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The daily relationship between subjective and objective sleep and ecological momentary assessment report of emotion in adolescents with an evening circadian preference

by

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Committee in Charge:

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Abstract

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Objectives: A link between sleep and emotion is well established. One prominent aspect of sleep and circadian functioning among youth is an evening circadian preference (ECP). Although under researched, the extant evidence raises the possibility that the relationship between sleep and emotion may be particularly prominent among ECP youth. As both sleep and emotion vary day-to-day and person-to-person, the present study examined the between- and within-person relationship between sleep and emotion in a sample of adolescents with an ECP.

Methods: For one week, 174 adolescents with an ECP (M_{age} =14.77$\pm$1.82) wore an actigraph and completed a sleep diary to assess sleep. They rated emotions using ecological momentary assessment. Data were analyzed using hierarchical linear modeling, controlling for age, sex, weekday/weekend, previous nights' sleep, and previous days' emotion.

Results: At the between-person level, higher negative emotion predicted a later bedtime, later sleep onset, and a shorter total sleep time (TST), which predicted higher next-day negative emotion. At the within-person level, higher-than-usual positive emotion predicted a later sleep onset, which predicted higher next-day positive emotion, while higher-than-usual negative emotion predicted a shorter TST. Sleep onset predicted higher next-day boredom at the between-person level, but lower next-day boredom at the within-person level.

Conclusions: A reciprocal, mutually maintaining relationship between sleep and emotion was observed at both the between- and within-person level. As sleep and emotion are linked through increased arousal and decreased neural connectivity, future interventions should target both positive and negative emotions as well as arousal before sleep to support overall well-being.

The daily relationship between subjective and objective sleep and ecological momentary assessment report of emotion in adolescents with an evening circadian preference

Adolescence

Beginning with puberty, adolescence is a developmental period defined by significant physical growth, hormonal changes, and brain development (Blakemore et al., 2010; Robeva & Kumanov, 2016). In particular, adolescence is characterized by development in the connectivity and maturation of brain regions critical for emotion reactivity and regulation (Casey et al., 2019). Moreover, the rapid and at times imbalanced neural development throughout adolescence may contribute to increased emotional reactivity, decreased emotion regulation, and increased engagement in emotionally-driven behaviors (e.g., alcohol and substance use, truancy, sexual activity (Cooper et al., 2003; Hessler & Katz, 2010)). Therefore, there is a need to identify and understand factors that support healthy emotion reactivity and regulation and that have potential to reduce emotionally-driven behaviors during adolescence. One possible factor is sleep and circadian functioning.

Sleep and Circadian Functioning

One prominent aspect of sleep and circadian functioning in youth is circadian preference, which refers to the preferred timing of sleep and activity (Carskadon et al., 1993). Approximately 40% of adolescents exhibit an evening circadian preference (ECP), characterized by increased evening activity and delayed sleep timing (Kuula et al., 2018). The biological tip toward increased evening activity can be exacerbated by a confluence of factors, including slower accumulation of and greater tolerance for sleep pressure resulting from pubertal changes to the homeostatic sleep regulating system, less parental control, homework, and increased technology use (Cain & Gradisar, 2010; Crowley et al., 2014; Díaz-Morales et al., 2014; Hagenauer & Lee, 2012; Hummer & Lee, 2016; Jenni et al., 2005; Meltzer et al., 2016; Roenneberg et al., 2004). Together, these influences can spiral into a pattern of late bedtimes. These late bedtimes can then conflict with early waketimes for school, contributing to insufficient sleep (Nahmod et al., 2017, 2019). Adolescents with an ECP are more likely to experience delayed sleep timing (i.e., late bedtime) and insufficient sleep (i.e., shorter total sleep time) compared to their peers (Collado Mateo et al., 2012; Russo et al., 2017). As a result, adolescents with an ECP may be more vulnerable to problems related to emotional reactivity, emotion regulation, and emotionally-driven behaviors.

Sleep and Emotion

There is a well-established bidirectional relationship between sleep and emotion (Kahn et al., 2013; Konjarski et al., 2018; Walker & van der Helm, 2009). Indeed, sufficient sleep is necessary for healthy emotional reactivity and regulation (Ben Simon et al., 2020; Goldstein & Walker, 2014; Palmer & Alfano, 2017). Among adults, sleep loss impairs cognitive control of emotion due to decreased connectivity between brain regions critical for emotion reactivity (i.e., amygdala) and regulation (i.e., prefrontal cortex) (Gujar et al., 2011; Simon et al., 2015; Yoo et al., 2007). The decrease in connectivity leads to increased emotional reactivity, decreased emotion regulation, and increased engagement in emotionally-driven behaviors (Gruber & Cassoff, 2014). Indeed, emotional reactivity to both positive and negative stimuli is amplified following sleep loss (Gujar et al., 2011; Yoo et al., 2007), indicating that sleep loss may affect how an individual perceives and responds to emotional stimuli.

Moreover, brain regions that support healthy emotion reactivity and regulation, and the connectivity between these regions, are still maturing during adolescence (Casey et al., 2019;

Gee et al., 2013; Giedd et al., 1999, 2015). As a result, the impact of sleep loss on emotional reactivity and regulation is likely magnified in adolescents. Indeed, a recent meta-analysis of 64 studies found that, compared to older adults, children and adolescents experienced increased negative emotion in response to sleep loss (Tomaso et al., 2020). A second meta-analysis of 74 studies found that shorter total sleep time was associated with increased negative affect, and decreased positive affect for adolescents (Short et al., 2020). Together, these two meta-analyses included over 100 cross-sectional, longitudinal, and experimental studies from several decades of sleep and emotion research (starting in 1998) and are consistent with the biological findings that poor sleep—and specifically insufficient sleep in the form of shorter total sleep time—was associated with increased negative emotion and decreased positive emotion. Thus, adolescence is a critical time to examine the relationship between sleep and emotion.

Sleep, Emotion, and Circadian Preference

Evidence from neuroscience points to the possibility of an ECP influencing the relationship between sleep and emotion. Biologically, an ECP is associated with hyperactivity in the amygdala in response to negative stimuli and decreased connectivity between the amygdala and dorsal anterior cingulate cortex (dACC) at rest, which results in amplified emotional reactivity and challenges with emotion regulation (Horne & Norbury, 2018a, 2018b). Since both insufficient sleep and an ECP are linked to decreased connectivity between areas responsible for emotion reactivity and regulation (Gujar et al., 2011; Horne & Norbury, 2018a; Simon et al., 2015; Yoo et al., 2007), a link between sleep, emotion, and an ECP seems biologically plausible.

The literature is mixed, however, about whether the relationship between emotion and ECP is driven by, or independent of, sleep. One recent study found that an ECP was associated with more emotional problems, less emotional well-being, more behavioral problems, and fewer prosocial behaviors, even after controlling for school start time and total sleep time (Gariépy et al., 2019). Total sleep time was determined using retrospective, self-reports of usual bedtime and waketime during the week. However, another study found that the relationship between an ECP and increased negative emotion was not significant once sleep disturbance was controlled (Cox & Olatunji, 2019). In this study, sleep disturbance was operationalized as a latent factor, including self-report measures of insomnia and sleep quality, as well as objective sleep efficiency and subjective sleep efficiency collected daily using actigraphy and sleep diary (Cox & Olatunji, 2019). One possible explanation for these findings is that the sleep measures that rely on retrospective reports of usual behavior may not be as sensitive as daily measures (Matthews et al., 2018). Going forward, the use of daily sleep measures, both objective and subjective, may produce a more accurate assessment of the relative contributions of sleep and circadian functioning (Mazza et al., 2020).

In sum, prior studies using various convergent methodologies point to the possibility that an ECP influences the relationship between sleep and emotion (Cox & Olatunji, 2019; Horne & Norbury, 2018a). The present study was conducted to continue developing knowledge in this domain by explicitly selecting a sample of adolescents with an ECP to examine the relationship between sleep, emotion, and circadian functioning.

Between and within individuals

Since both sleep (Becker et al., 2017; Bei et al., 2016) and emotion (Houben et al., 2015; Kuppens et al., 2010) vary day-to-day and person-to-person, it is essential to examine both the between-person and within-person relationship between sleep and emotion. Between-person analyses examine varying levels of specific predictors across individuals (e.g., higher negative affect, a later bedtime). In contrast, within-person analyses examine a specific predictor's daily variation within one person (e.g., days with higher than average negative affect, days with a later than usual bedtime). Moreover, research consistently shows that between-person and within-person variations in emotion are distinct phenomena (Brose et al., 2015). Since we cannot assume within-person relationships can be deduced from between-person analyses (Kramer, 1983), this study will use both between-person and within-person analyses to provide a more accurate picture of the relationship between sleep and emotion.

Prior research has found between-person and within-person associations between sleep and emotion in children, adolescents, and adults. At the between-person level, higher positive affect and lower negative affect were associated with longer total sleep time (Shen et al., 2018), while longer sleep onset latency and shorter total sleep time were associated with higher negative affect and lower positive affect in children and adolescents (Fuligni & Hardway, 2006; Kouros & El-Sheikh, 2015; Shen et al., 2018). At the within-person level, days with higher-than-usual positive affect predicted shorter sleep onset latency and longer total sleep time in adults (Kalmbach et al., 2014), while days with higher-than-usual negative affect predicted longer sleep onset latency in children and adults (Kalmbach et al., 2014; Kouros & El-Sheikh, 2015; Slavish et al., 2018) and longer total sleep time in youth with depression (Cousins et al., 2011). Moreover, longer-than-usual total sleep time predicted higher next-day positive affect and lower next-day negative affect in adults and in youth with depression and anxiety (Cousins et al., 2011; Fuligni & Hardway, 2006; Wrzus et al., 2014). Thus, the present study is designed to build on prior research by examining both the between-person and within-person relationship between sleep and emotion in adolescents, specifically a novel, high-risk group due to an ECP.

