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The Whole Is Not the Sum of Its Parts: Specific Types of Positive Affect Influence Sleep Differentially

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Given the known detrimental effects of poor sleep on an array of psychological and physical health processes, it is critical to understand the factors that protect sleep, especially during times of stress when sleep particularly suffers. Positive affect (PA) arises as a variable of interest given its known associations with health and health behaviors and its ability to buffer stress. In 2 studies, we examined which types of PA (distinguished by arousal level and trait/state measurement) were most beneficial for sleep and whether these associations varied depending on the stress context. In Study 1, college students ($N = 99$) reported on their PA and sleep during the week of a major exam. In Study 2, 2 weeks of daily PA and sleep data were collected during a period with no examinations in a similar sample of students ($N = 83$). Results indicated that high trait vigor was tied to better sleep efficiency and quality, especially during high stress. Trait calm was generally unhelpful to sleep, and was related negatively to sleep duration. State calm, on the other hand, interacted with stress in Study 2 to predict more efficient day-to-day sleep on days with higher average stress. These findings illustrate the importance of considering arousal level, affect duration, and the stress context in studies of PA and health.

Keywords: positive affect, sleep, vigor, calm, stress

Poor sleep has been implicated in an array of negative health outcomes such as cardiovascular disease, infectious illness, and even mortality (Ayas, White, Al-Delaimy, et al., 2003; Ayas, White, Manson, et al., 2003; Cribbet et al., 2014; Patel et al., 2004; Prather, Janicki-Deverts, Hall, & Cohen, 2015). This supports the hypothesis that sleep is a critical restorative behavior for neuronal, physiological, and health resources (Cirelli & Tononi, 2008; Davies et al., 2008). Given these detrimental consequences, it is vital to understand the individual differences and contexts associated with good sleep outcomes, like high sleep efficiency (i.e., being able to fall asleep quickly and stay asleep) and high sleep quality (i.e., feeling rested upon awakening), especially during times of stress when sleep typically suffers (van Schalkwijk, Blessinga, Willemen, Van Der Werf, & Schuengel, 2015).

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Positive Affect and Sleep

Positive affect (PA), at both the state and trait level, is associated with better sleep. For example, an ecological momentary assessment (EMA) study found that high daily state PA was associated with fewer self-reported sleep problems the following night in young women (Kalmbach, Pillai, Roth, & Drake, 2014). Similarly, EMA state PA data averaged over the course of one day was correlated with fewer self-reported sleep problems in older adults (Steptoe, O'Donnell, Marmot, & Wardle, 2008). Trait PA has also been associated with better self-reported sleep (i.e., feeling rested and reporting higher sleep quality) in a large nationally representative sample (Ong et al., 2013). Importantly, this benefit is not simply due to a lack of negative affect (NA), a factor frequently studied with sleep. For example, a recent review found that the presence of PA, and not just the absence of NA, was associated with better sleep (Baglioni, Spiegelhalder, Lombardo, & Riemann, 2010).

While these studies infer PA to sleep directionality, there is also circularity in the connections (Kahn, Sheppes, & Sadeh, 2013). Experimental sleep deprivation studies have shown decreases in PA and activation (e.g., Paterson et al., 2011; Franzen, Siegle, & Buysse, 2008), likely due to a lack of rapid eye movement (REM; Vandekerckhove & Cluydts, 2010) and changes in emotional inhibitory processes in the brain (Goldstein & Walker, 2014). Past studies have dealt with this bidirectionality by using prospective or experimental study designs (e.g., Armon, Melamed, & Vinokur, 2014; for review see Ong, Kim, Young, & Steptoe, 2016) but it is frequently true that some part of affect, especially state affect, is influenced by sleep (Paterson et al., 2011; for review see Kahn et al., 2013).

Which Types of Positive Affect Matter for Sleep?

While the above findings are provocative, there are many remaining unanswered questions in the PA–sleep literature. Foremost is the question of what type of PA matters for good sleep. In most studies of PA, it is common to treat all forms of PA equally (see exceptions: e.g., Campos, Shiota, Keltner, Gonzaga, & Goetz, 2013; Shiota, Neufeld, Yeung, Moser, & Perea, 2011), and to assume that all types are beneficial. This contrasts with the highly differentiated NA domain. For sleep and NA specifically, which has been extensively studied (e.g., Brand, Gerber, Pühse, & Holsboer-Trachsler, 2010; Gerber, Hartmann, Brand, Holsboer-Trachsler, & Pühse, 2010; Golding & Aneshensel, 1989; Lee, Shaver, Giblin, & Woods, 1990; Sing & Wong, 2010; Wiegand et al., 2010), research has found distinctions in the effects of different kinds of NA (e.g., anxiety, depression, sadness, fear; Alfano, Zakem, Costa, Taylor, & Weems, 2009; Kalmbach et al., 2014; Kim-Spoon, Holmes, & Deater-Deckard, 2015; Suls, 2013), although all types appear harmful (e.g., Leotta, Carskadon, Acebo, Seifer, & Quinn, 1997).

For PA, what might determine whether a subtype is helpful versus harmful is its arousal level. High physiological arousal has been tied to sleep problems (e.g., Riemann et al., 2010), for example, in insomniacs who report greater presleep arousal as compared to good sleepers (Morin, Rodrigue, & Ivers, 2003). Thus, to the extent that induced state high arousal PA translates into high physiological activation (e.g., Shiota et al., 2011), proximal sleep could be harmed (Cohen & Pressman, 2006; Riemann et al., 2010). Should this be the case, we would expect that on a given day, low arousal feelings (e.g., calm, relaxed) would be tied to the best sleep since they seem most suited to encourage the transition from wakefulness to rest. Consistent with this, a single study has shown that in young women, state feelings of serenity were tied to better sleep that night (Kalmbach et al., 2014). Similarly, trait and state mindfulness, known to encourage and be associated with calm (e.g., Weinstein, Brown, & Ryan, 2009; Hill & Updegraff, 2012), have been associated with sleep benefits (e.g., Carlson & Garland, 2005; Howell, Digdon, Buro, & Sheptycki, 2008). That being said, high activation PA can also arise from mindfulness practice (Erisman & Roemer, 2010), making it unclear which parts of PA underlie these benefits.

Surprisingly, there are reasons to believe that high arousal PA may be helpful to sleep. First, most studies of PA and health rely on trait high arousal PA measures (e.g., Watson, Clark, & Tellegen, 1988) and these have been consistently tied to better health (Pressman & Cohen, 2005; Boehm & Kubzansky, 2012). Furthermore, these effects seem to be driven by high arousal PA when subcomponents effects are contrasted (e.g., Pressman & Cohen, 2012; Cohen, Alper, Doyle, Treanor, & Turner, 2006). Given that sleep is frequently cited as a plausible mechanism underlying PA–health benefits (Boehm & Kubzansky, 2012; Pressman & Cohen, 2005), whether high arousal PA is good for sleep is an important question worth exploring.

How Does Stress Factor Into the PA–Sleep Association?

Chronic and acute stress are associated with disruptions in sleep efficiency, quality, and duration (Åkerstedt et al., 2002; Cheeta, Ruigt, van Proosdij, & Willner, 1997; Hefez, Metz, & Lavie, 1987; Kant et al., 1995; Kim & Dimsdale, 2007; Morin et al., 2003) even with minor school and work stress (Zawadzki, Graham, & Gerin, 2013). Coping with stress necessitates alertness, thus it is not surprising that it hampers sleep. Specifically, stress-related arousal triggers changes in neuropeptide circulation, autonomic activation, and hormonal activity that are also connected to wakefulness (Kim & Dimsdale, 2007; Hall et al., 2004; Sanford, Suchecki, & Meerlo, 2014). That being said, this relation is complex. Acute stress and arousal have also been tied to increased and deeper sleep in animals (Sanford et al., 2014), potentially due to the need to recover (e.g., Meerlo, Pragt, & Daan, 1997). Unfortunately, the same may not be true of humans who often extend stress by ruminating, and in turn, disrupt their sleep (Sanford et al., 2014).

