetes, hypertension, arthritis) [35]. We omitted "chronic sleep conditions," "anxiety, depression, or some other emotional disorder," and "alcohol or drug problems" from analyses, due to their possible causal or confounding roles with sleep duration, affect, and health conditions. The remaining 27 chronic conditions were grouped into 15 categories (see Table 2). The number of chronic conditions were positively-skewed, with a median of 2 health conditions reported at Wave 2 (range = 0–12). Following previous research [43], participants were then grouped based on whether they reported *none, one, two, three*, or *four or more* conditions.

Sleep duration

As part of the daily diary telephone interviews at Wave 2, participants were asked to report their prior-night sleep duration: "Since this time yesterday, how much time did you spend sleeping, not including time you may have spent napping?" Sleep quality was not assessed in the daily diary study. For our primary analyses, we examined sleep duration in three ways. First, we considered nightly sleep duration as a person-centered continuous variable. This approach assumes that each increment of sleep duration (i.e., per additional hour or fraction thereof, compared to one's mean sleep duration) would be associated with incrementally greater health benefits. However, although short sleep duration is often associated with health risks, long sleep duration beyond approximately 8–9 hr does not always confer additional benefits for healthy adults [44, 45]. Thus, we also created dummy-coded variables to indicate short sleep using two alternative thresholds: ≤6 hr based on the National Sleep Foundation's guidelines for recommended and appropriate sleep durations for healthy adults ages 26–64 years old [46], and <7 hr based on the consensus recommendation of the American Academy of Sleep Medicine and Sleep Research Society for adults ages 18–60 years old [45, 47]. For our secondary analyses, a dummy-coded variable for sleep ≥9 hr was created as an indicator of long sleep duration.

Daily emotions

Positive and negative emotions were assessed in daily diaries using measures developed for the MIDUS study [48, 49]. Participants were asked to report the frequency of emotions experienced each day using a 5-point scale ranging from 0 (*None of the Time*) to 4 (*All of the Time*). Positive emotions were assessed with 13 items: *in good spirits*, *cheerful*, *extremely happy*, *calm and peaceful*, *satisfied*, *full of life*, *close to others*, *like you belong*, *enthusiastic*, *attentive*, *proud*, *active*, and *confident*. Negative emotions were assessed with 14 items: *restless or fidgety*, *nervous*, *worthless*, *so sad nothing could cheer you up*, *everything was an effort*, *hopeless*, *lonely*, *afraid*, *jittery*, *irritable*, *ashamed*, *upset*, *angry*, and *frustrated*. The items were averaged within each subscale to compute scores for daily positive and negative emotions. Multilevel reliability was computed using procedures outlined by Geldhof et al. [50]. Within-person reliabilities were 0.85 for positive emotions and 0.82 for negative emotions, and between-person reliabilities were 0.97 for positive emotions and 0.92 for negative emotions.

Data analytic strategy

Multilevel structural equation modeling (MSEM) analyses were used to permit a multivariate examination of short sleep duration and chronic health conditions across time-scales and levels of analysis. These models handled the hierarchical structure of the data, in which daily measurement occasions were nested within people, and allowed random slope coefficients to be simultaneously modeled as either exogenous predictor variables or endogenous outcome variables across levels of analysis. All effects were estimated simultaneously in Mplus Version 8 using Bayesian estimation, which made use of all available data. Participants with more days of daily diary data were weighted more heavily in statistical models than participants with fewer days of data.

At the within-person level, prior-night sleep duration or $Short\ Sleep_{ij}$ was included as a predictor of daily levels of $Emotions_{ij}$ (Fig. 1). Separate models were run for positive and negative emotions. The daily within-person association between short sleep and emotions (i.e., emotional vulnerability to short sleep) was modeled as a random slope and was permitted to vary across individuals. Weekend (vs. weekday) was included as a within-person covariate to adjust for its associations with daily levels of $Emotions_{ij}$. At the between-person level of analysis, individual differences in $Emotional\ Vulnerability_{i}$ was modeled as a latent slope, indicating that it was estimated from the model and reflected the strength of the daily association for individual *i*. $Emotions_{i}$ was modeled as a latent mean that reflected average levels of positive or negative emotions for individual *i* across days. Individual differences in emotional vulnerability to short sleep and mean levels of emotions were used to predict individual differences in chronic health conditions measured