Facets of Emotion

The present study was designed to examine several facets inherent to the concept of emotion. Emotion can be assessed in a variety of ways (Mauss & Robinson, 2009). We used the Positive and Negative Affect Scale for Children (PANAS-C; Laurent et al., 1999) because it is a well-established and widely used measure of emotion. Specifically, the PANAS is a measure of emotion used to assess both state (i.e., "at this moment") and trait (i.e., "in general") emotion, as well as emotional reactivity (Boyes et al., 2017; Ehring et al., 2010). Moreover, the PANAS has been validated to measure between-person (Watson et al., 1988) and within-person (Bleidorn & Peters, 2011) variations in emotion.

In the present study, and consistent with the model of emotion proposed by Watson and Tellegen (1985), a specific emotion refers to ratings of individual positive and negative emotions (e.g., happy, sad), while global emotion refers to the higher-order, composite ratings of positive affect (PA) and negative affect (NA). Indeed, prior findings have supported this more nuanced approach to examining emotion, emphasizing the importance of including both global composites (PA and NA) and specific emotions to more appropriately characterize emotional experiences (Möwisch et al., 2019). This proposition is consistent with existing studies finding the relationship between sleep and emotion varies based on the specific emotion evaluated. For example, in a sample of healthy adolescents, higher ratings of positive specific emotions—classified as “high-arousal positive affect” (e.g., excited, happy)—were associated with longer sleep onset latencies, while higher ratings of negative specific emotions—classified as "dysphoric" (e.g., sad)—were associated with longer total sleep time (Tavernier et al., 2016). In other words, the relationship between sleep and emotion differed depending on the specific emotion assessed. These findings are echoed by recent meta-analytic findings that insufficient sleep reduced positive emotion, but not negative emotion, to the same degree as total sleep deprivation (Tomaso et al., 2020). Thus, the present study assessed positive and negative specific emotions and calculated global emotions (i.e., PA, NA) to assess and understand the relationship between sleep and emotion more accurately.

The selection of specific emotions was guided by prior research using the same EMA methodology as the present study (Cousins et al., 2011; Silk et al., 2011). However, one new emotion was added: boredom. Boredom can be conceptualized as an aversive state where one struggles to engage attention (Eastwood et al., 2012). Since both insufficient sleep and an ECP have been linked to problems with engaging attention (Giannotti et al., 2002; Vriend et al., 2011) and because boredom is associated with increased technology use, increased risky behavior, bedtime procrastination, poor sleep quality, and shorter total sleep time (Biolcati et al., 2018; Teoh et al., 2021; Tolor, 1989), boredom was included as a specific negative emotion.

The Present Study

The overarching goal was to examine the relationship between sleep and emotion in a sample of adolescents with an ECP using concurrent, timestamped measurements as well as subjective and objective measurements of sleep to evaluate between- and within-person associations.

The first aim was to evaluate the relationship between emotion (global and specific) during the day and subsequent nighttime sleep. At the between-person level, we hypothesized that higher PA, higher specific positive emotions (happy, cheerful, excited, interested), lower NA, and lower specific negative emotions (sad, angry, upset, nervous, bored) would be associated with an earlier subjective bedtime, an earlier objective sleep onset, and longer subjective and objective total sleep time. At the within-person level, we hypothesized that on days when individuals reported relatively greater (i.e., higher than their person-mean) PA and positive specific emotions and relatively less (i.e., lower than their person-mean) NA and negative specific emotions, they would also report an earlier subjective bedtime, an earlier objective sleep onset, and longer subjective and objective total sleep time that night.

The second aim was to evaluate the relationship between nighttime sleep and next-day emotion (global and specific). At the between-person level, we hypothesized that an earlier subjective bedtime, an earlier objective sleep onset, and longer subjective and objective total sleep time would be associated with higher PA, higher specific positive emotions, lower NA, and lower specific negative emotions. At the within-person level, we hypothesized that on days when individuals reported relatively earlier (i.e., earlier than their person-mean) subjective bedtime, objective sleep onset, and relatively greater (i.e., greater than their person-mean) subjective and objective total sleep time, they would also report higher PA, higher specific positive emotions, lower NA, and lower specific negative emotions the following day.

Method

Participants

One hundred seventy-three participants (102 females, average age = 14.76 years) participated in the current study. Participants were recruited for an NICHD-funded randomized controlled trial (RCT). A total of 398 participants were assessed for eligibility, and 220 (55.6%) were excluded for not meeting inclusion criteria (n=154) or refusing to participate (n=66). A total of 176 participants were enrolled in the larger RCT (Harvey et al., 2018). Three participants from the larger RCT were excluded from the current study due to corrupted or missing data (1.7%).

Individuals were included if they were (a) between 10 and 18 years old, living with a parent or guardian, and had a regularly scheduled activity (e.g., school or work) starting no later than 9 AM at least three days/week; (b) fluent in English; (c) able and willing to give informed assent; and (d) reported an evening circadian preference by scoring within the lowest quartile of the Children's Morningness-Eveningness Preference Scale (CMEP; 27 or lower; Dagys et al., 2012) and had a 7-day sleep diary (Carney et al., 2012) showing a bedtime of 10:40 PM or later for 10-13-year-olds, 11 PM or later for 14-16-year-olds, and 11:20 PM or later for 17-18-year-olds at least three nights per week for the last three months (Giannotti et al., 2002; Maslowsky & Ozer, 2014). Participants also needed to be 'at risk' in at least one of five health domains (Emotional, Behavioral, Social, Cognitive, or Physical) as defined elsewhere (Harvey et al., 2018).

Individuals were excluded if they had (a) an active, progressive physical illness or degenerative neurological disease directly related to the onset and course of their sleep disturbance; (b) evidence of obstructive sleep apnea, restless leg syndrome, or periodic limb movement disorder assessed using the Duke Structured Interview for Sleep Disorders (Edinger et al., 2004); (c) intellectual disability, autism spectrum disorder, or other significantly impairing pervasive developmental disorder; (d) bipolar disorder, schizophrenia, or another current Axis I disorder if there was a risk of harm if treatment was curtailed. Participants stopped taking medications that altered sleep (e.g., hypnotics) 4 weeks before the assessment (2 weeks for melatonin); otherwise, they were excluded. Finally, individuals were excluded if they had a history of substance dependence in the past six months or current suicide risk sufficient to preclude treatment on an outpatient basis. All study procedures were approved by the University of California, Berkeley Institutional Review Board. Parents or guardians of all participants provided informed consent, and participants provided informed assent.

Procedures and Materials

For the current study, the sleep and emotion measures described below were collected concurrently during the week following the pre-treatment assessment and before the beginning of treatment. A full description of the RCT is presented elsewhere (Harvey et al., 2018).

Ecological Momentary Assessment (EMA). The EMA protocol was designed to derive real-time data on emotion using cellular phones and was based on Silk and colleagues (Silk et al., 2011). Participants received two daily phone calls on weekdays and four daily phone calls on weekends for seven days. During each phone call, participants were asked to rate their current emotion on a scale from 1 (not at all) to 5 (extremely) using a subset of the emotion scales from the Positive and Negative Affect Schedule for Children (PANAS-C; Laurent et al., 1999). Four positive emotions were assessed: happy, cheerful, interested, and excited. Five negative emotions were assessed: sad, nervous, upset, angry, and bored. Positive emotions in each call were averaged to create a positive affect (PA) score. Negative emotions in each call were averaged to create a negative affect (NA) score. The final PA and NA scores were derived by averaging ratings across the 2-4 calls participants received each day. The PANAS-C has been shown to have good convergent and discriminant validity (Laurent et al., 1999). Moreover, the PANAS has been validated as a measurement tool for examining between-person (Watson et al., 1988) and within-person variation (Bleidorn & Peters, 2011) in PA and NA. The full EMA script can be found in Appendix A.

Actigraphy. The Actiwatch Spectrum (Philips Respironics) is a small, wrist-worn device containing an accelerometer to sample physical motion. Actigraphy is a widely used objective measure of sleep and has been validated against the gold standard objective measure, polysomnography, in adolescents (Quante et al., 2018; Sadeh, 2011). Participants wore the actiwatch during the same seven days that EMA was collected. Participants were asked to wear an actiwatch on the non-dominant wrist and were instructed to remove the actiwatch only when showering. Activity data were logged in 30-second epochs and analyzed using the Actiware software v.6 (Philips Respironics, Bend, OR, USA). The scoring algorithm's sensitivity for wake/sleep detection was set to medium.

The main sleep window was the longest sleep period identified by the scoring algorithm within a 24-hour window. The sleep window was then adjusted using visual inspection and a concurrently collected sleep diary. First, the sleep windows were visually inspected and adjusted to begin with a visible decrease in activity and to end with a visible increase in activity. When available, data from a concurrently collected sleep diary was used to confirm and adjust the sleep window (Boyne et al., 2013; Matthews et al., 2018). The sleep window was adjusted to match the sleep diary when bedtime and risetime values fell within 30 minutes of the onset/offset time set by the algorithm and visual inspection of the sleep window. If the sleep diary values were greater than 30 minutes or the sleep diary was unavailable, only the scoring algorithm and visual inspection were used to confirm the sleep window. Participants rarely pushed event markers as instructed. Therefore, data from event markers were not available and could not be used to adjust the sleep window.

Two objective variables were derived from actigraphy: sleep onset and total sleep time. Sleep onset values were converted to decimal hours and midnight was set to 24.00. Sleep onsets occurring after midnight were converted by adding 24.00 to the decimal hour value (e.g., 1:05 AM = 25.08). Total sleep time was calculated as the interval between sleep onset and sleep offset minus wake after sleep onset.