Together, this indicates a need to understand the complex factors that ameliorate the pathogenic effects of stress on sleep. PA emerges as an ideal candidate since it has been specifically hypothesized and shown to be a stress buffer via its ability to alter stress appraisals, reduce reactivity, and hasten recovery (Cohen & Pressman, 2006; Fredrickson & Levenson, 1998; Kraft & Pressman, 2012; Ong, Bergeman, Bisconti, & Wallace, 2006; Steptoe, Wardle, & Marmot, 2005). PA is also thought to help in the midst of stress by broadening mindsets and helping to regulate negative emotional experiences (i.e., Broaden & Build; Fredrickson, 1998). The ability for PA to buffer an individual from the negative effects of stress is distinct from the construct of trait resilience, which aids an individual to successfully adapt and bounce back (or grow) from adverse conditions (the latter not proposed by the Stress-Buffering Hypothesis; Cohen & Pressman, 2004; Bonanno, 2005). Resilient individuals do, however, use PA to aid in coping with and bouncing back from stressful experiences (Tugade & Fredrickson, 2004), further pointing to PA's likely role in helping sleep during stress. PA has also been proposed to play a critical role in restorative behaviors (i.e., the behaviors that encourage homeostasis following challenge; Boehm & Kubzansky, 2012; Pressman & Cohen, 2005; Pressman et al., 2009; Siegel, 2003), sleep included. Given the above research, it is surprising that the role of PA in the stress–sleep connection has gone untested.

Problematic, however, is that while PA may serve as a stress arousal-reducing antidote, much of PA is high arousal (e.g., feeling interested, excited, vigorous, enthusiastic; e.g., Watson et al., 1988). Thus, the issue of emotional activation becomes of central importance to understanding the PA–sleep–stress connection. While this issue has not been directly addressed, stress interventions commonly include calm-inducing components (e.g., meditation, slow breathing exercises, relaxation activities; Creswell, Myers, Cole, & Irwin, 2009; Rabin, Pinto, Dunsiger, Nash, & Trask, 2009) and have been shown to result in sleep benefits (Howell et al., 2008). To our knowledge, activated PA has not been examined in stress or sleep interventions.

Does Duration of PA Matter for PA, Stress, and Sleep Connections?

State versus trait PA may have different implications for sleep and understanding these differences can inform future sleep interventions and research. In the PA–health literature, it is typically assumed that trait PA will be most important since how you feel regularly will be more impactful on your overall physiology, behavior, and relationships (Pressman & Bowlin, 2014). That being said, strong changes in state PA clearly influence physiology. For example, although trait PA may determine an individual's baseline physiological profile, PA inductions alter physiology beyond baseline levels (see review by Pressman & Cohen, 2005), and have influences on behavior and other important outcomes (Lyubomirsky, King, & Diener, 2005).

When considering both the arousal and duration aspects of PA, we anticipate that when elevated energy is needed to approach and cope with stress demands, feeling generally high in activated PA (e.g., high trait vigor) will be most beneficial for sleep. It will match and aid in the accomplishment of stress-associated needs, supporting the ability to solve problems during the day and transition into restoration at night. The distinction of trait versus state is essential here as high state arousal (e.g., feeling vigorous before bed) could interfere with sleep, but general high trait vigor on a regular basis might not. Next, given the counterindicated effects of high state arousal PA on sleep, we hypothesize that low arousal state emotions like calm will be most helpful for sleep when stress is high on the same day. Although we have made certain predictions about high and low arousal PA, we do not have strong hypotheses regarding the specific effects of midarousal PA in this context, given that it is neither high nor low arousal. However, we include it in these studies for exploratory purposes.

What Is Good Sleep?

Before moving on to the current research, it is important to explain what we mean by "good sleep." Sleep is a multidimensional construct, and it is well established that while different sleep dimensions partially overlap they are also associated differentially with health, and in some cases, are independent in their health predictions (e.g., Jarrin, McGrath, & Drake, 2013). Sleep–affect research has frequently focused on the sleep duration, that is, the number of hours slept per night (Fillo et al., 2016). This measure reflects factors such as biological needs as well as contextual demands (e.g., school/work start time). It is weak in some ways, however, because it does not reflect the dimensions underlying sleep that disrupt and fragment the sleep experience. Thus, many researchers prefer sleep efficiency, which utilizes duration as a starting point, but also accounts for sleep disruption and problems with sleep latency or maintenance (e.g., tossing and turning, waking in the middle of the night). This is typically done by creating a ratio of sleep duration to total minutes spent in bed, which reflects the percentage of time in bed actually sleeping (Cousins et al., 2011; Kouros & El-Sheikh, 2015; Buysse, Reynolds, Monk, Berman, & Kupfer, 1989). Sleep efficiency is likely a more accurate reflection of good sleep in college students because they have many external pressures that influence the time they go to bed and wake up (e.g., late night studying needs, work and course obligations, and extensive social activities). Thus, what may be more important is how readily and consistently they can sleep when they want to (i.e., can they quickly transition to sleep and stay asleep?).

Sleep quality is also an important and distinct construct when judging "good sleep." It reflects a complex self-assessment of the quantitative aspects of one's sleep (e.g., number of arousals, duration, latency, waking too early), but also the purely subjective aspects such as feelings of restfulness upon waking or the perceived depth of sleep. It is distinct from efficiency and duration, as well as objective markers of quality from polysomnography, since it reflects a holistic and subjective evaluation of sleep (Krystal & Edinger, 2008).

Finally, it is important to note that while there are physiological and behavioral indicators of sleep (e.g., polysomnography and actigraphy, respectively), self-reports of sleep constructs have been connected to numerous medical, psychological, and sleep disorders (e.g., Karacan, Thornby, & Williams, 1983; Cohen, Doyle, Alper, Janicki-Deverts, & Turner, 2009; Matthews et al., 2013; Lauderdale, Knutson, Yan, Liu, & Rathouz, 2008; Lockley, Skene, & Arendt, 1999) and have been shown to compare favorably with lab-based measures (Buysse et al., 1989) and other sleep measurement methods (Lauderdale et al., 2008; Lockley et al., 1999).

Considering Reverse Causality

As discussed earlier, poor sleep is connected to future negative alterations in affect (Walker, 2009; Zohar, Tzischinsky, Epstein, & Lavie, 2005), affective disorder (Tsuno, Besset, & Ritchie, 2005), and stress responsivity (Meerlo, Sgoifo, & Suchecki, 2008). Sleep and circadian disruption have even been hypothesized to be chronic stressors themselves, causing allostatic load and health problems (McEwen & Karatsoreos, 2015). Thus, while stress and PA may alter sleep, sleep variations may cause initial trait and state differences in affect due to the ability of sleep to alter brain functionality and structure (e.g., McEwen & Chattarji, 2004; McEwen & Karatsoreos, 2015; Yoo, Gujar, Hu, Jolesz, & Walker, 2007). While this study will not be able to completely tease apart reverse causality, we take a longitudinal approach in our data collection, examining daily effects and parsing out differences between trait versus state affect on sleep recorded after affect. When examining state PA, this prospective design allows for an examination of the temporal patterns to be expected if the state PA causal effects on sleep are true (i.e., we are looking at the occurrence of state PA before sleep occurs).

The Current Studies

This manuscript examines the broad question of whether PA is helpful to sleep as a buffer of stress, then probes more deeply into the question of which types of affect are most helpful during stress. We hypothesize that trait vigor and state calm will be most beneficial for sleep under times of higher stress. We anticipate that the sleep measure that will be most tied to affective outcomes is sleep efficiency, since it is likely the best indicator of good sleep in this population. We will also examine sleep quality, as this is an important indicator of an individual's overall perception of their sleep. In addition, we thought it important to test whether the effects of PA are distinct from other nonemotion-based, health-beneficial positive constructs. Optimism arose as the natural variable to test given that it is conceptually distinct from PA but also tied to an array of health outcomes (Rasmussen, Scheier, & Greenhouse, 2009) and stress (albeit, in a complex manner; e.g., see Segerstrom, 2001). It also has no clear arousal component, and since we hypothesize this to be an important factor in the PA-to-sleep connection, the effects should be separable. Thus, we test whether PA and PA subtypes predict sleep independently from optimism (by statistically controlling for optimism) to examine whether the effects remain over and above the effects of related positive expectancies. We also control for NA in analyses given the close connections between PA and NA, and the extensive NA–sleep literature previously discussed.

To test these questions, we chose a population that commonly faces stress and poor sleep behaviors: college students. On average, these young adults obtain less than 6.5 hours of sleep each night, with 20% reporting no sleep at least once per month (Lund, Reider, Whiting, & Prichard, 2010). This is significantly less than the recommended 7 to 9 hours of sleep per night (National Sleep Foundation, 2015). This population also has clearly delineated high and low stress periods (examinations vs. average stress periods; e.g., van Schalkwijk et al., 2015). We use two naturalistic studies to test our questions. In the first, we examined how different types of trait PA influence sleep before and during examinations (high stress), while Study 2 investigated the relations between different types of trait and state PA with sleep in a 2-week (average stress period) daily diary study.