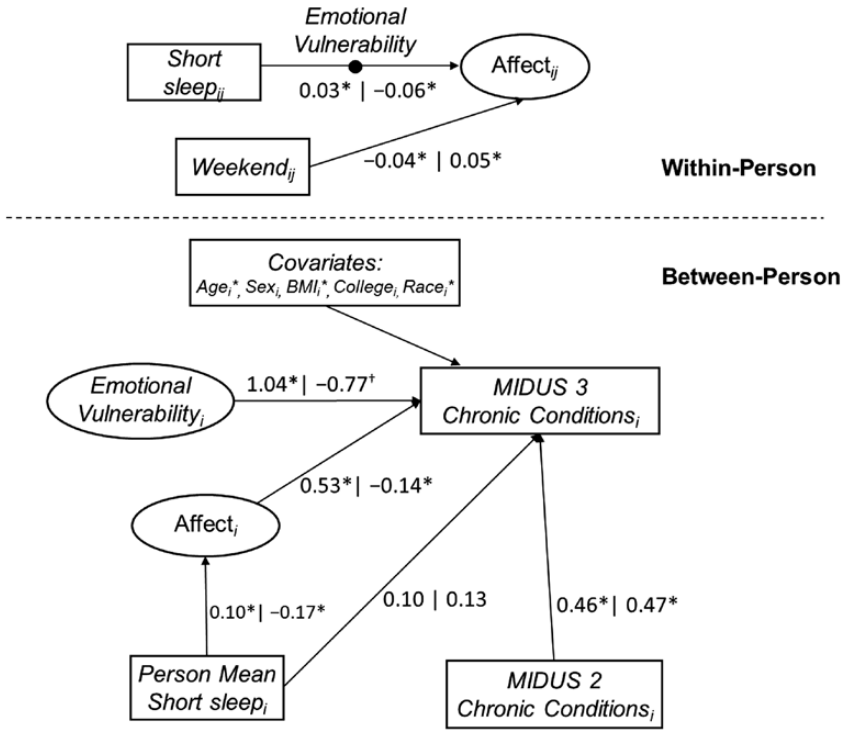

Figure 1. Estimated multilevel structural equation model for emotional vulnerability to short sleep (≤6 hr) at Wave 2 predicting chronic conditions at Wave 3. Note. N = 1,426 participants and 10,665 daily assessments. Values are unstandardized coefficients from negative emotions | positive emotions model, respectively. Ovals indicate variables were estimated within the model. Black dot indicates that pathway was modeled as a random slope. Affect = negative emotions | positive emotions, respectively. Short sleep (1 = prior-night sleep ≤6 hr; 0 = prior-night sleep >6 hr). Sex (1 = female; 0 = male). BMI = body mass index. College (1 = some college or more; 0 = high school or less). Race (1 = nonwhite; 0 = white). †p = .054. *p < .05.

approximately 8 years later at Wave 3. The number of chronic health conditions was modeled as an ordered categorical variable (0, 1, 2, 3, 4+).

A set of covariates were included to adjust for the following effects on Wave 3 chronic health conditions: Wave 2 age (centered at the grand mean), sex (male vs. female), education (some college or higher vs. high school graduate or lower), race (white vs. nonwhite), body mass index at Wave 3, number of chronic conditions at Wave 2, person-mean daily emotions at Wave 2, and person-mean sleep duration at Wave 2 (i.e., number of nightly hours of sleep, or the proportion of days with ≤6 or <7 hr of prior-night sleep). By adjusting for the association between Wave 2 chronic conditions and Wave 3 chronic conditions, the models examined predictors of residual change in the number of chronic conditions. We considered prior-day affect as a covariate; however, because the findings were similar before and after controlling for prior-day affect, we chose to omit it to keep the models parsimonious.

We conducted several secondary analyses. First, age and sex were evaluated as potential moderators. Second, the models were repeated to separately examine each of the 15 categories of chronic conditions as outcomes; each chronic condition was modeled as a categorical binary variable. Third, the analyses were conducted using ≥9 hr of sleep to evaluate whether emotional vulnerability to long sleep duration might predict future risk for chronic health conditions.