Sleep Diary. The consensus sleep diary (Carney et al., 2012) was collected by phone every morning by a trained research assistant. The sleep diary data were collected concurrently with actigraphy and EMA. Two subjective variables were derived: bedtime ("What time did you try to fall asleep?") and total sleep time, the interval from bedtime to waketime minus sleep onset latency and wake after sleep onset. Bedtimes occurring after midnight were converted by adding 24.00 to the decimal hour value (e.g., 1:05 AM = 25.08). The full sleep diary can be found in Appendix B.

Selection of Sleep Parameters. Sleep parameters were selected with the goal of capturing two aspects of adolescent sleep: timing and duration. Due to the differences in the outcomes available from sleep diary and actigraphy, the a priori decision was made to use subjective bedtime ("What time did you try to fall asleep?") and objective sleep onset (e.g., time sleep period began) as complementary measures for assessing sleep timing in the evening. Use of these sleep parameters is also consistent with previous research using both actigraphy and sleep diary in the same sample (Gasperetti et al., 2021). Additionally, as TST can be derived from both actigraphy and sleep diary, the a priori decision was made to use objective TST and subjective TST as complementary measures for assessing nighttime sleep duration. It is acknowledged that other sleep parameters could have been selected. In particular, sleep onset latency (SOL) is one commonly used outcome (Konjarski et al., 2018). Since SOL is significantly correlated with both subjective bedtime and objective sleep onset in the present sample ($t = 6.83$, $p < .001$), the *a priori* decision was made to limit the number of parameters assessed and not include SOL.

Statistical Analysis

All analyses were performed in R (R Development Core Team, 2018). Hierarchical linear models (HLM) with restricted maximum likelihood estimation and unstandardized regression coefficients were used for all analyses (Bates et al., 2015). All HLM analyses included a random intercept for participant. The first aim included emotion (positive affect, negative affect, happy, cheerful, interested, excited, sad, angry, upset, nervous, bored) as the predictor and sleep (subjective bedtime, objective sleep onset, objective total sleep time, subjective total sleep time) as the outcome. The second aim included sleep (subjective bedtime, objective sleep onset, objective total sleep time, subjective total sleep time) as the predictor and emotion (positive affect, negative affect, happy, cheerful, interested, excited, sad, angry, upset, nervous, bored) as the outcome.

Analyses included day as the level 1 unit of analysis (within-person effects) and participant as the level 2 unit of analysis (between-person effects). We centered all predictor variables at level 1 using person-mean centering, which allowed us to parse the between-person effects from the within-person effects. We centered the person means at Level 2 using grand mean centering so the intercept would reflect the sample average. All models tested both between- and within-person associations between the predictor and the outcome simultaneously.

Age group (0 = 10-13, 1 = 14-16, 2 = 17-18), sex (0 = male, 1 = female), and a dummy variable for weekend (0 = weekday, 1 = weekend) were entered into the model as covariates and coded as factors, so were not centered. Given the wide age range covered by this study, the inclusion criteria varied based on three age groups (i.e., 10-13, 14-16, 17-18). Due to the variation in inclusion criteria, we decided to include age as a categorical group variable rather than a continuous variable. For Aim 1, the previous night's sleep was entered as a time lagged-outcome covariate and person-mean centered. For Aim 2, the previous day's emotion was entered as a time lagged-outcome covariate and person-mean centered. Models for objective sleep measured by actigraphy and subjective sleep measured by sleep diary were run separately.

The present study followed recommendations to use multiple parameters to assess sleep (Sadeh et al., 2000). Furthermore, the inclusion of the nine specific emotions, in addition to the two global emotion composites, allows for a more complete understanding of how emotion and sleep are related. Procedures that correct for multiple comparisons tend to reduce power and increase the likelihood of type II error (Nakagawa & Cuthill, 2007). For the present study, a critical p-value of 0.05 was maintained, and for all analyses, effect sizes and confidence intervals are provided.

Results

Demographic information and descriptive statistics for emotion and sleep are presented in Table 1.

Aim 1: Daytime emotion predicting subsequent nighttime sleep

A summary of all fixed effects for global emotion are depicted in Figure 1. A summary of all fixed effects for specific positive and negative emotion are depicted in Figures 2 and 3.

At the between-person level, higher NA predicted a later subjective bedtime, a later objective sleep onset, and a shorter subjective total sleep time (Table 2). Furthermore, higher daytime sad, nervous, upset, and angry emotions predicted a later subjective bedtime and a shorter subjective total sleep time (Table 3). Higher daytime nervous, upset, and angry emotions predicted a later objective sleep onset (Table 3). Higher excited, sad, nervous, and upset emotions predicted a shorter objective total sleep time (Table 3).

At the within-person level, days with higher than usual (i.e., above their personal average) PA were associated with a later objective sleep onset (Table 2). Furthermore, days with higher than usual (i.e., above their personal average) NA were associated with a shorter objective total sleep time (Table 2). Furthermore, days with higher than usual (i.e., above their personal average) interest, excited, and nervous emotions were associated with a later objective sleep onset (Table 3). Furthermore, days with higher than usual (i.e., above their personal average) nervous emotions were associated with shorter subjective total sleep time (Table 3).

Aim 2: Nighttime sleep and next-day emotion

A summary of all fixed effects for global emotion is shown in Figure 1. A summary of all fixed effects for specific positive and negative emotion are depicted in Figures 2 and 3.

At the between-person level, a later subjective bedtime, a later objective sleep onset, and a shorter subjective total sleep time predicted higher next-day NA (Table 4). Furthermore, a later subjective bedtime was associated with higher sad, nervous, upset, angry, and bored emotions (Table 5). A later objective sleep onset was also associated with higher sad, nervous, upset, and angry emotions (Table 5). Additionally, shorter subjective total sleep time was associated with higher sad, nervous, upset, and angry emotions (Table 5).

At the within-person level, days with a later than usual (i.e., later than their personal average) subjective bedtime were associated with higher cheerful and excited emotions as well as lower bored emotions (Table 4). Furthermore, days with a later than usual (i.e., later than their personal average) objective sleep onset were associated with higher excited emotions and lower bored emotions (Table 5).

Discussion

The relationship between sleep and emotion is well-established in the literature (e.g., Kahn et al., 2013; Konjarski et al., 2018; Walker & van der Helm, 2009). The present study was conducted to extend the existing research by focusing on adolescents with an ECP and examining between- and within-person relationships concurrently. This is important for at least three reasons. First, an ECP may influence the relationship between sleep and emotion (Cox & Olatunji, 2019; Horne & Norbury, 2018a, 2018b). Second, adolescents with an ECP are at risk for challenges with both sleep and emotion (Collado Mateo et al., 2012; Horne et al., 2019; Russo et al., 2017), and are therefore a particularly high-risk group. Third, since both sleep (Becker et al., 2017; Bei et al., 2016) and emotion (Houben et al., 2015; Kuppens et al., 2010) vary day-to-day and person-to-person, the examination of both average and daily variation provides two independent, but complementary, perspectives on the sleep and emotion relationship (Fuligni & Hardway, 2006).

The first aim was to evaluate the relationship between emotion during the day and subsequent nighttime sleep. At the between-person level, we hypothesized that higher PA, higher specific positive emotions, lower NA, and lower specific negative emotions would be associated with an earlier subjective bedtime and objective sleep onset and longer subjective and objective TST. We found partial support for these hypotheses. Indeed, at the between-person level, higher NA, nervous, upset, and angry emotions were associated with a later subjective bedtime, later objective sleep onset, and a shorter subjective TST. Moreover, more sad emotions were associated with a later subjective bedtime and a shorter subjective TST. In other words, higher daytime negative emotion predicted a delay in sleep timing (i.e., later bedtime, later sleep onset) as well as a decrease in sleep duration. These findings are consistent with prior reports in adults that higher negative affect is associated with a later bedtime (Shin et al., 2005) and shorter TST (Kalmbach et al., 2014). However, the findings are contrary to a previous study in healthy adolescents where higher dysphoria (i.e., sadness) predicted longer TST (Tavernier et al., 2016). There are several possible accounts of this discrepant finding between healthy adolescents and the present sample of adolescents with an ECP. First, given that sleep is important for emotion processing (Walker & van der Helm, 2009), one possibility is that healthy adolescents respond to feelings of sadness by sleeping longer as a means of effective emotion processing, whereas this opportunity is not available to youth with an ECP. If so, this might confer an important "risk pathway" for ECP youth. Second, individuals with an ECP are more likely to use maladaptive emotion regulation strategies, such as self-blame and rumination, relative to non-ECP individuals (Antypa et al., 2017; Van den Berg et al., 2018). In turn, these emotion regulation strategies may interfere with sleep. Third, adolescents with an ECP are at greater risk of experiencing negative emotions (Dagys et al., 2012) and negative emotions may be associated with higher levels of arousal, which can interfere with sleep (Baglioni et al., 2010). Fourth, individuals with an ECP are more likely to delay bedtime and engage in bedtime procrastination (Kadzikowska-Wrzosek, 2020). Bedtime procrastination is associated with depression, anxiety, and increased media use in the hours before bedtime (Chung et al., 2020). Therefore, it is possible that experiencing higher negative emotion during the day contributes to bedtime procrastination and engagement in activities that displace sleep, such as technology use or rumination (Cain & Gradisar, 2010; Nauts et al., 2019), which delays sleep onset and reduces sleep duration.