Study 1

Method

Participants. A total of 99 participants from Carnegie Mellon University (54% male), primarily Caucasian (52%) and Asian or Pacific Islander (32%), between the ages of 17 and 24 years (M = 19.7, SD = 1.25) were recruited and enrolled in the study over a 6-month period. The only requirement for participation was that participants had an upcoming examination (prior to the final exam period). The study protocol was approved by the Carnegie Mellon Institutional Review Board. Participants received course research credit in exchange for participation.

Procedure. Participants signed-up for this two-part study via an online Psychology Department web system. They first attended a baseline (T1) session where they consented to participate then completed a packet of questionnaires assessing demographics, trait affect, optimism, and general sleep behavior. Participants provided the date of their next exam (T2: approximately 1–2 weeks following T1) and their e-mail address. Participants received their first credit for participation following T1.

On the morning of their examination (T2), participants were e-mailed a link to a secure online questionnaire. Participants reported their sleep behavior for the previous night (i.e., immediately prior to the exam). Following completion of the T2 questionnaires, participants were sent an e-mail containing debriefing information and received credit for the second part of the study.

Measures.

Positive and negative affect. A 25-item checklist of adjectives assessed trait NA and PA at T1. Items were drawn from a factor analytic study of the Profile of Mood States (POMS) Affect Scale (Usala & Hertzog, 1989). This questionnaire has been used in past studies connecting emotion to health (e.g., Cohen, Doyle, Turner, Alper, & Skoner, 2003; Pressman et al., 2009). Participants reported the extent to which each item reflected how they felt in general from 1 (*not at all accurate*) to 5 (*extremely accurate*). PA was measured using three categories: vigor (items: full of pep, energetic, lively), well-being (items: happy, pleased, and cheerful), and calm (items: at ease, calm, and relaxed). NA was measured with five subscales including anxiety, fatigue, depression, hostility, and fear. Internal reliability for the full-length POMS is high (Shacham, 1983), and shortened versions of the POMS similar to the version used in the current study have been found to have similar internal consistency (Bourgeois, LeUnes, & Meyers, 2010). Internal consistency among the PA and NA items in this study were .84 and .91, respectively. Internal consistency among the PA subscales for vigor, well-being, and lively were .87, .79, and .87, respectively.

Optimism. Dispositional optimism was assessed at T1 with the 8-item Life Orientation Test (revised; Scheier, Carver, & Bridges, 1994). Items such as "In uncertain times, I usually expect the best" and "I hardly ever expect things to go my way" were rated on a scale from 0 (*strongly disagree*) to 4 (*strongly agree*). Internal consistency for this measure was .74.

Sleep. Six items derived from the Pittsburgh Sleep Quality Index (PSQI) were used to assess sleep (Buysse et al., 1989; Monk et al., 1994). Sleep duration (i.e., minutes/quantity), efficiency, and quality were all assessed at both T1 and T2. General (T1) sleep duration was determined by asking participants "During the past month, what time have you usually [gone to bed at night/gotten up in the morning]?" and calculating the difference in minutes between these two responses as well as subtracting out minutes participants reported in response to the following prompt: "During the past month, how many minutes of sleep did you generally lose each night (e.g., because you were lying in bed awake, woke up too early, woke up in the middle of the night)?" Sleep duration the night before the exam was determined using the same questions altered to inquire about the previous night's sleep. These questions were also used to determine sleep efficiency (in general and the night before the exam), which was calculated by dividing each participant's actual sleep duration by his or her total length of time in bed (either in general or the night before the exam). Sleep efficiency represents the percentage of time an individual is asleep in bed out of their total time in bed. Sleep quality was assessed with a single item from the PSQI asking participants to rate their sleep quality in general and the night before their exam on a scale of 1 (*very bad*) to 5 (*very good*). These questions and the overall PSQI have excellent validity (Aloba, Adewuya, Ola, & Mapayi, 2007) and reliability (Backhaus, Junghanns, Broocks, Riemann, & Hohagen, 2002).

Demographics. Participants self-reported on basic demographics including race, age, and sex.

Statistical procedure. Previous literature has shown that demographic variables, such as age, sex, and race, are related to sleep (Regestein et al., 2010; Smith, Perlis, Smith, Giles, & Carmody, 2000; Stewart, Rand, Hawkins, & Stines, 2011). Therefore, we tested the relationship between each of these potential covariates and our study variables and found that age and race were significantly related to at least one of our independent or dependent measures, $ps < .05$. Subsequently, age and race were controlled in all analyses. Trait PA, the different types of trait PA (when used as individual predictors), baseline optimism, and trait NA were all mean centered before being included in models as a part of an interaction term.

Two-level multilevel models were used to examine the effect of PA on sleep. Analyses were estimated using Time (T1: General [coded as 0] vs. T2: Before Exam [coded as 1]) as the Level 1 unit of analysis (i.e., within-individual effects) while participant was the Level 2 unit of analysis (i.e., between-individual effects). Multilevel modeling is the preferable method of analysis when time is nested within participants as this method results in more accurate standard errors (Hox, 2002). All analyses were conducted using Stata version 14 (StataCorp, 2015).

Model 1 used the interaction between trait PA (assessed at T1 and treated as a Level 2 unit of analysis) and Time (T1 vs. T2 treated as a Level 1 unit of analysis) to predict each sleep outcome (see Model 1 Equation). Interactions were used to determine whether the effect of PA on sleep differed between T1 and T2. Model 2 used the three types of PA and each of their interactions with Time to predict sleep efficiency. Because of some high correlations between the three types of PA (trait calm and trait well-being: $r = .43$, $p < .001$; trait vigor and trait well-being: $r = .54$, $p < .001$; trait calm and trait vigor: $r = -0.04$, $p = .54$), each of the types and their interactions with time were used separately to predict each sleep outcome in Models 2a, 2b, and 2c (calm, vigor, and well-being, respectively). Model 3 built on Model 2 by adding in optimism and NA and each of their interactions with Time. Given the conservative nature of Model 3 (in which all PA subtypes and control variables are included in the model), when a PA type from Models 2a, 2b, or 2c was significant, we tested the effects of that PA type independently on sleep controlling for NA as a follow up test.

Model 1 Equation:

$$\text{Level 1: } Sleep_{ti} = \pi_{0i} + \pi_{1i}Time_{ti} + e_{ti}$$

$$\text{Level 2: } \pi_{0i} = \beta_{00} + \beta_{01}TraitPA_i + r_{0i}$$

$$\pi_{1i} = \beta_{10} + \beta_{11}TraitPA_i + r_{1i}$$

$$\text{Combined: } Sleep_{ti} = \beta_{00} + \beta_{01}TraitPA_i + \beta_{10}Time_{ti} + \beta_{11}TraitPA_iTime_{ti} + r_{0i} + r_{1i}Time_{ti} + e_{ti}$$

Results

Descriptive statistics. The night before an exam, participants slept fewer minutes ($M = 343.87$, $SD = 110.80$) but had better sleep efficiency ($M = 93.83\%$, $SD = 5.60$) and sleep quality ($M = 3.12$, $SD = 0.83$) compared to their baseline general (nonexam) reported sleep duration ($M = 408.49$, $SD = 89.79$), sleep efficiency ($M = 90.14\%$, $SD = 6.66\%$), and sleep quality ($M = 2.82$, $SD = 0.74$), (duration: $z = -4.64$, $p < .001$; efficiency: $z = 3.66$, $p < .001$; quality: $z = 2.35$, $p = .02$). Sleep efficiency was moderately correlated with quality (in general: $r = .43$, $p < .001$; before exam: $r = .31$, $p = .02$) and duration (in general: $r = .26$, $p = .02$; before exam: $r = .28$, $p = .03$). Sleep quality and duration were only correlated the night before the exam but not generally as assessed at baseline (in general: $r = .18$, $p = .11$; before exam: $r = .37$, $p = .003$).