Results

Descriptives and correlations

Sample descriptives and correlations among study variables are provided in Table 1, and the percentages of participants with each chronic condition are shown in Table 2. Participants reported a mean of 1.87 chronic conditions at Wave 2 and 2.28 chronic conditions at Wave 3. Self-reported mean sleep duration was 7.11 hr per night, and ≤6 hr of sleep was reported on an average of 26% of diary days. Participants with more nights of ≤6 hr of sleep had higher mean daily negative emotions, lower positive emotions, and more chronic conditions at both waves, compared to those with fewer nights of short sleep.

Table 1. Means, standard deviations, and correlations among study variables

Variable	*M* (*SD*) or *N* (%)		Correlation										
			1	2	3	4	5	6	7	8	9	10	11
1. Age at Wave 2	56.25	(12.20)	–										
2. Sex (1 = female)	813	(57%)	–.02	–									
3. Education (1 = some college or higher)	984	(69%)	–.11**	–.07**	–								
4. Race (1 = nonwhite)	228	(16%)	–.07**	.05*	–.10**	–							
5. Body mass index	28.43	(6.32)	–.11**	–.00	–.12**	.18**	–						
6. Daily sleep duration	7.11	(1.03)	.06**	.00	.07**	–.16**	–.10**	–					
7. Percentage of days with sleep ≤6 hr	26%	(30%)	–.08**	.03	–.10**	.18**	.14**	–.83**	–				
8. Daily negative emotions	0.21	(0.28)	–.16**	.07**	–.03	.10**	.05	–.12**	.16**	–			
9. Daily positive emotions	2.72	(0.71)	.20**	–.00	–.04	–.02	–.07**	.06**	–.10**	–.50**	–		
10. Wave 2 chronic conditions	1.87	(1.40)	.29**	.13**	–.08**	.07**	.12**	–.04	.08**	.15**	–.14**	–	
11. Wave 3 chronic conditions	2.28	(1.39)	.26**	.11**	–.08**	.10**	.18**	–.03	.07**	.15**	–.11**	.55**	–
12. Age at wave 3	64.34	(11.36)	1.0**	.00	–.11**	–.04	–.10**	.05*	–.08**	–.18**	.25**	.26**	.27**

Note. N = 1,426 participants. *p < .05. **p < .01.

Table 2. Percentage of participants reporting chronic health conditions at Wave 2 and Wave 3

Chronic condition category	Wave 2 Percentage of sample	Wave 3 Percentage of sample
1. Autoimmune disorders	1.54	2.03
2. Cancer	13.24	22.81
3. Cardiovascular conditions	37.11	50.14
4. Diabetes	9.15	15.71
5. Digestive conditions	21.72	28.05
6. Foot trouble	10.47	13.25
7. Hay fever	11.17	12.41
8. Gall bladder trouble	2.16	1.89
9. Lung conditions	12.43	13.89
10. Neurological conditions	2.51	2.73
11. Pain-related conditions	39.27	41.94
12. Skin trouble	8.59	9.61
13. Thyroid disease	7.75	12.34
14. Dental, mouth, and gum trouble	9.08	9.33
15. Urinary or bladder problems	10.75	15.50

Note. N = 1,426 participants.

Emotional vulnerability to short sleep and chronic conditions

Figure 1 and Table 3 show MSEM results for short sleep defined as ≤6 hr. At the within-person level, short prior-night sleep predicted higher next-day negative emotions and lower positive emotions. Between-persons, individuals with higher mean negative emotions and lower mean positive emotions had more chronic conditions at the Wave 3 follow-up. Age, nonwhite race, higher body mass index, and a higher number of chronic conditions at Wave 2 were also significantly associated with more Wave 3 chronic conditions across all models.

People who were more emotionally vulnerable to short sleep—that is, heightened negative emotions following nights of sleep ≤6 hr, compared to their negative emotions following nights of sleep >6 hr—had greater increases in chronic conditions at follow-up than people who were less emotionally vulnerable to short sleep (Est. = 1.035, SE = .512, p = .028). For positive emotions, larger estimates for *emotional vulnerability to short sleep* refer to smaller decreases (i.e., better maintenance) in positive emotions after nights of ≤6 hr of sleep versus after >6 hr of sleep. As shown in Fig. 1 and Table 3, there was a marginally significant trend (Est. = −0.774, SE = .438, p = .054) such that people who were better able to maintain positive emotions following short sleep had less-increased chronic conditions at follow-up, compared to those who experienced greater loss of positive emotions in response to short sleep.