For the within-person level, we hypothesized that on days when individuals reported higher than their person-mean PA and positive specific emotions and lower than their person-mean NA and negative specific emotions, they would also report an earlier subjective bedtime and objective sleep onset and longer subjective and objective TST that night. Consistent with our hypothesis, higher-than-usual NA, sad, nervous, and upset emotions was associated with a shorter objective TST. Higher-than-usual nervous emotions were also associated with a later objective sleep onset and a shorter subjective TST. These findings are consistent with previous research showing that higher-than-usual anxious-nervous emotions predicted more difficulty staying asleep in a sample of healthy adolescents (Tavernier et al., 2016). Nervous and upset are both high arousal negative emotions and, as mentioned previously, higher arousal can interfere with sleep (Baglioni et al., 2010). Taken together, one pathway by which higher-than-usual high arousal negative emotions leads to decreased sleep duration may be via increased arousal.

There were several unexpected findings for our first aim. First, at the within-person level, higher-than-usual PA, interest, and excited emotions were associated with later objective sleep onset. It is important to note all of the emotions included in the PA composite can be classified "high-arousal positive affect", which could be resulting in increased physiological arousal, which can delay sleep onset (Tavernier et al., 2016). Thus, it is possible that adolescents who are experiencing higher positive affect may experience increased physiological arousal and are either using the associated energy to deliberately or mindlessly delay bedtime (Nauts et al., 2019) or they are strategically delaying bedtime until they are tired enough to fall asleep more quickly (Carskadon et al., 1997; Randler, 2008). Second, greater-than-usual excited emotions were associated with a shorter objective TST at the within-person level. As noted previously, it is possible that higher excitement leads to increased arousal which can delay sleep (Nauts et al., 2019). Moreover, many adolescents have early school start times that require early wake-ups during the school week (Au et al., 2014). Therefore, one possibility is that higher-than-usual excitement leads to increased arousal and a delayed sleep onset in the evening. Delayed sleep onset combined with early waketimes for school in the morning results in a shorter TST. Third, there was no relationship between positive affect and TST. This finding is contrary to prior research that has demonstrated that higher positive affect is associated with longer TST at the between-person (Shen et al., 2018) and within-person (Kalmbach et al., 2014) levels in healthy individuals. While it is possible that positive affect during the day is a weaker influence on TST for individuals with an ECP, it is also possible that the delay between collecting ratings of daytime emotion and nighttime sleep made it difficult to observe this relationship. Specifically, the final rating took place an average of 4 hours before sleep. Future studies should examine positive affect closer to bedtime.

The second aim was to evaluate the relationship between nighttime sleep and next-day emotion. At the between-person level, we hypothesized that an earlier subjective bedtime, an earlier objective sleep onset, and longer subjective and objective TST would be associated with higher PA and positive specific emotions and lower NA and negative specific emotions. We found partial support for these hypotheses. At the between-person level, a later subjective bedtime, a later objective sleep onset, and a shorter subjective TST were associated with higher next-day NA, sad, nervous, upset, and angry emotions. These findings are consistent with prior reports that shorter subjective TST and a later sleep onset are associated with higher next-day negative affect (Fuligni & Hardway, 2006; Kouros & El-Sheikh, 2015; Shen et al., 2018; Short et al., 2020; Totterdell et al., 1994). Biologically, an ECP is associated with hyperactivity in the amygdala in response to negative stimuli and decreased connectivity between the amygdala and dorsal anterior cingulate cortex (dACC) at rest, which contributes to emotional reactivity and challenges with emotion regulation (Horne & Norbury, 2018a). Moreover, both insufficient sleep and an ECP are linked to decreased connectivity between areas responsible for emotion reactivity (i.e., amygdala) and regulation (Gujar et al., 2011; Horne & Norbury, 2018a; Simon et al., 2015; Yoo et al., 2007). In other words, adolescents in the present sample were already at-risk for increased emotion reactivity and difficulty with emotion regulation because of an ECP and this risk was likely increased when they experienced insufficient sleep, resulting in increased reactivity to negative stimuli and higher next-day negative emotion.

For the within-person level, we hypothesized that on days when individuals reported earlier than their person-mean subjective bedtime, objective sleep onset, and greater than their person-mean subjective and objective TST, they would also report higher PA, higher specific positive emotions, lower NA, and lower negative specific emotions the following day. Contrary to our hypothesis, at the within-person level, a later-than-usual subjective bedtime was associated with higher next-day cheerful emotions, and both a later-than-usual subjective bedtime and objective sleep onset were associated with higher next-day excited emotions. An ECP is characterized by increased evening activity and delayed sleep timing (Kuula et al., 2018), One possibility is that adolescents with an ECP may be delaying sleep until they are tired enough to fall asleep easily (Carskadon et al., 1997; Randler, 2008) and may use that evening time to engage in activities, such as television or video games (Cain & Gradisar, 2010; Gaarde et al., 2020; Hoyt et al., 2018; Nauts et al., 2019). Indeed, taking less time to fall asleep has also been linked to higher next-day positive emotions (Cousins et al., 2011; Kouros & El-Sheikh, 2015). Additionally, prior research in the same sample has found that watching television and playing video games were also associated with higher next-day positive emotion (Gumport et al., 2021). Thus, it is possible that when adolescents with an ECP are able to delay bedtime until they are sleepy and use that evening time to do activities they enjoy, they experience higher positive emotions the next day. Future studies should continue to examine how sleep timing and chronotype contribute to next-day emotion.

Limitations

Our findings must be interpreted within the confines of several limitations. First, the last EMA call each day was placed approximately 4 hours before bedtime. While this ensured that calls did not interfere with participants' sleep, it meant that we were unable to capture emotion in the hours closest to bedtime. Second, emotion and sleep are both influenced by age, gender, and pubertal status (Campbell et al., 2012; Carskadon et al., 1993; Dolsen et al., 2018; Knutson, 2005; Wrzus et al., 2014). While age and gender were included as covariates in the current study, an important next step will be to consider puberty as a moderator (Lustig et al., 2021) and explore possible interactions with puberty hormones (testosterone, DHEA, estradiol). Third, participants in this study were drawn from a larger randomized controlled trial that recruited adolescents who were at risk in one of five health domains. Accordingly, the findings from this study are most generalizable to a high risk sample. Future research is needed to explore the generalizability of these findings. Fourth, the study selected participants who had an ECP. Therefore, an important next step will be to compare different chronotypes and see whether the results of the present study are replicated. Fifth, the inclusion of both objective and subjective measures of sleep is a strength of the present study; the daily sleep diary remains the gold-standard self-report measure for sleep (Carney et al., 2012) and complements actigraphy by providing a subjective perspective to objective sleep values (Mazza et al., 2020). However, it is possible for subjective and objective measures of sleep to be discrepant (Harvey & Tang, 2012) and it remains challenging to disentangle which values are the truest representation of sleep in daily life. Finally, the present study did not specifically assess based on valence and arousal, instead selecting for individual emotions, so future research should consider including both high and low arousal emotions.

Summary and Implications

Theoretical Implications. Several bioregulatory (i.e., slower accumulation of sleep pressure, phase delays with pubertal onset), psychosocial (i.e., bedtime autonomy, academic pressures, screen time, technology and social networking), and societal (i.e., school start times) factors have been proposed to comprise "perfect storm" of insufficient and delayed sleep during adolescence (Carskadon, 2011; Crowley et al., 2018). The present findings point to emotion—both positive and negative—as another factor that contributes to, and is impacted by, insufficient and delayed sleep.

Consistent with our hypothesis, higher negative emotion was associated with later subjective bedtime, later objective sleep onset and shorter subjective and objective TST, which in turn were associated with higher next-day negative emotions. Surprisingly, higher positive emotion was also associated with a later subjective bedtimes and later objective sleep onset, which in turn were associated with higher next-day positive emotions. Central to the interpretation of the findings herein, is the concept of arousal. The profound impact of arousal on sleep has been well-established in the sleep literature, with both physiological and cognitive aspects of arousal receiving empirical attention (Garde et al., 2011; Schmidt et al., 2007). Furthermore, pre-sleep arousal specifically has been identified as a possible contributor to poor sleep in both children and adults (Garde et al., 2011; Gregory et al., 2008). Mechanistically, we know that experiencing high arousal positive and negative emotions is associated with increased physiological arousal, which can interfere with sleep (Baglioni et al., 2010) and lead to bedtime procrastination (Nauts et al., 2019). The present findings extend existing conceptualizations by demonstrating that both positive and negative emotions may contribute to delayed and insufficient sleep via increased arousal. Moreover, since both insufficient sleep and an ECP are linked to decreased connectivity between brain regions responsible for emotion reactivity and regulation (Gujar et al., 2011; Horne & Norbury, 2018a; Simon et al., 2015; Yoo et al., 2007), and these regions are still developing during adolescence (Casey et al., 2019; Gee et al., 2013; Giedd et al., 1999, 2015), youth with an ECP represent a particularly "at risk" population who are more likely to experience amplified emotional reactivity and challenges with emotion regulation. Indeed, the present study found that, at the between-person, higher negative emotion was associated with delayed and insufficient sleep, which resulted in higher next-day negative emotions. Additionally, at the within-person level, days with higher-than-usual positive emotions were associated with delayed sleep, while days with higher-than-usual negative emotions were associated with insufficient sleep. In other words, for youth with an ECP, insufficient and delayed sleep appear to contribute to challenges with emotion reactivity and regulation, which in turn results in insufficient and delayed sleep. Taken together, it is possible that emotion may impact several of the bioregulatory and psychosocial factors contributing to insufficient delayed sleep through increased arousal and decreased connectivity between brain regions necessary for emotion reactivity and regulation, resulting in a bi-directional, mutually maintaining vicious cycle (Kahn et al., 2013; Walker & van der Helm, 2009). Thus, emotion may be considered an additional, independent factor to be added to the "perfect storm" model of adolescent sleep.