Sleep efficiency. In Model 1 (see Table 1), there was a main effect of trait PA on sleep efficiency ($b = 2.44$, $z = 2.21$, $p = .03$, 95% CI [0.28, 4.61]) such that individuals with higher trait PA experienced higher sleep efficiency. However, the interaction between Time and trait PA did not significantly predict sleep efficiency ($b = 0.43$, $z = 0.32$, $p = .75$, 95% CI [−2.18, 3.03]) indicating that the benefits of PA on sleep efficiency did not differ between T1 and T2. In Model 2, when predicting sleep efficiency with trait calm, vigor, and well-being entered together, only vigor ($b = 2.06$, $z = 2.01$, $p = .04$, 95% CI [0.05, 4.06]) was a significant predictor of sleep efficiency. Individuals with more trait vigor fell asleep faster and stayed asleep more effectively compared to individuals lower in trait vigor. In Model 2, none of the interactions between each of the three types of PA and Time were significant predictors of sleep efficiency. In Models 2a, 2b, and 2c, when predicting sleep efficiency with trait calm, vigor, and well-being (independently), only vigor ($b = 2.14$, $z = 2.68$, $p = .01$,

Table 1
Effect of Trait PA on Sleep During Exam Period

Outcome	Model	Time	PA	PA * Time	Calm	Calm * Time	Vigor	Vigor * Time	WB	WB * Time	Opt	Opt * Time	NA	NA * Time
Sleep efficiency	1	**3.00**	**2.44**	.43	—	—	—	—	—	—	—	—	—	—
	2	**2.86**	—	—	.50	−.43	**2.06**	−1.47	.06	1.92	—	—	—	—
	2a	**2.93**	—	—	.51	.49	—	—	—	—	—	—	—	—
	2b	**3.05**	—	—	—	—	**2.14**	−.48	—	—	—	—	—	—
	2c	**2.95**	—	—	—	—	—	—	1.56†	.87	—	—	—	—
	3	**2.80**	—	—	.47	−.52	**2.08**	−1.56	−.84	2.89†	.21	−.29	−.65	.22
Sleep quality	1	**.28**	**.52**	−.21	—	—	—	—	—	—	—	—	—	—
	2	**.27**	—	—	.11	.01	**.23**	−.26	.18	.03	—	—	—	—
	2a	**.26**	—	—	.17†	.05	—	—	—	—	—	—	—	—
	2b	**.27**	—	—	—	—	**.32**	−.23†	—	—	—	—	—	—
	2c	**.28**	—	—	—	—	—	—	**.37**	−.13	—	—	—	—
	3	**.27**	—	—	.02	.06	.20†	−.25	.07	.00	−.02	.04	**−.37**	.19
Sleep duration	1	**−60.00**	−12.04	9.29	—	—	—	—	—	—	—	—	—	—
	2	**−67.97**	—	—	−22.97†	11.27	9.54	.93	.74	−2.95	—	—	—	—
	2a	**−68.44**	—	—	**−22.83**	10.85	—	—	—	—	—	—	—	—
	2b	**−68.40**	—	—	—	—	10.76	−2.97	—	—	—	—	—	—
	2c	**−68.97**	—	—	—	—	—	—	−5.06	3.80	—	—	—	—
	3	**−67.68**	—	—	−22.96†	.06	9.57	−1.01	1.13	−2.73	−.22	−4.31	−1.54	−36.74

Note. PA = Positive Affect; WB = Well-being; Opt = Optimism; NA = Negative Affect.
† $p < .10$; boldface and underlined = $p < .05$.

95% CI [0.58, 3.70]) was a significant predictor of sleep efficiency (see Figure 1). In Models 2a, 2b, and 2c, none of the interactions between each of the three types of PA and Time were significant predictors of efficiency. In Model 3, when optimism and NA were added to Model 2, the main effect of vigor remained significant ($b = 2.08$, $z = 2.04$, $p = .04$, 95% CI [0.08, 4.08]). Not surprisingly, given the lack of NA effects in Model 3, when pitting vigor alone against NA, vigor remained significantly associated with efficiency, ($b = 1.83$, $z = 2.20$, $p = .027$, CI [0.20, 3.46]).

Sleep quality. In Model 1 (see Table 1), trait PA had a main effect on sleep quality ($b = 0.52$, $z = 4.23$, $p < .001$, 95% CI [0.28, 0.76]) such that individuals with higher trait PA reported better quality sleep. Again, the interaction between Time and trait PA did not significantly predict sleep quality ($b = -0.21$, $z = -1.16$, $p = .24$, 95% CI [−0.57, 0.14]). In Model 2, when predicting sleep quality with trait calm, vigor, and well-being (together), only vigor ($b = 0.23$, $z = 2.11$, $p = .04$, 95% CI [0.02, 0.45]) was a significant predictor of sleep quality. Individuals with more vigor had higher sleep quality compared to individuals with less vigor. In Model 2, none of the interactions between each of the three types of PA and Time were significant predictors of sleep quality. In Models 2a, 2b, and 2c, when predicting sleep quality separately with trait calm, vigor, and well-being, the main effects of vigor ($b = 0.32$, $z = 3.62$, $p < .001$, 95% CI [0.15, 0.50]) and well-being ($b = 0.37$, $z = 3.85$, $p < .001$, 95% CI [0.18, 0.56]) significantly predicted sleep quality such that individuals with higher vigor and those with higher well-being experienced better sleep quality (see Figure 1). In Models 2a, 2b, and 2c, none of the interactions between each of the three types of PA and Time were significant predictors of quality. In Model 3, when optimism and NA were added to Model 2, the main effect of vigor became marginally significant ($b = 0.20$, $z = 1.92$, $p = .06$, 95% CI [−0.00, 0.41]). When pitting vigor alone against NA, the main effect of vigor remained significant ($b = 0.22$, $z = 2.55$, $p = .01$, 95% CI [0.05, 0.39]). However, when pitting well-being alone against NA, the main effect of well-being became nonsignificant, ($b = 0.19$, $z = 1.67$, $p = .10$, 95% CI [−0.03, 0.42]).

Sleep duration. In Model 1 (see Table 1), neither the main effect of trait PA ($b = -12.04$, $z = -0.74$, $p = .46$, 95% CI [−43.74, 19.66]) nor the interaction between trait PA and Time ($b = 9.29$, $z = 0.39$, $p = .70$, 95% CI [−37.29, 55.86]) significantly predicted sleep duration. In Model 2, when predicting sleep duration with trait calm, vigor, and well-being together, only calm ($b = -22.97$, $z = -1.78$, $p = .08$, 95% CI [−48.27, 2.34]) was a marginally significant predictor of sleep duration. Interestingly, this was in the opposite direction of past findings such that high calm individuals had lower sleep duration (i.e., fewer minutes of sleep). In Model 2, none of the interactions between each of the three types of PA and Time were significant predictors of sleep duration. In Models 2a, 2b, and 2c, when predicting sleep duration separately with trait calm, vigor, and well-being, only the main effect of baseline calm was a significant (negative) predictor of sleep duration ($b = -22.83$, $z = -2.10$, $p = .04$, 95% CI [−44.12, −1.54]; see Figure 1). In Models 2a, 2b, and 2c, none of the interactions between each of the three types of PA and Time were significant predictors of sleep duration. In Model 3, when optimism and NA were added to Model 2, the significant main effect of calm became marginally significant ($b = -22.96$, $z = -1.67$, $p = .10$, 95% CI [−49.93, 4.01]). When pitting calm alone against NA, the main effect of calm remained significant ($b = -24.89$, $z = -2.04$, $p = .04$, 95% CI [−48.80, −0.99]).

Discussion

Study 1 found that, overall, trait PA was a predictor of higher sleep quality and efficiency reported generally (~1 week before a test) and the night before a test. This was primarily driven by the effects of trait vigor, which were relatively independent of the

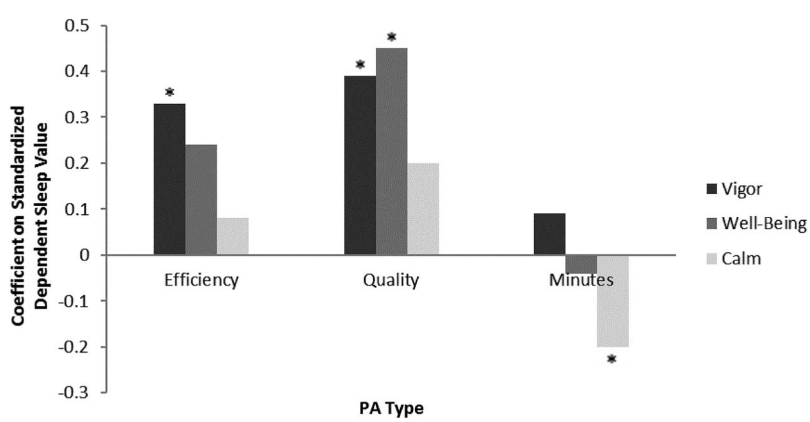

Figure 1. Standardized effects of vigor, well-being, and calm on sleep during exam period. The dependent sleep variables (sleep efficiency, quality, and minutes) were standardized for this figure using z scores to put them all on the same scale. For example, we calculated the mean and standard deviation of efficiency and then subtracted this mean from each person's efficiency score and then divided the resulting value by the overall efficiency standard deviation. We repeated this same technique for the other two dependent variables and then used these dependent values in the same models reported in this section to create this figure. Asterisks indicate that a PA type was a significant predictor of a sleep outcome. This technique was used to create a similar scale for the three dependent variables so that findings could be visually represented in the same figure. All statistics in-text were calculated using the unstandardized dependent variables.

effects of the other PA subtypes, NA, and optimism. In the most conservative predictive models (Model 3), vigor withstood simultaneous controls for other PA subtypes in efficiency analyses, and in quality analyses, while the effect became marginal, follow-up analyses of only the significant predictors (with removed highly correlated variables) indicated that the effects of NA and vigor were both significant and somewhat independent.