Electronic Supplementary Tables S1 and S2 present results for MSEM analyses in which sleep duration was entered as <7 (vs. ≥7 hr) or as a continuous variable, respectively. Person-means for <7 hr of sleep and for continuous sleep duration were not associated with chronic conditions at Wave 3. The within-person association between sleep duration and next-day positive or negative emotions (i.e., emotional vulnerability to short sleep) did

Table 3. MSEM analyses of emotional vulnerability to short sleep (≤6 hr) at Wave 2 predicting chronic conditions at Wave 3

Variable	Negative emotions model			Positive emotions model		
	Estimate (*SE*)	*p*-value	95% CI	Estimate (*SE*)	*p*-value	95% CI
Fixed effects						
Within-person variables predicting daily emotions						
Emotions intercept	**0.169 (.008)**	**<.001**	**[0.153, 0.185]**	**2.792 (.025)**	**<.001**	**[2.743, 2.841]**
Prior-night short sleep	**0.034 (.008)**	**<.001**	**[0.019, 0.049]**	**−0.062 (.013)**	**<.001**	**[−0.088, −0.036]**
Weekend	**−0.044 (.005)**	**<.001**	**[−0.054, −0.035]**	**0.050 (.008)**	**<.001**	**[0.033, 0.067]**
Between-person variables predicting Wave 3 chronic conditions						
Female	0.106 (.060)	.076	[−0.009, 0.225]	**0.123 (.059)**	**.042**	**[0.005, 0.237]**
College education	0.025 (.065)	.724	[−0.101, 0.152]	0.029 (.061)	.656	[−0.096, 0.147]
Race (1 = nonwhite)	**0.202 (.085)**	**.018**	**[0.034, 0.369]**	**0.233 (.085)**	**.004**	**[0.065, 0.398]**
Body mass index	**0.026 (.005)**	**<.001**	**[0.016, 0.036]**	**0.025 (.005)**	**<.001**	**[0.016, 0.035]**
Wave 2 age	**0.021 (.003)**	**<.001**	**[0.015, 0.027]**	**0.021 (.003)**	**<.001**	**[0.016, 0.027]**
Wave 2 chronic conditions	**0.465 (.025)**	**<.001**	**[0.417, 0.513]**	**0.472 (.024)**	**<.001**	**[0.426, 0.518]**
Person-mean emotions	**0.529 (.163)**	**<.001**	**[0.214, 0.851]**	**−0.141 (.031)**	**<.001**	**[−0.202, −0.082]**
Person-mean short sleep	0.097 (.105)	.348	[−0.101, 0.311]	0.130 (.103)	.206	[−0.063, 0.334]
Emotional vulnerability to short sleep	**1.035 (.512)**	**.028**	**[0.088, 2.074]**	−0.774 (.438)	.054	[−1.687, 0.017]
Random effects						
Within-person emotions	**0.044 (.001)**	**<.001**	**[0.043, 0.045]**	**0.137 (.002)**	**<.001**	**[0.133, 0.141]**
Between-person						
Emotions intercept	**0.044 (.002)**	**<.001**	**[0.040, 0.049]**	**0.459 (.018)**	**<.001**	**[0.424, 0.498]**
Emotional vulnerability to short sleep	**0.019 (.002)**	**<.001**	**[0.014, 0.024]**	**0.035 (.008)**	**<.001**	**[0.023, 0.052]**

Note. Results are based on 10,665 daily assessments (N = 1,426 participants). CI = confidence interval. Short sleep (≤6 hr prior-night sleep = 1; >6 hr sleep = 0). Estimates of fixed effects are reported as unstandardized regression coefficients. Estimates of random effects are reported as variances. Bold values represent $p < .05$.

not significantly predict longitudinal changes in chronic conditions.

Because prior-day affect could drive associations with both prior-night sleep and current-day affect, we repeated the analyses for sleep duration ≤6 versus >6 hr, controlling for prior-day affect (Supplementary Table S3). These analyses had 20 fewer participants and 1,803 fewer days of observation due to missingness in consecutive days of data. The findings were similar, such that emotional vulnerability to ≤6 hr of sleep remained significantly predictive of higher risk for subsequent chronic conditions in the negative emotions model (Est. = 1.196, SE = .468, p = .006) and marginally predictive in the positive emotions model (Est. = −1.297, SE = .717, p = .052). Controlling for prior-day affect also did not alter the nonsignificant results for emotional vulnerability to <7 hr of sleep and continuous sleep duration.