Clinical Implications. There are several clinical implications. In the present study, both higher positive and higher negative emotions were associated with a later subjective bedtime, a later objective sleep onset and shorter subjective and objective TST. These findings point to the possibility of targeting both positive and negative emotion in the hours before sleep to facilitate an effective wind down period, avoid bedtime procrastination, and promote appropriate sleep timing, especially in the context of early school start times. Furthermore, since the majority of the emotions assessed in the present study can be classified as high arousal, it will also be important to consider developing interventions that specifically target arousal and support engaging in evening activities that reduce arousal to promote sleep.

Conclusions

In summary, this study found partial support for a relationship between sleep and emotion in a sample of adolescents with an ECP. These results are consistent with the theory that disruptions in nighttime sleep and daytime emotion may be mutually maintaining (Kahn et al., 2013; Konjarski et al., 2018; Walker & van der Helm, 2009). Given that adolescence is a critical developmental period characterized by a shift towards an ECP, the present study extends the current literature by specifically selecting for a sample of adolescents with an ECP, by suggesting that both positive and negative emotions can negatively impact nighttime sleep, by highlighting the role of arousal in the relationship between sleep and emotion, and by finding these relationships to be present both between- and within-person.

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Table 1. Participant demographics, sleep and circadian variables, emotion variables (n = 173)

Characteristic	*M* or N	*SD* or %
Female	102	58.96
Age (Years)	14.76	1.82
Race		
Asian	17	9.82
African American or Black	12	6.93
Caucasian	112	64.74
Native Hawaiian	2	1.15
Mixed Race	30	17.34
Ethnicity		
Hispanic or Latino	26	15.03
Not Hispanic or Latino	147	84.97
Sleep and Circadian Variables		
CMEP	21.24	3.80
Sleep Onset (Decimal Hours; actigraphy)	24.13	0.96
BT (Decimal Hours; sleep diary)	23.58	1.06
TST (Hours; actigraphy)	6.66	0.98
TST (Hours; sleep diary)	7.78	1.04
Emotion Variables		
PA	10.04	2.56
NA	7.24	1.81
Specific Emotion Variables		
Happy	3.05	0.73
Cheerful	2.40	0.80
Interested	2.52	0.69
Excited	2.08	0.72
Sad	1.36	0.45
Nervous	1.42	0.54
Upset	1.34	0.42
Angry	1.26	0.32
Bored	1.87	0.57

Note. CMEP = Children's Morningness-Eveningness Preference Scale, BT = Bedtime, TST = Total Sleep Time, PA = Positive Affect, NA = Negative Affect

Table 2. Multilevel models of global emotion predicting objective and subjective sleep

Outcome	Predictor	B	*t*	*p*	95% CI	d
Subj BT[a] (decimal hrs.)	PA (bw)	0.05	1.63	.104	-0.01, 0.11	0.26
	PA (wn)	0.02	1.32	.187	-0.01, 0.06	0.11
	NA (bw)	0.18	4.59	<.001***	0.10, 0.26	0.74
	NA (wn)	0.03	1.27	.205	-0.20, 0.08	0.10
Obj SleepOn[b] (decimal hrs.)	PA (bw)	0.00	0.12	.909	-0.06, 0.07	0.02
	PA (wn)	0.06	2.65	.008**	0.02, 0.10	0.22
	NA (bw)	0.10	2.11	.037*	0.01, 0.19	0.36
	NA (wn)	0.03	1.06	.291	-0.03, 0.09	0.09
Obj TST[b] (hrs.)	PA (bw)	0.02	0.57	.571	-0.06, 0.10	0.12
	PA (wn)	-0.02	-0.61	.542	-0.08, 0.04	-0.06
	NA (bw)	-0.05	-0.83	.406	-0.15, 0.06	-0.17
	NA (wn)	-0.10	-2.31	.022*	-0.19, -0.02	-0.23
Subj TST[a] (hrs.)	PA (bw)	-0.01	-0.45	.650	-0.07, 0.05	-0.07
	PA (wn)	-0.01	-0.34	.738	-0.06, 0.04	-0.03
	NA (bw)	-0.13	-3.07	.002**	-0.21, -0.05	-0.48
	NA (wn)	-0.06	-1.69	.093	-0.12, 0.01	-0.14

Notes: BT = Bedtime, SleepOn = Sleep Onset, TST = Total Sleep Time, PA = Positive Affect, NA = Negative Affect, bw = between, wn = within, hrs. = hours, subj = subjective, obj = objective. Age, sex, weekday/weekend, and previous night sleep were included as covariates. [a] Measured using sleep diary. [b] Measured using actigraphy.

Table 3. Multilevel models of specific emotion predicting objective and subjective sleep

Outcome	Predictor	B	*t*	*p*	95% CI	d
Subj BT[a] (decimal hrs.)	Happy (bw)	0.12	1.17	.246	-0.08, 0.32	0.19
	Happy (wn)	0.07	1.11	.269	-0.05, 0.19	0.09
	Cheerful (bw)	0.14	1.54	.126	-0.04, 0.33	0.25
	Cheerful (wn)	0.05	0.97	.334	-0.06, 0.17	0.08
	Interested (bw)	0.15	1.35	.178	-0.07, 0.36	0.22
	Interested (wn)	0.01	0.78	.781	-0.09, 0.11	0.02
	Excited (bw)	0.17	1.67	.095	-0.03, 0.38	0.27
	Excited (wn)	0.10	1.79	.074	-0.01, 0.20	0.15
	Sad (bw)	0.58	3.66	<.001***	0.27, 0.90	0.59
	Sad (wn)	0.01	0.10	.920	-0.16, 0.17	0.01
	Nervous (bw)	0.60	4.38	<.001***	0.33, 0.87	0.70
	Nervous (wn)	0.14	1.77	.077	-0.01, 0.29	0.14
	Upset (bw)	0.73	4.25	<.001***	0.39, 1.06	0.69
	Upset (wn)	0.14	1.77	.078	-0.02, 0.30	0.14
	Angry (bw)	0.98	4.20	<.001***	0.52, 1.43	0.69
	Angry (wn)	0.11	1.11	.268	-0.08, 0.29	0.09
	Bored (bw)	0.24	1.87	.064	-0.01, 0.49	0.30
	Bored (wn)	-0.02	-0.41	.684	-0.13, 0.09	-0.03
Obj SleepOn[b] (decimal hrs.)	Happy (bw)	0.01	0.07	.941	-0.23, 0.24	0.01
	Happy (wn)	0.06	0.77	.445	-0.10, 0.22	0.06
	Cheerful (bw)	0.04	0.32	.751	-0.19, 0.26	0.06
	Cheerful (wn)	0.12	1.65	.100	-0.02, 0.25	0.14
	Interested (bw)	0.07	0.52	.603	-0.18, 0.32	0.09
	Interested (wn)	0.15	2.52	.012*	0.04, 0.28	0.21
	Excited (bw)	-0.07	-0.55	.582	-0.31, 0.17	-0.10
	Excited (wn)	0.20	3.10	.002**	0.07, 0.33	0.26
	Sad (bw)	0.31	1.64	.104	-0.06, 0.69	0.28
	Sad (wn)	0.07	0.58	.560	-0.16, 0.29	0.05
	Nervous (bw)	0.38	2.50	.014*	0.08, 0.68	0.44
	Nervous (wn)	0.23	2.35	.020*	0.04, 0.42	0.20
	Upset (bw)	0.49	2.31	.023*	0.07, 0.90	0.40
	Upset (wn)	0.15	1.45	.147	-0.05, 0.35	0.12
	Angry (bw)	0.71	2.62	.010**	0.18, 1.23	0.44
	Angry (wn)	0.07	0.64	.524	-0.15, 0.30	0.05
	Bored (bw)	0.01	0.06	.956	-0.30, 0.32	0.01
	Bored (wn)	-0.06	-0.86	.393	-0.19, 0.07	-0.07
Obj TST[b] (hrs.)	Happy (bw)	0.02	0.17	.866	-0.25, 0.29	0.04
	Happy (wn)	0.03	0.27	.790	-0.19, 0.25	0.03
	Cheerful (bw)	0.05	0.42	.678	-0.19, 0.30	0.09
	Cheerful (wn)	0.05	0.57	.566	-0.13, 0.25	0.06
	Interested (bw)	-0.01	-0.07	.949	-0.29, 0.27	-0.01
	Interested (wn)	-0.05	-0.57	.567	-0.22, 0.12	-0.06

	Excited (bw)	0.23	1.64	.104	-0.05, 0.52	0.36
	Excited (wn)	-0.18	-1.97	.049*	-0.36, -0.00	-0.20
	Sad (bw)	-0.00	-0.02	.983	-0.44, 0.44	-0.00
	Sad (wn)	-0.35	-2.16	.031*	-0.66, -0.03	-0.22
	Nervous (bw)	-0.22	-1.20	.233	-0.57, 0.14	-0.26
	Nervous (wn)	-0.33	-2.21	.028*	-0.62, -0.04	-0.22
	Upset (bw)	-0.24	-0.99	.325	-0.72, 0.24	-0.22
	Upset (wn)	-0.31	-2.12	.034*	-0.61, -0.02	-0.21
	Angry (bw)	-0.44	-1.37	.175	-1.07, 0.19	-0.30
	Angry (wn)	-0.30	-1.86	.063	-0.61, 0.02	-0.19
	Bored (bw)	-0.00	-0.02	.981	-0.36, 0.35	-0.00
	Bored (wn)	0.02	0.17	.867	-0.17, 0.20	0.02
Subj TST[a] (hrs.)	Happy (bw)	-0.03	-0.27	.786	-0.24, 0.18	-0.04
	Happy (wn)	-0.01	-0.16	.873	-0.17, 0.15	-0.01
	Cheerful (bw)	-0.05	-0.49	.622	-0.24, 0.14	-0.08
	Cheerful (wn)	-0.01	-0.10	.922	-0.15, 0.14	-0.01
	Interested (bw)	-0.06	-0.51	.611	-0.28, 0.16	-0.08
	Interested (wn)	-0.03	-0.38	.708	-0.16, 0.11	-0.03
	Excited (bw)	-0.03	-0.26	.796	-0.24, 0.19	-0.04
	Excited (wn)	-0.03	-0.37	.708	-0.17, 0.11	-0.03
	Sad (bw)	-0.45	-2.69	.008**	-0.78, -0.12	-0.42
	Sad (wn)	0.08	0.68	.500	-0.14, 0.30	0.05
	Nervous (bw)	-0.43	-2.97	.003**	-0.71, -0.14	-0.46
	Nervous (wn)	-0.27	-2.72	.007**	-0.47, -0.08	-0.22
	Upset (bw)	-0.57	-3.19	.002**	-0.93, -0.22	-0.51
	Upset (wn)	-0.12	-1.05	.294	-0.33, 0.10	-0.08
	Angry (bw)	-0.53	-2.16	.033*	-1.02, -0.05	-0.35
	Angry (wn)	-0.09	-0.70	.483	-0.35, 0.17	-0.06
	Bored (bw)	-0.17	-1.24	.217	-0.43, 0.10	-0.19
	Bored (wn)	-0.07	-0.94	.349	-0.21, 0.07	-0.08