More counterintuitive were the findings for sleep duration. While trait PA was not related to sleep duration, there was an interesting result where higher trait calm was associated with individuals generally sleeping less, including on the night before the exam. There are many possible reasons for this effect, but it is possible that characteristics of trait calm are not well suited to the stressful undergraduate midterm experience. That is, calm may not motivate individuals to get work done ahead of time and/or exert energy into studying, resulting in staying up later to get things done. As far as why there was no general PA–duration association, it may be that the raw amount of sleep that an undergraduate gets during a midterm examination period may be more strongly predicted by external forces like studying habits.

When originally designing this study, we had expected that T1 of Study 1 would be a relatively low stress period; however, upon consideration, we realized that even 1–2 weeks before the midterm period of a semester, many college students face high anticipatory stress. Because of the nature of the study design, "baseline" measures were collected close to the actual test, which may have meant that exam stress leached into the baseline period. Students were likely already concerned about their upcoming exam. This interpretation is consistent with the lack of interaction effects with Time, but there may also have been differences in results due to the sleep measurement approach (i.e., asking about sleep in general vs. sleep last night at T1 and T2, respectively).

These findings indicate that during a period of high stress examinations (i.e., the week(s) immediately before an exam), high trait vigor is helpful for sleep, but high trait calm is not. We thought it important to examine whether the same observed subtype effects were true during a nonexam period with average/lower stress and improved sleep assessments. A period less influenced by exams altering sleep behavior would also allow us to more fully explore whether PA and PA subtypes operate on sleep in a generally healthful way (i.e., main effect) or whether they operate as stress buffers (i.e., interact with stress). We were also interested in exploring the effects of state PA as opposed to the reliance on trait PA in Study 1. Although trait and state PA may be related, they may have differential effects on sleep, especially when examined at a more micro level (i.e., on a given day). Finally, it was also a limitation that sleep at T1 was assessed as sleep in general. It is possible that participants are less accurate at reporting how their sleep is overall and may be more precise when reporting sleep immediately after it occurs for each time point.

Given these open questions, Study 2 examined the same PA–sleep questions over a 2-week period that was not during midterm or final exams. This was done in a similar Carnegie Mellon student population and included measures of both trait and state affect, as well as perceived stress. We focused on three questions: (a) Do the trait PA and trait PA subtype effects found in Study 1 hold when assessing daily sleep and stress for 13 straight days, (b) Do Study 1 trait PA/PA subtype effects replicate when the stress context varies (during a nonexam period), and (c) Do state PA/PA subtypes assessed on a daily level have the same effects on nightly sleep as trait PA and its subtypes?

Study 2

Method

Participants. Eighty-three healthy college freshmen from Carnegie Mellon (44% male), primarily Caucasian (66%) and Asian (24%), between the ages of 18 and 25 years ($M = 18.29$, $SD = 0.90$), were recruited to participate during a non-final-exam and nonmidterm period of the school year. Participants were part of a larger study on vaccination and were compensated $120 for full study participation. Informed consent was obtained from all participants in accordance with the Carnegie Mellon University Institutional Review Board.

Procedure. Study participants were recruited via local advertisements and announcements at academic functions. Using methods described previously (Miller et al., 2004; Pressman et al., 2005), participants were scheduled for a baseline visit where they completed demographic and psychosocial questionnaires (including perceived stress) and received training on how to complete ambulatory monitoring, including assessments of sleep duration and quality. Participants then began 13 consecutive days of monitoring. Sleep data collection was facilitated by use of a handheld computer (ThinkPad, IBM Corp; White Plains, NY). Each morning, participants were alerted by an alarm 1 hour after their reported typical waking time and were asked about the past night's sleep. One, 4, 9, and 11 hours after they woke up ($M_{\text{wake up time}} =$ 9:19 am, $SD = 2$ hr and 3 min), they were asked to report on their state affect and daily stress.

Measures.

Positive and negative affect. Trait PA and NA were assessed using the same 25-item checklist of adjectives that assessed trait PA and NA at baseline in Study 1. Trait PA, vigor, well-being, calm, and NA had Cronbach's alphas of .87, .84, .79, .77, and .91. State PA and NA were assessed with a 16-item affect measure that included the majority of the items from the Study 1 trait affect measure. These items similarly reflected all arousal subtypes of PA, including vigor (items: active, intense, enthusiastic, lively), well-being (items: happy, cheerful), and calm (items: relaxed, calm). It also included six negative items (e.g., nervous, sad, tired) that were averaged to create the state NA score. State items were asked about the current moment, and scores were averaged to get a day average of each affective state (i.e., day state affect). State vigor, well-being, calm, and NA had Cronbach's alphas for each of the 13 days that ranged from .76 to .88, .83 to .93, .82 to .93, and, .86 to .91, respectively.

Sleep. Participants completed an electronic sleep diary approximately 1 hour after awakening for 13 consecutive nights with high adherence. Each morning, participants reported on their bedtime, wake time, number of minutes of sleep lost across the night, and sleep quality using the same questions utilized in T2 of Study 1.

Average stress. Average stress for this sample was assessed at baseline using the Perceived Stress Scale (PSS; Cohen, Kamarck, & Mermelstein, 1983), which included 14 items assessing average daily stress (e.g., "In the last month, how often have you felt nervous and "stressed"?) rated on a scale from 0 (*Never*) to 4 (*Very Often*). Items were added together to create a total average stress value.

Daily stress. Daily stress was assessed four times a day by having participants rate the extent to which they felt "stressed" and "overwhelmed," each day on a scale from 1 (*not at all accurate*) to 5 (*extremely accurate*). A total daily stress score was calculated by averaging the two items at each time point, then averaging across the entire day.

Statistical procedure. As in Study 1, we tested the relationship between potential demographic covariates (age, sex, and race) and our study variables. All three potential covariates were associated with at least one of our study variables, $ps < .05$, and were therefore controlled for in all analyses. Trait and state PA, PA subtypes, daily stress, and NA were all mean centered before being included in models as a part of an interaction term.

We examined the difference in average stress between this sample and the sample from Study 1 using an independent samples *t* test using the PSS as the dependent variable and study as the independent variable.

Day-to-day sleep (assessed with the 13-day daily diary) was analyzed using two-level multilevel modeling. Analyses were estimated using day as the Level 1 unit of analysis (i.e., within-individual effects while participant was the Level 2 unit of analysis (i.e., between-individual effects). All analyses were conducted using Stata version 14 (StataCorp, 2015).

Similar to Study 1, Model 1 used the interaction between trait PA (Level 2) and daily stress (Level 1) to predict each sleep outcome. Model 2 used the three trait PA subtypes (all Level 2) and each of their interactions with daily stress to predict each of the sleep outcomes. Because of the high correlations between the three types of PA (trait calm and trait well-being: $r = .57$, $p < .001$; trait vigor and trait well-being: $r = .73$, $p < .001$; trait calm and trait vigor: $r = .36$, $p = .001$), each of the types and their interactions with daily stress were used separately to predict each sleep outcome in Models 2a, 2b, and 2c (calm, vigor, and well-being, respectively). Model 3 built on Model 2 by adding in trait NA (Level 2) and its interaction with daily stress.

Next, the same models were tested with state PA in place of trait PA. For each model, state PA that day was used to predict sleep that night. Model 1 used the interaction between state PA (Level 1) and daily stress (Level 1) to predict each sleep outcome. Model 2 used the three state PA subtypes (all Level 1) and each of their interactions with daily stress to predict each of the sleep outcomes. Because of the high correlations between the well-being and the other two types of state PA on each of the 13 days (state well-being and state calm: $rs = .22$ to $.59$, $ps < .05$ for 12 of 13 days; state well-being and state vigor: $rs = 0.44$ to $.76$, $ps < .001$), each of the types and their interactions with daily stress were used separately to predict each sleep outcome in Models 2a, 2b, and 2c (calm, vigor, and well-being, respectively). Model 3 built on Model 2 by adding in state NA (Level 1) and its interaction with daily stress.