Secondary analyses

In secondary analyses, age and sex did not moderate any associations between emotional vulnerability to short sleep and subsequent chronic conditions.

Next, we ran additional models to examine emotional vulnerability to short sleep (≤6 hr) as predictors of each of the 15 types of chronic conditions (Supplementary Table S4). For the negative emotion analyses, the estimates for most of the chronic conditions (e.g., cardiovascular, cancer, digestive, lung) were not statistically significant, yet they were in the predicted direction of the association. Greater negative emotions following short sleep were significantly associated with future skin trouble and marginally associated with pain-related conditions, but also predicted *lower* risk for thyroid disease. For the positive emotion analyses, better maintenance of positive emotions following short sleep was only marginally predictive of lower prospective risks for cardiovascular, digestive, and pain-related conditions. Unexpectedly, lower positive emotional vulnerability to short sleep was associated with a *greater* risk for skin trouble. The positive emotion results for the remaining health conditions were nonsignificant. Overall, the mostly nonsignificant results suggest that no single condition was responsible for driving the health risks associated with emotional vulnerability to short sleep. Rather, aggregating across the chronic conditions provided more sensitivity for detecting the association between

emotional vulnerability to short sleep and risk for a variety of subsequent chronic conditions.

Finally, ≥9 hr of sleep were reported on 10% of study days. Emotional vulnerability to long sleep duration was not predictive of chronic conditions in either the negative or positive emotions models (Supplementary Table S5).

Discussion

Abundant evidence has established high negative emotions [12], low positive emotions [51, 52], and short sleep duration [3, 4] as unique contributors to future health and well-being. The current study extends this previous work by demonstrating that individual differences in emotional vulnerability to short sleep were prospectively associated with future chronic conditions. Specifically, people with greater increases in negative emotions following nights of sleep ≤6 hr (vs. their usual level of negative emotions after longer sleep) were more likely to have increased chronic conditions across a median of 8 years of follow-up, compared to people who were less emotionally vulnerable to short sleep. In addition, loss of positive emotions following short sleep was a marginally-significant risk factor for long-term chronic conditions. Importantly, these associations were independent of person-mean emotions and sleep duration, baseline chronic conditions, and sociodemographic factors. The findings demonstrate that dynamic psychological and behavioral processes in daily life can add meaningful information about health risk and resilience, beyond the information provided by static measures.

The prospective relationship between emotional vulnerability to ≤6 hr of sleep and chronic conditions was evident when aggregating across all chronic conditions and did not appear to be consistently driven by any single condition. In analyses examining separate categories of health conditions, there were two unexpected associations: Higher negative emotions and greater loss of positive emotions following short sleep predicted *lower* risks for thyroid disease and skin trouble, respectively. Because we had conducted multiple tests and these health conditions were reported relatively less frequently than others (e.g., compared to cancers, cardiovascular, and pain-related conditions), we are cautious in interpreting these results from individual conditions. Sleep duration, emotions, and their dynamic relationship may be related to pathways that underlie a variety of chronic conditions, including immune [53], neuroendocrine [54], and cardiometabolic mechanisms [13], as well as the psychosocial and behavioral mechanisms described below.

When short sleep was examined as a continuous variable or defined as <7 hr, emotional vulnerability to short sleep did not significantly predict future risk for chronic conditions. Emotional vulnerability to long sleep (defined as ≥9 hr) was also not associated with chronic conditions at follow-up. Based on the consensus statement of the American Academy of Sleep Medicine and Sleep Research Society, 7 hr is the recommended minimum sleep duration for promoting optimal health among adults aged 18–60 [45, 47]. The National Sleep Foundation recommends 7–9 hr of sleep for adults aged 26–64 years, yet indicate that as little as 6 hr or up to 10 hr may be appropriate for some people [46]. Our results showed that a more stringent definition for short sleep (i.e., ≤6 hr) was needed to observe the associations of within-person sleep and emotions dynamics with long-term chronic conditions. However, because the results for sleep duration as a continuous variable and for <7 hr of sleep were in the predicted direction (albeit nonsignificant), it is unlikely that ≤6 hr is a strict threshold. In fact, an analysis of the U.S. National Health and Nutrition Examination Survey showed that people who reported typically sleeping <5 hr had a greater risk for adverse cardiometabolic outcomes, compared to those who typically slept 5–6 hr [55]. Likewise, a meta-analysis of prospective studies showed a graded association between short sleep durations (<6, <5, and <4 hr) and mortality risk [4]. Unfortunately, we were unable to distinguish sleep duration from sleep need and therefore could not account for each individual's specific amount of sleep needed for optimal emotional well-being. Because people differ from one another in their sleep need, future research could examine emotional vulnerability following nights when an individual's sleep need is met versus unmet (e.g., using morning reports of perceived sleep sufficiency).