Notes: BT = Bedtime, SleepOn = Sleep Onset, TST = Total Sleep Time, bw = between, wn = within, hrs. = hours, subj = subjective, obj = objective. Age, sex, weekday/weekend, and previous night sleep were included as covariates. [a] Measured using sleep diary. [b] Measured using actigraphy.

Table 4. Multilevel models of objective and subjective sleep predicting global emotion

Outcome	Predictor	B	*t*	*p*	95% CI	d
PA	Subj BT[a] (bw; decimal hrs.)	0.40	1.79	.076	-0.04, 0.83	0.29
	Subj BT[a] (wn; decimal hrs.)	0.17	1.83	.068	-0.01, 0.35	0.15
NA	Subj BT[a] (bw; decimal hrs.)	0.63	4.09	<.001***	0.33, 0.93	0.73
	Subj BT[a] (wn; decimal hrs.)	-0.11	-1.65	.101	-0.24, 0.02	-0.13
PA	Obj SleepOn[b] (bw; decimal hrs.)	-0.15	-0.56	.574	-0.65, 0.36	-0.10
	Obj SleepOn[b] (wn; decimal hrs.)	0.10	1.32	.188	-0.05, 0.27	0.12
NA	Obj SleepOn[b] (bw; decimal hrs.)	0.47	2.62	.010*	0.12, 0.81	0.50
	Obj SleepOn[b] (wn; decimal hrs.)	-0.09	-1.37	.171	-0.22, 0.04	-0.12
PA	Obj TST[b] (bw; hrs.)	0.37	1.13	.262	-0.27, 1.01	0.22
	Obj TST[b] (wn; hrs.)	-0.09	-1.10	.274	-0.25, 0.07	-0.12
NA	Obj TST[b] (bw; hrs.)	-0.22	-0.99	.328	-0.66, 0.22	-0.21
	Obj TST[b] (wn; hrs.)	0.04	0.63	.527	-0.08, 0.16	0.07
PA	Subj TST[a] (bw; hrs.)	-0.07	-0.29	.770	-0.51, 0.37	-0.05
	Subj TST[a] (wn; hrs.)	-0.01	-0.23	.818	-0.14, 0.11	-0.02
NA	Subj TST[a] (bw; hrs.)	-0.43	-2.86	.005**	-0.73, -0.14	-0.50
	Subj TST[a] (wn; hrs.)	0.05	1.07	.287	-0.04, 0.14	0.09

Notes: BT = Bedtime, SleepOn = Sleep Onset, TST = Total Sleep Time, PA = Positive Affect, NA = Negative Affect, bw = between, wn = within, hrs. = hours, subj = subjective, obj = objective. Age, sex, weekday/weekend, and previous night sleep were included as covariates. [a] Measured using sleep diary. [b] Measured using actigraphy.

Table 5. Multilevel models of objective and subjective sleep predicting specific emotion

Outcome	Predictor	B	*t*	*p*	95% CI	d
Happy	Subj BT[a] (bw; decimal hrs.)	0.10	1.56	.122	-0.03, 3.26	0.26
	Subj BT[a] (wn; decimal hrs.)	0.03	1.18	.238	-0.02, 0.08	0.09
Cheerful	Subj BT[a] (bw; decimal hrs.)	0.12	1.76	.080	-0.01, 0.26	0.29
	Subj BT[a] (wn; decimal hrs.)	0.06	2.00	.046*	0.00, 0.12	0.16
Interested	Subj BT[a] (bw; decimal hrs.)	0.10	1.57	.119	-0.02, 0.22	0.26
	Subj BT[a] (wn; decimal hrs.)	0.02	0.54	.589	-0.05, 0.08	0.04
Excited	Subj BT[a] (bw; decimal hrs.)	0.08	1.24	.219	-0.05, 0.20	0.20
	Subj BT[a] (wn; decimal hrs.)	0.08	2.45	.015*	0.01, 0.14	0.19
Sad	Subj BT[a] (bw; decimal hrs.)	0.12	3.02	.003**	0.04, 0.20	0.52
	Subj BT[a] (wn; decimal hrs.)	-0.03	-1.46	.145	-0.06, 0.01	-0.12
Nervous	Subj BT[a] (bw; decimal hrs.)	0.20	4.25	<.001***	0.11, 0.29	0.73
	Subj BT[a] (wn; decimal hrs.)	0.01	0.68	.496	-0.03, 0.06	0.06
Upset	Subj BT[a] (bw; decimal hrs.)	0.14	3.66	<.001***	0.06, 0.21	0.62
	Subj BT[a] (wn; decimal hrs.)	-0.01	-0.68	.495	-0.05, 0.03	-0.06
Angry	Subj BT[a] (bw; decimal hrs.)	0.09	3.31	.001**	0.04, 0.14	0.56
	Subj BT[a] (wn; decimal hrs.)	-0.00	-0.03	.973	-0.03, 0.03	-0.00
Bored	Subj BT[a] (bw; decimal hrs.)	0.11	2.24	.027*	0.01, 0.21	0.38
	Subj BT[a] (wn; decimal hrs.)	-0.07	-2.38	.018*	-0.12, -0.01	-0.19
Happy	Obj SleepOn[b] (bw; decimal hrs.)	-0.03	-0.40	.692	-0.18, 0.12	-0.07
	Obj SleepOn[b] (wn; decimal hrs.)	0.02	0.88	.382	-0.03, 0.07	0.08
Cheerful	Obj SleepOn[b] (bw; decimal hrs.)	-0.06	-0.75	.454	-0.22, 0.10	-0.13
	Obj SleepOn[b] (wn; decimal hrs.)	0.03	1.27	.203	-0.02, 0.09	0.11
Interested	Obj SleepOn[b] (bw; decimal hrs.)	0.02	0.36	.717	-0.12, 0.17	0.06
	Obj SleepOn[b] (wn; decimal hrs.)	0.01	0.41	.608	-0.04, 0.07	0.05
Excited	Obj SleepOn[b] (bw; decimal hrs.)	-0.08	-1.15	.250	-0.23, 0.06	-0.20
	Obj SleepOn[b] (wn; decimal hrs.)	0.06	2.30	.022*	0.01, 0.12	0.20
Sad	Obj SleepOn[b] (bw; decimal hrs.)	0.13	2.76	.007**	0.04, 0.22	0.50
	Obj SleepOn[b] (wn; decimal hrs.)	-0.03	-1.62	.106	-0.06, 0.01	-0.14
Nervous	Obj SleepOn[b] (bw; decimal hrs.)	0.15	2.76	.007**	0.04, 0.26	0.49
	Obj SleepOn[b] (wn; decimal hrs.)	-0.02	-0.93	.353	-0.05, 0.02	-0.08
Upset	Obj SleepOn[b] (bw; decimal hrs.)	0.13	2.89	.005**	0.04, 0.21	0.52
	Obj SleepOn[b] (wn; decimal hrs.)	0.01	0.36	.718	-0.03, 0.05	0.03
Angry	Obj SleepOn[b] (bw; decimal hrs.)	0.09	2.51	.013*	0.02, 0.16	0.45
	Obj SleepOn[b] (wn; decimal hrs.)	-0.00	-0.06	.955	-0.04, 0.03	-0.00
Bored	Obj SleepOn[b] (bw; decimal hrs.)	0.03	0.42	.672	-0.10, 0.15	0.08
	Obj SleepOn[b] (wn; decimal hrs.)	-0.06	-2.27	.024*	-0.11, -0.01	-0.20
Happy	Obj TST[b] (bw; hrs.)	0.06	0.60	.553	-0.13, 0.24	0.11
	Obj TST[b] (wn; hrs.)	0.01	0.61	.541	-0.03, 0.06	0.07
Cheerful	Obj TST[b] (bw; hrs.)	0.12	1.14	.256	-0.09, 0.33	0.22
	Obj TST[b] (wn; hrs.)	-0.04	-1.36	.175	-0.09, 0.02	-0.15
Interested	Obj TST[b] (bw; hrs.)	0.08	0.80	.427	-0.11, 0.26	0.15
	Obj TST[b] (wn; hrs.)	-0.03	-0.94	.348	-0.08, 0.03	-0.10