Trait PA Model 1 equation:

$$\text{Level 1: } Sleep_{ti} = \pi_{0i} + \pi_{1i}Stress_{ti} + e_{ti}$$

$$\text{Level 2: } \pi_{0i} = \beta_{00} + \beta_{01}TraitPA_i + r_{0i}$$

$$\pi_{1i} = \beta_{10} + \beta_{11}TraitPA_i + r_{1i}$$

$$\text{Combined: } Sleep_{ti} = \beta_{00} + \beta_{01}TraitPA_i + \beta_{10}Stress_{ti} + \beta_{11}TraitPA_iStress_{ti} + r_{0i} + r_{1i}Stress_{ti} + e_{ti}$$

State PA Model 1 equation:

$$\text{Level 1: } Sleep_{ti} = \pi_{0i} + \pi_{1i}Stress_{ti} + \pi_{2i}StatePA_{ti} + \pi_{3i}Stress_{ti}StatePA_{ti} + e_{ti}$$

$$\text{Level 2: } \pi_{0i} = \beta_{00} + r_{0i}$$

$$\pi_{1i} = \beta_{10} + r_{1i}$$

$$\pi_{2i} = \beta_{20} + r_{2i}$$

$$\pi_{3i} = \beta_{30} + r_{3i}$$

$$\text{Combined: } Sleep_{ti} = \beta_{00} + \beta_{10}Stress_{ti} + \beta_{20}StatePA_{ti} + \beta_{30}Stress_{ti}StatePA_{ti} + r_{0i} + r_{1i}Stress_{ti} + r_{2i}StatePA_{ti} + r_{3i}Stress_{ti}StatePA_{ti} + e_{ti}$$

Results

Descriptive statistics. On average, participants slept 401.98 minutes ($SD = 60.00$), had a sleep efficiency of 96.36% ($SD = 3.25$), and sleep quality of 3.12 ($SD = 0.50$).[1] Sleep efficiency was moderately correlated with quality, $r = .32$, $p = .004$ and duration, $r = .29$, $p = .01$. Sleep quality and duration were not correlated, $r = .13$, $p = .26$. Participants were highly adherent in their diary responses, with 87% of responses occurring within 1 hour of alert. Similarly, there was very little missing data across the 13 days (with a range of 2.4% to 27.7% when examining each time point).

Perceived stress. The group in Study 2 had significantly lower stress ($M = 15.22$, $SD = 6.76$) compared to the group in Study 1 ($M = 23.83$, $SD = 4.94$; $t(147.18) = 9.644$, $p < .001$) indicating that we successfully captured a lower stress period.

Trait PA.

Sleep efficiency. In Model 1 (see Table 2), there was no main effect of trait PA on sleep efficacy, but the interaction between trait PA and stress significantly predicted sleep efficiency ($b = 0.33$, $z = 2.02$, $p = .04$, 95% CI [0.01, 0.65]) such that on days with higher stress, greater amounts of PA led to higher sleep efficiency. In Model 2 (where all PA subtypes were included together), none of the trait PA components significantly predicted sleep efficiency. However, in Models 2a, 2b, and 2c when subtypes were considered separately, trait vigor and well-being, significantly interacted with stress such that on days with high stress, greater amounts of vigor ($b = 0.28$, $z = 2.13$, $p = .03$, 95% CI [0.02, 0.53]) and well-being ($b = 0.31$, $z = 2.02$, $p = .04$, 95% CI [0.01, 0.62]) led to higher sleep efficiency (see Figures 2 and 3). In contrast, on days with low stress, vigor and well-being did not alter sleep efficiency. In Model 3, when including NA and its interaction with stress, the

[1] Study 2 participants had significantly better sleep quality ($t(172.62) = -3.256$, $p = .001$) and efficiency ($t(147.37) = -9.201$, $p < .001$) but no significant difference in sleep minutes ($p > .05$) compared to the baseline sleep of Study 1 participants.

Table 2
Effect of Trait PA on Sleep Over 13 Days During Nonexam Period

Outcome	Model	Stress	PA	PA * Stress	Calm	Calm * Stress	Vigor	Vigor * Stress	WB	WB * Stress	NA	NA * Stress
Sleep efficiency	1	−.09	.51	**<u>.33</u>**	—	—	—	—	—	—	—	—
	2	−.13	—	—	−.41	−.07	.09	.19	.78	.23	—	—
	2a	−.11	—	—	.13	.14	—	—	—	—	—	—
	2b	−.14	—	—	—	—	.40	**<u>.28</u>**	—	—	—	—
	2c	−.08	—	—	—	—	—	—	.53	**<u>.31</u>**	—	—
	3	−.11	—	—	−.47	−.06	.10	.19	.57	.24	−.77	.07
Sleep quality	1	−.02	.05	−.01	—	—	—	—	—	—	—	—
	2	−.01	—	—	.09	−.00	.02	−.03	−.04	.02	—	—
	2a	−.01	—	—	.07	.00	—	—	—	—	—	—
	2b	−.02	—	—	—	—	.02	−.02	—	—	—	—
	2c	−.02	—	—	—	—	—	—	.03	−.00	—	—
	3	−.00	—	—	.07	.01	.02	−.03	−.12	.02	**<u>−.28</u>**	.02
Sleep duration	1	**<u>−10.93</u>**	11.10	−6.22†	—	—	—	—	—	—	—	—
	2	**<u>−10.46</u>**	—	—	2.71	−4.24	−11.94	−4.47	22.49†	3.02	—	—
	2a	**<u>−11.56</u>**	—	—	9.73	−4.40	—	—	—	—	—	—
	2b	**<u>−11.01</u>**	—	—	—	—	1.42	−4.83†	—	—	—	—
	2c	**<u>−10.41</u>**	—	—	—	—	—	—	13.00	−3.65	—	—
	3	**<u>−9.46</u>**	—	—	1.35	−4.46	−11.91	−4.87	17.24	2.94	−19.36†	.12

Note. PA = Positive Affect; WB = Well-being; Opt = Optimism; NA = Negative Affect.
† $p < .10$; boldface and underlined = $p < .05$.

interactions of trait vigor and well-being with stress became nonsignificant.[2]

Sleep quality and duration. In the models predicting sleep quality and duration, none of the trait PA variables predicted these sleep outcomes (see Table 2).

State PA.

Sleep efficiency. In Model 1 (see Table 3), while there was no main effect of state PA on sleep efficiency, state PA significantly interacted with stress to predict sleep efficiency (b = 0.46, z = 2.28, p = .02, 95% CI [0.06, 0.86]) such that on days with higher stress, greater amounts of PA led to higher sleep efficiency. In Model 2, when predicting sleep efficiency with state calm, vigor, and well-being together, only state calm interacted with daily stress such that on days with higher levels of stress, state calm was more beneficial for sleep while on days with lower levels of stress more calm was associated with worse sleep efficiency (b = 0.51, z = 2.31, p = .02, 95% CI [0.08, 0.95]; see Figure 4). This relationship held in Model 2a when calm and its interaction with stress were included alone in the model. In Model 2c, state well-being had a similar effect on efficiency such that as stress increased, greater levels of well-being led to more sleep efficiency (b = 0.29, z = 1.99, p = .047, 95% CI [0.003, 0.57]). In Model 3, when including NA and its interaction with stress to Model 2, the interaction of calm and stress stayed significant while the interaction between well-being and stress became nonsignificant.

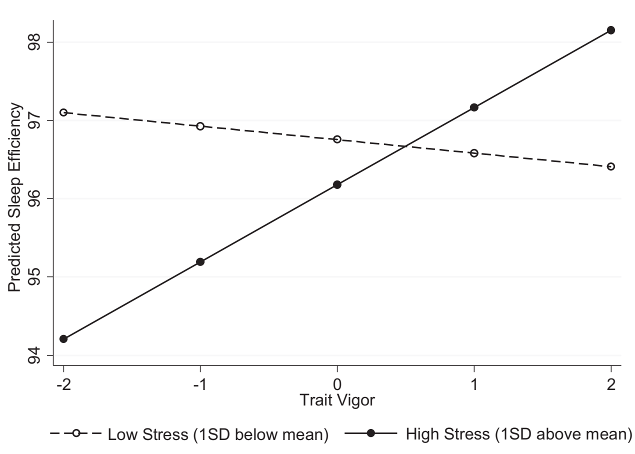

Figure 2. Trait vigor by stress interaction on day-to-day sleep efficiency.

Sleep quality and duration. In the models predicting sleep quality and duration, none of the state PA variables predicted these sleep outcomes. When the variables in Tables 2 and 3 are combined into one model, the pattern of results remains the same indicating that the effects of trait PA versus state PA are somewhat independent.