Our findings are in line with previous work demonstrating that individual differences in the link between sleep duration and elevated next-day stressors were cross-sectionally associated with higher body mass index [42], and that trait-like propensity for exaggerated sleep disturbance in response to common real-life stressors was predictive of insomnia and depression across 1–2 years [38]. The current study extends the existing literature as it is the first investigation, to our knowledge, to examine the within-person relationships between sleep duration and emotions as a vulnerability factor for long-term physical health outcomes.

A number of potential explanations and mechanisms could be evaluated in future research. Building on the emotion regulation framework [25, 26], it is possible that people who are more emotionally vulnerable to short sleep might regulate their emotions (e.g., selecting and modifying situations, directing their attention, modifying their thoughts, modulating responses to emotion-eliciting situations) in ways that are detrimental for

downstream health. For example, those with greater emotional vulnerability may be more likely to select themselves into stressful situations following short sleep [18], exhibit impairments in decision-making and impulse control that can lead to poorer health behaviors (e.g., physical inactivity, dietary indiscretion) [56], and greater daytime sleepiness and fatigue could prompt them to modify activities such as reducing work and social activities [57]. In addition, individuals with greater emotional vulnerability to short sleep might be relatively more likely to attend to negative aspects of situations, perhaps leading to greater stress reactivity [20, 27], unfavorable stress appraisals [28], and difficulties navigating interpersonal conflicts [58]. These potential consequences for day-to-day activities, health behaviors, social relationships, and stress, in turn, might accumulate over time to increase prospective risks for chronic conditions. Furthermore, given that sleep reactivity to stressors has a substantial genetic component as well as an environmental component [59], future work could examine the heritability of emotional vulnerability to short sleep and the extent to which its genetic and environmental influences overlap with those for health indicators.

Several limitations should be considered when interpreting the findings of this study. First, our measure of sleep duration was self-reported, and we had no other subjective or any objective assessments of sleep. Because the associations of sleep with subsequent daily psychological outcomes can vary based on sleep indices and based on the method of assessment [16, 28, 60], additional research is needed to evaluate the health implications of fluctuations in daily emotions in response to other indicators of sleep. Second, this study assumes that individual differences in emotional vulnerability to short sleep are stable and reflect a snapshot of a person's typical pattern of responding to short sleep duration, but whether this pattern is stable and trait-like is unknown. Lastly, our data came from a large national study, but it is unknown whether the current findings would extend to special populations such as night-shift workers or people with chronic insomnia.

To conclude, this study found that people with more heightened negative emotions following nights of ≤6 hr of sleep had a greater risk for developing chronic conditions after approximately 8 years, with marginally-significant findings regarding the loss of positive emotions following short sleep. Adding to the well-established evidence—from separate literatures—that sleep and emotions contribute to chronic disease risk, we demonstrated that emotional vulnerability to short sleep was a unique risk factor for downstream health. This study provides avenues for future inquiry on within-person dynamics in sleep and emotions.

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Compliance with Ethical Standards

Authors' Statement of Conflict of Interest and Adherence to Ethical Standards Outside of the current work, Orfeu M. Buxton discloses that he received subcontract grants to Penn State from Proactive Life LLC (formerly Mobile Sleep Technologies) doing business as SleepScape (NSF/STTR #1622766, NIH/NIA SBIR R43-AG056250, R44-AG056250), received honoraria/travel support for lectures from Boston University, Boston College, Tufts School of Dental Medicine, New York University and Allstate, and receives an honorarium for his role as the Editor in Chief of Sleep Health (sleephealthjournal.org). The other authors have no conflicts of interest to disclose.

Ethics Approval All procedures performed in studies involving human participants were in accordance with the ethical standards of the institutional and/or national research committee and with the 1964 Helsinki declaration and its later amendments or comparable ethical standards.

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