Excited	Obj TST[b] (bw; hrs.)	0.12	1.34	.184	-0.06, 0.30	0.25
	Obj TST[b] (wn; hrs.)	-0.04	-1.33	.184	-0.09, 0.02	-0.14
Sad	Obj TST[b] (bw; hrs.)	-0.03	-0.56	.579	-0.15, 0.08	-0.11
	Obj TST[b] (wn; hrs.)	0.01	0.69	.493	-0.02, 0.05	0.08
Nervous	Obj TST[b] (bw; hrs.)	-0.04	-0.52	.603	-0.17, 0.10	-0.10
	Obj TST[b] (wn; hrs.)	-0.01	-0.35	.728	-0.04, 0.03	-0.03
Upset	Obj TST[b] (bw; hrs.)	-0.07	-1.16	.248	-0.18, 0.05	-0.23
	Obj TST[b] (wn; hrs.)	0.00	0.05	.959	-0.03, 0.04	0.01
Angry	Obj TST[b] (bw; hrs.)	-0.07	-1.55	.124	-0.16, 0.02	-0.30
	Obj TST[b] (wn; hrs.)	-0.00	-0.32	.749	-0.04, 0.03	-0.03
Bored	Obj TST[b] (bw; hrs.)	-0.05	-0.62	.537	-0.22, 0.11	-0.12
	Obj TST[b] (wn; hrs.)	0.01	0.22	.828	-0.05, 0.06	0.02
Happy	Subj TST[a] (bw; hrs.)	-0.02	-0.25	.802	-0.14, 0.11	-0.04
	Subj TST[a] (wn; hrs.)	0.00	0.10	.917	-0.03, 0.04	0.01
Cheerful	Subj TST[a] (bw; hrs.)	-0.01	-0.17	.864	-0.15, 0.13	-0.03
	Subj TST[a] (wn; hrs.)	-0.01	-0.26	.798	-0.05, 0.03	-0.02
Interested	Subj TST[a] (bw; hrs.)	-0.05	-0.79	.431	-0.17, 0.07	-0.13
	Subj TST[a] (wn; hrs.)	-0.01	-0.49	.625	-0.05, 0.03	-0.04
Excited	Subj TST[a] (bw; hrs.)	0.01	0.20	.842	-0.11, 0.14	0.03
	Subj TST[a] (wn; hrs.)	-0.00	-0.11	.912	-0.04, 0.04	-0.01
Sad	Subj TST[a] (bw; hrs.)	-0.10	-2.44	.016*	-0.17, -0.02	-0.41
	Subj TST[a] (wn; hrs.)	0.01	1.03	.302	-0.01, 0.04	0.08
Nervous	Subj TST[a] (bw; hrs.)	-0.15	-3.15	.002**	-0.24, -0.06	-0.53
	Subj TST[a] (wn; hrs.)	-0.00	-0.05	.961	-0.03, 0.03	-0.00
Upset	Subj TST[a] (bw; hrs.)	-0.11	-3.01	.003**	-0.18, -0.04	-0.51
	Subj TST[a] (wn; hrs.)	0.02	1.25	.212	-0.01, 0.04	0.10
Angry	Subj TST[a] (bw; hrs.)	-0.06	-2.06	.041*	-0.11, -0.00	-0.34
	Subj TST[a] (wn; hrs.)	0.01	0.77	.442	-0.01, 0.03	0.06
Bored	Subj TST[a] (bw; hrs.)	-0.06	-1.19	.238	-0.16, 0.04	-0.20
	Subj TST[a] (wn; hrs.)	0.00	0.03	.980	-0.04, 0.04	0.00

Notes: BT = Bedtime, SleepOn = Sleep Onset, TST = Total Sleep Time, bw = between, wn = within, hrs. = hours, subj = subjective, obj = objective. Age, sex, weekday/weekend, and previous night sleep were included as covariates. [a] Measured using sleep diary. [b] Measured using actigraphy.

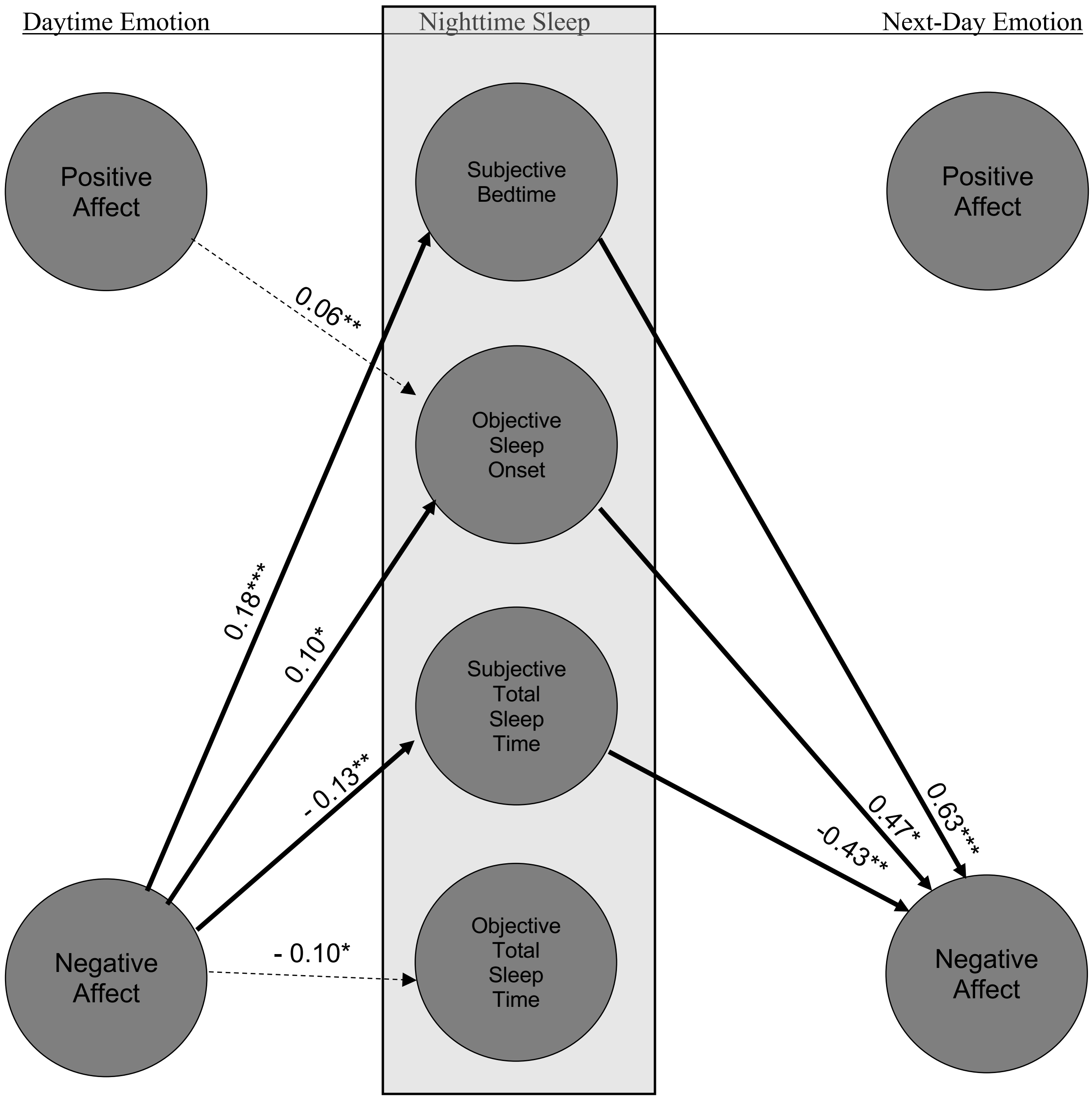

Figure 1. Schematic summary of the interplay between global emotion and sleep. Summarized are the significant unstandardized fixed effects of multilevel models (full results in Tables 2 and 4). Sleep includes subjective bedtime (measured by sleep diary, in decimal hours), objective sleep onset (measured by actigraphy, in decimal hours), subjective total sleep time (measured by sleep diary, in hours), and objective total sleep time (measured by actigraphy, in hours). Dashed lines represent significant within-person relationships (variations above or below the person's average) and straight lines represent significant between-person relationships. Beta values are presented with significance denoted as * $p < .05$, ** $p < .01$, *** $p < .001$. A bold line represents a bidirectional relationship.