Discussion

Study 2 found similar patterns as Study 1 when looking at the effect of trait PA on sleep. Specifically, trait vigor and well-being predicted more sleep efficiency but interacted with stress such that vigor and well-being were most effective during high stress (with no effect during low stress). Study 2 added to Study 1 by assessing state PA in addition to trait PA. When examining state affect, overall state PA was associated with better sleep during times of higher stress (as was the case for trait PA); however, in this case calm was the PA component driving this effect. When daily stress is high, state calm enables better sleep efficiency; however, when daily stress is low, calm was associated with worsened sleep efficiency, closer to the findings from Study 1. State calm effects on sleep were independent from NA; however, the trait PA subscale effects were not (unlike Study 1).

[2] There has been some interest in the literature regarding the overlap between perceived health and PA (e.g., Pressman & Cohen, 2005). Thus, in Study 2, we examined the effects of PA controlling for perceived health and the pattern of findings between PA measures and sleep outcomes remained the same.

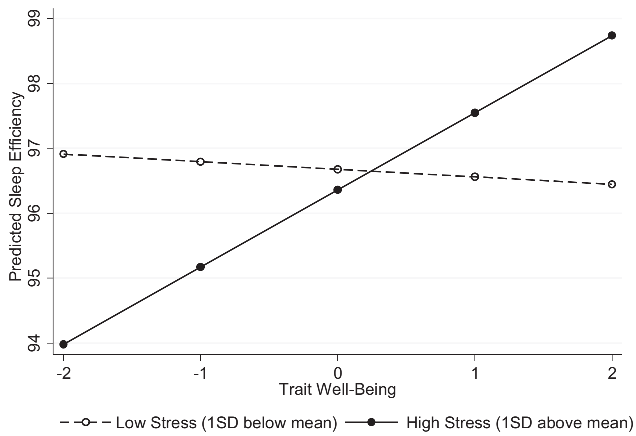

Figure 3. Trait well-being by stress interaction on day-to-day sleep efficiency.

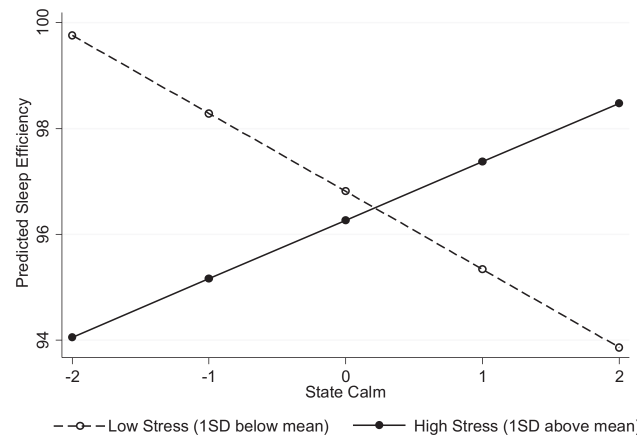

Figure 4. State calm by stress interaction on day-to-day sleep efficiency.

General Discussion

The current studies examined how PA influences sleep efficiency, quality, and duration during a time of high stress (Study 1) and during a time of relatively lower and variable stress (Study 2). This study adds to the literature by examining many unexplored questions including (a) the types of PA underlying PA–sleep effects with a focus on the role of arousal, (b) the role of stress in changing the nature of these associations, (c) whether trait versus state PA subtypes have differential effects on sleep, and (d) whether the effects of PA and PA subtypes are independent from a related positive construct and/or NA. It also adds to the PA–health literature more generally by exploring whether PA is always beneficial to sleep (main effect) or whether a stress-buffering model is more appropriate (i.e., PA is most beneficial to sleep under stress).

Our first questions were focused on replication and extension: Does average PA relate to sleep and which subtypes of PA drive this effect? In Study 1, trait PA was related to higher quality and more efficient sleep overall, but not to duration. Benefits of PA were almost entirely driven by the effects of high arousal PA, and even more interestingly, low arousal PA was negatively associated with sleep duration. In Study 2, it was trait vigor and state calm as well as both trait and state well-being that were most tied to better sleep efficiency. This highlights the importance of considering different types of PA, since without these analyses many interesting effects would not have been evident.

Next, was the critical question of what role stress played in these associations? All of the effects described above are coached in stress, and consistent with PA acting as a buffer against the aversive sleep effects from stress. In Study 1, both time points were high stress, and PA was associated with sleep at both. When originally conceived, we anticipated that we could contrast T1

Table 3
Effect of State PA on Sleep Over 13 Days During Nonexam Period

Outcome	Model	Stress	PA	PA ∗ Stress	Calm	Calm ∗ Stress	Vigor	Vigor ∗ Stress	WB	WB ∗ Stress	NA	NA ∗ Stress
Sleep efficiency	1	−.14	−.00	**.46**	—	—	—	—	—	—	—	—
	2	−.12	—	—	−.27	**.51**	.04	−.24	.12	.21	—	—
	2a	−.13	—	—	−.19	**.62**	—	—	—	—	—	—
	2b	−.16	—	—	—	—	.11	.04	—	—	—	—
	2c	−.13	—	—	—	—	—	—	.07	**.29**	—	—
	3	−.16	—	—	−.25	**.54**	.07	−.25	.19	.24	.44	.08
Sleep quality	1	−.02	−.06	.05†	—	—	—	—	—	—	—	—
	2	−.02	—	—	−.10	.02	−.06	.04	.06	.01	—	—
	2a	−.03	—	—	−.08	.03	—	—	—	—	—	—
	2b	−.02	—	—	—	—	−.03	.05	—	—	—	—
	2c	−.02	—	—	—	—	—	—	−.00	.03	—	—
	3	−.02	—	—	−.10	.01	−.05	.04	.07	−.01	.07	−.05
Sleep duration	1	**−10.24**	9.58	−1.70	—	—	—	—	—	—	—	—
	2	**−11.30**	—	—	−7.83	6.91	26.54†	−1.40	−6.32	−2.39	—	—
	2a	**−10.93**	—	—	−8.18	5.16	—	—	—	—	—	—
	2b	**−10.54**	—	—	—	—	18.07†	−2.57	—	—	—	—
	2c	**−10.34**	—	—	—	—	—	—	4.51	−.65	—	—
	3	**−14.02**	—	—	−4.34	6.69	31.95	−2.57	5.73	−4.29	**69.04**	**−12.89**

Note. PA = Positive Affect; WB = Well-being; Opt = Optimism; NA = Negative Affect.
† $p < .10$; boldface and underlined = $p < .05$.

(baseline) and T2 within Study 1 as a low stress versus high stress comparison. However, when examining T1 perceived stress (Cohen et al., 1983), the average (M_{PSS} = 23.65, SD = 5.15) was considerably higher than population samples, which are 6–7 points lower (Cohen & Janicki-Deverts, 2012). Study 2 successfully captured students during an average stress period (M_{PSS} = 15.22, SD = 6.76). As a result, we were able to more closely examine possible moderation effects of stress on the PA–sleep connection in a more typical 2-week period. Under high stress, trait PA conferred more efficient sleep; in particular, due to the effects of vigor and sometimes midarousal well-being. Under average stress, PA subtype by stress interactions were found for both state and trait affect subtypes (rather than main effects), with most PA benefits evident under times of high stress, and in the case of one state affect subscale, low arousal PA was in fact harmful during a time of low stress. Thus, PA may be especially important for enabling healthy sleep function during high stress. Future work should explore sleep and PA connections during nonstress periods (e.g., vacation) to examine whether PA operates differently in that context (similar to methods of Vitaliano, Maiuro, Russo, & Mitchell, 1989).

Next we considered whether affect duration mattered. As anticipated, this was a complex question with nuanced answers that vary based on context and affect type. Consistent with the broader PA–health literature (e.g., Pressman & Cohen, 2012), trait vigor (measured by feeling full of pep, lively, and energetic) is helpful for better sleep. It is tied to better sleep efficiency and quality during high stress, in general, before an exam, and on average days when stress is higher than normal. Why is this the case? As discussed earlier, vigor, despite its high arousal properties, could be good for sleep, especially during stress. Trait high positive energy not only represents the ideal affect state for most Americans (Tsai, 2007), but it is also potentially the trait most closely aligned with the energy needs of a high stress context that requires active coping and perceptions of stress controllability. Feeling high arousal PA might help an individual study, focus, and maintain coping efforts for longer periods than someone without these feelings. Alternatively, high positive energy may simply be a symptom of effective biological energy management and, perhaps, some reverse causality is having an important role here, as discussed below. That is, individuals who sleep better feel more vigor (Bower, Bylsma, Morris, & Rottenberg, 2010), and this in turn translates into better sleep in the future. However, high state arousal PA was not related to daily sleep, further indicating that vigor benefits are unique to stable trait assessments and that the transient arousal paired with feelings of enthusiasm, vigor, and so forth may not aid in sleep on a given day.

State low arousal PA was associated with better sleep efficiency in Study 2 on days with higher than average stress. Unlike trait vigor, but consistent with past studies of health, trait calm was not helpful to sleep in Study 1, and was actually harmful for sleep duration. State calm was also associated with worse sleep efficiency in Study 2 during times of low stress, painting a confusing picture as to the role of calm in sleep processes. One possible reason for these mixed findings is that calm is not highly valued by North Americans (Tsai, 2007), despite its high value in numerous other cultures and the numerous attempts to raise calm feelings via antistress manipulations and interventions. It may be then, given the North American inattention to this trait and state, that self-reported values mean something different. Another possibility is that, at least in Study 1, trait calm did not match the energy needs of the lasting high stress period. To study for long hours and remain actively engaged in schoolwork, it may be most helpful to have trait levels of positive high energy as opposed to low arousal feelings of relaxation and peacefulness. This may translate into less sleep because demands are not easily met with this lack of energy. The opposite effect may also underlie this result. It is possible that students who sleep less are calmer than those who sleep more because they spend more time preparing for all of their school tasks and studying. This is an interesting contrast to Study 2 where state calm benefited sleep during typical stress. Therefore, it might be that feelings of calm in the moment lead to better sleep that day because of the immediate antiarousal benefits and/or the ability to match lower stress needs; however, it still does not explain why calm would be associated with lessened sleep efficiency on days with low stress. Regardless of the explanation, this interesting set of findings on low arousal PA warrants further investigation. Unfortunately, many PA measures do not include this form of PA (e.g., the PANAS; Watson et al., 1988); thus, researchers interested in this topic should take this into consideration when selecting assessment tools.

What about the effects on sleep from midarousal PA? We didn't have hypotheses regarding the effects of emotions like happiness, contentment, and well-being, given that they are neither high nor low arousal. However, we thought it important to include this measure given the focus on happiness in much of the PA literature. Unsurprisingly, midarousal PA went in both directions, sometimes having effects like high arousal PA, and sometimes having effects like low arousal PA. Trait midarousal PA was related to better sleep quality in Study 1 and better sleep efficiency (interacting with stress) in Study 2. In Study 2, midarousal state well-being had similar effects as state calm such that higher state well-being led to better sleep efficiency during high stress. However, when included in combined models, the effect of well-being was often wiped out indicating that it may be vigor and calm driving PA–sleep effects.

A more minor question examined whether PA and PA subtype effects were independent of a related positive construct and from NA. In Study 1, we tested this by contrasting the effects of optimism with PA. In all of the models in which optimism was included, optimism was never a significant predictor of sleep. This provides some evidence that PA sleep effects are independent from a closely related construct. Similarly, analyses controlling for NA revealed that NA made little or no difference to the found effects. For example, in Study 2 when trait and state NA were added to the models with the three subtypes of PA, NA was not associated with efficiency and did not eliminate the effects of PA on sleep. Similarly, in Study 1 when NA and vigor were used to predict sleep quality, vigor remained significant. This indicates that associations between PA and sleep may be relatively independent of NA, as has been shown previously (Baglioni et al., 2010). There were some exceptions when NA did reduce effects to nonsignificant levels (i.e., the trait vigor and trait well-being effects on sleep efficiency in Study 2, the wellbeing effect on sleep quality in Study 1) indicating, not surprisingly, that there is some shared variance between PA and NA and their respective sleep effects; however, the overlap is far from complete.

Some might ask why sleep efficiency followed by sleep quality were the measures most tied to PA, while duration rarely showed effects. As discussed earlier, college students frequently sacrifice sleep time due to school, work, and social demands. As a result, efficiency and quality become more important sleep outcomes. A good example of that arises from T2 of Study 1, where we found that students did sleep fewer minutes the night before the exam (i.e., due to studying) but that their sleep efficiency and quality were actually higher the night before the exam. Since college students get less sleep before an exam (5.73 hours on average in this study), it is even more important that they sleep for the entire time they are in bed (efficiency) and procure the best quality of sleep possible. Similar interpretations may be generated for Study 2. Although students may not have had major exams, they were still in school and may have had minor stress due to assignments and social demands. Students frequently sacrifice duration for these other commitments making efficiency aspects of sleep more important. Of interest here, efficiency was the measure most closely tied to PA. So, while high PA students may not go to bed earlier, when they do go to sleep, they fall asleep faster and stay asleep better.

One limitation of this work is our reliance on self-report measures for sleep. There are many measures of sleep activity; however, given the logistical constraints offered by the present studies, self-rated sleep was our method of choice. While self-reported sleep is a valid and useful assessment methodology, physiological assessments would provide a nuanced picture of the types of sleep (e.g., REM vs. non-REM) most influenced, and neuroscience approaches would aid in capturing the mechanisms by which PA subtypes alter sleep characteristics. Future research should be sensitive to these possibilities.

A second limitation is the lack of diversity in our samples. As a result, these findings may not generalize beyond primarily Caucasian and Asian students at an elite American university. Future studies should examine to what extent these findings apply to other populations. Of particular interest is the possibility that ideal affect (i.e., the preferred emotional traits and states of individuals and different cultures; Tsai, 2007) may make a difference in these results. Given known cross-cultural differences between idealized arousal states (e.g., high arousal preferences for many white/American samples, low arousal preferences for many east Asian samples), and the recent evidence that these preferences may make some difference for health (Curhan et al., 2014; Pressman, Gallagher, Lopez, & Campos, 2014; Sims, Tsai, Koopmann-Holm, Thomas, & Goldstein, 2014), this is a critical new direction for this area of research.

Future work will also have to probe more deeply into the circular and bidirectional nature of these associations since current study methods prevent causal interpretations. Emotions are influenced by past sleep. For example, trait vigor and enthusiasm might be indicators of generally good sleep and energy recovery (Zohar et al., 2005), and good sleep may even be partially responsible for this type of trait as evidenced by work on the changes to emotion areas of the brain from circadian disruption and sleep deprivation (see review by McEwen & Karatsoreos, 2015). Also relevant here is that a large portion of PA variance is due to a natural circadian rhythm in factors like body temperature (Murray et al., 2009). Thus, future studies should explore the physiological underpinnings of trait PA and vigor. It should also examine the sleep effects of experimentally induced PA subtypes, which has yet to be explored, though research has begun to test the objective sleep architecture changes resulting from induced NA or stress (see review by Deliens, Gilson, & Peigneux, 2014). Work of this nature paired with thoughtful longitudinal designs and objective measures of sleep will advance this literature in important ways.

Future research on this topic should also consider underlying physical health and how this plays a role in PA–sleep associations. There has been concern that some general health benefits of PA are due to the conceptual overlap between measures of high arousal positive psychological constructs with better health and/or physical fitness (Pressman & Cohen, 2005; Liu et al., 2016). This is well exemplified by self-reported physical health scales that include "vigor" as one of their items (Ware & Sherbourne, 1992; McHorney, Ware, & Raczek, 1993). It is also likely that people who are more physically fit report feeling more high energy emotions like excitement and enthusiasm. Importantly, in Study 2, when controlling for self-reported physical health, our patterns of findings remained the same (see Footnote 2). This pattern has also been found in studies controlling for baseline health when examining high arousal PA as a predictor of future health (Cohen et al., 2003; Pressman & Cohen, 2012).

Finally, there are many other interesting questions that could be explored relating to this study to expand understanding of the complex associations between affect and sleep. For example, the timing of the sleep–wake cycle may be critical given the above-mentioned circadian effects. That is, does when you go to sleep influence the PA–sleep association? Similarly, there is the possibility that these connections vary if days of the week are considered (e.g., weekend vs. weekday) or times that affect is sampled (e.g., late at night PA vs. 11 hours postwake). There may be certain times of day or specific days of the week when specific emotions matters most for sleep; however, further work is needed to thoroughly unpack the possibilities.

While more research is necessary given the small amount of research in the PA–sleep area, if confirmed, these growing findings may have implications for how we treat sleep disorders and sleep intervention development. There is clearly value to considering the types of PA and the nature of the stress context when advising individuals on the traits and emotions most tied to good sleep. We hope that researchers in the PA–sleep field, and PA–health literature more broadly, heed this message and consider these nuances in their future work.

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