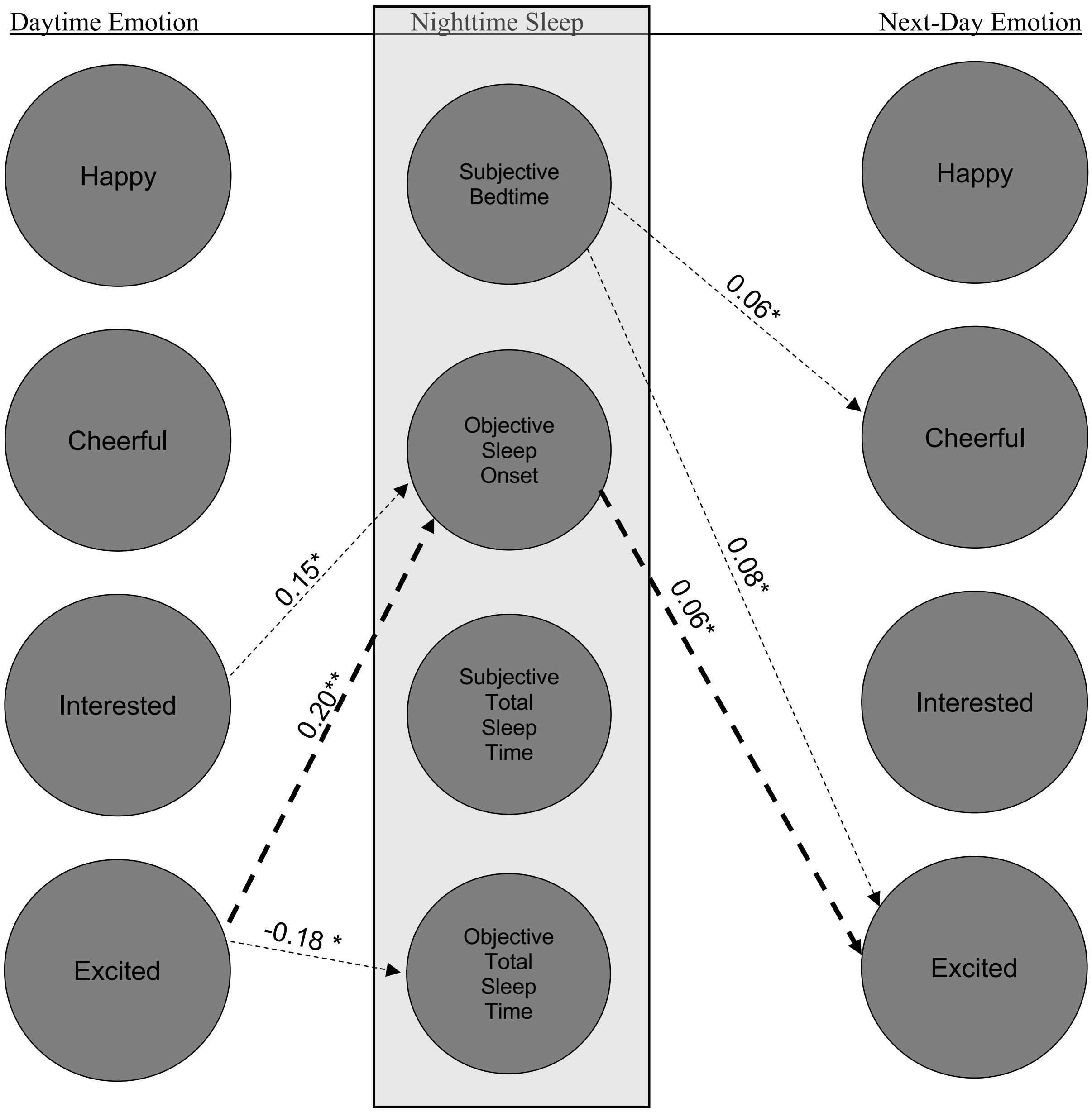

Figure 2. Schematic summary of the interplay between specific positive emotion and sleep. Summarized are the significant unstandardized fixed effects of multilevel models (full results in Tables 3 and 5). Sleep includes subjective bedtime (measured by sleep diary, in decimal hours), objective sleep onset (measured by actigraphy, in decimal hours), subjective total sleep time (measured by sleep diary, in hours), and objective total sleep time (measured by actigraphy, in hours). Dashed lines represent significant within-person relationships (variations above or below the person's average) and straight lines represent significant between-person relationships. A bold line represents a bidirectional relationship.

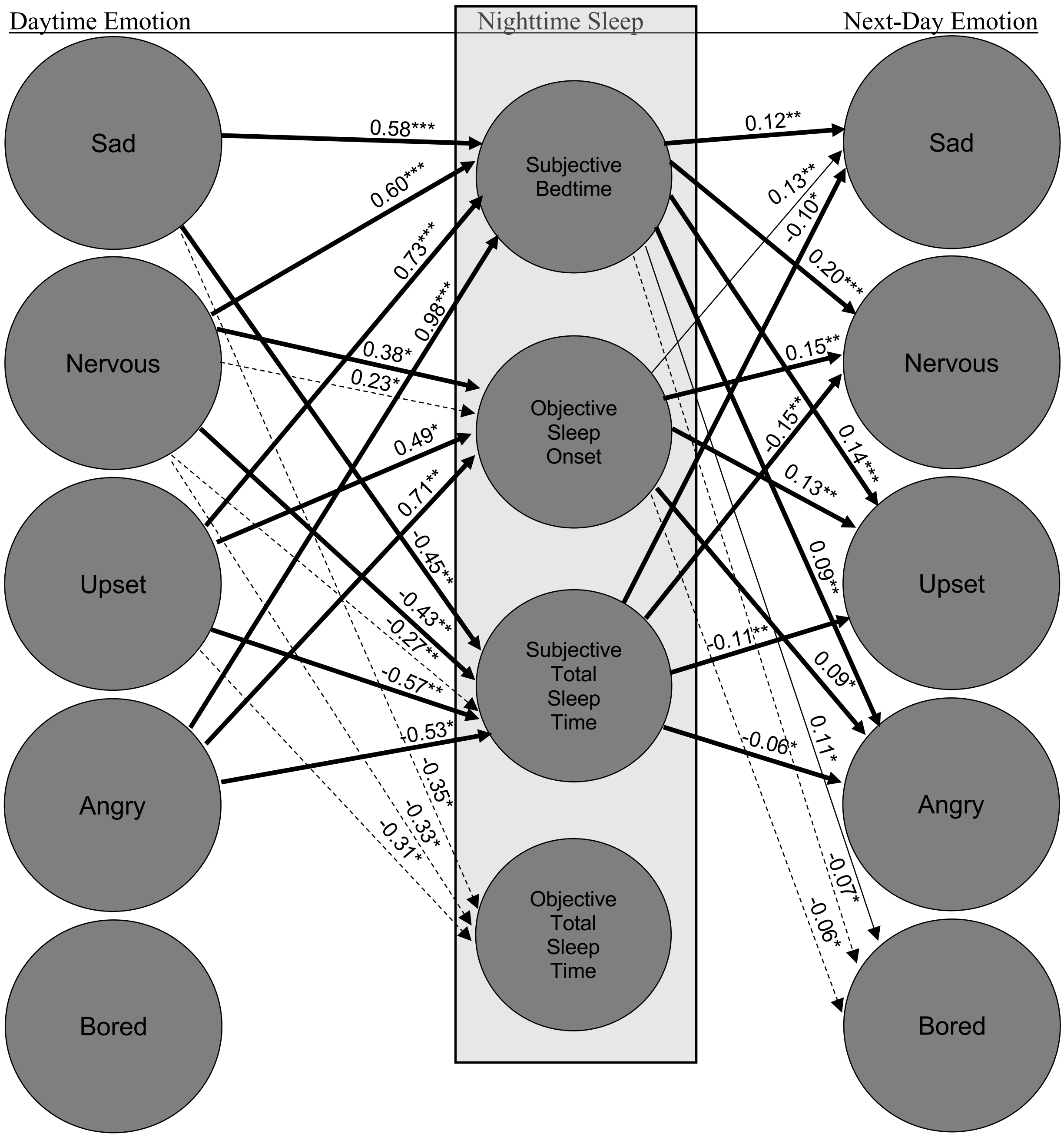

Figure 3. Schematic summary of the interplay between specific negative emotion and sleep. Summarized are the significant unstandardized fixed effects of multilevel models (full results in Tables 3 and 5). Sleep includes subjective bedtime (measured by sleep diary, in decimal hours), objective sleep onset (measured by actigraphy, in decimal hours), subjective total sleep time (measured by sleep diary, in hours), and objective total sleep time (measured by actigraphy, in hours). Dashed lines represent significant within-person relationships (variations above or below the person's average) and straight lines represent significant between-person relationships. A bold line represents a bidirectional relationship.

Appendix A

Ecological Momentary Assessment Script

Current Feelings
Ask on every call

I am going to ask you some questions about how you were feeling when the phone rang.

Use the 1-5 scale on the back of your phone to tell me how you were feeling

1	**2**	**3**	**4**	**5**
Very slightly or not at all	**A little**	**Moderately**	**Quite a bit**	**Extremely**

1.	How would you rate how **happy** (good, satisfied) you were?	1 2 3 4 5
2.	How would you rate how **sad** (blue, unhappy) you were?	1 2 3 4 5
3.	How would you rate how **cheerful** (full of good spirits) you were?	1 2 3 4 5
4.	How would you rate how **nervous** (worried, uneasy) you were?	1 2 3 4 5
5.	How would you rate how **upset** (disturbed or agitated, emotional or mental distress) you were?	1 2 3 4 5
6.	How would you rate how **interested** (really paying attention to something, being involved in what you were doing) you were?	1 2 3 4 5
7.	How would you rate how **angry** (feeling or showing anger) you were?	1 2 3 4 5
8.	How would you rate how **excited** (waiting for something good) you were?	1 2 3 4 5
9.	How would you rate how **bored** (wearingly dull, repetitive, tedious) you were?	1 2 3 4 5

Appendix B

Sleep Diary

Date	
Day	
For which night's sleep?	
1) What time did you get into bed last night?	_ _ : _ _ PM / AM
2) What time did you try to go to sleep?	_ _ : _ _ PM / AM
3) How long did it take you to fall asleep?	_____hh:mm
4) How many times did you wake up, not counting your final awakening?	_ _ times
5) For how long did each awakening last?	1st awakening _____hh:mm 2nd awakening_____ hh:mm 3rd awakening_____ hh:mm 4th awakening_____ hh:mm 5th awakening_____ hh:mm 6th awakening_____ hh:mm 7th awakening_____ hh:mm 8th awakening_____ hh:mm 9th awakening_____ hh:mm 10th awakening_____ hh:mm
6) What time was your final awakening?	_ _ : _ _ PM / AM
7) What time did you get out of bed for the day?	_ _ : _ _ AM / PM
8) How did you wake up this morning?	☐ Alarm Clock/Radio ☐ Someone whom I asked to wake me ☐ Noises ☐ Just Woke up
9) Think back to yesterday, how many times did you nap or doze?	
10) What time/s did you nap or doze?	
11) In total, how long did you nap or doze?	
12) During the one hour before you got into bed last night, did you use any type of technology (e.g., computer, cell phone, TV etc)? If so, for how long?	Not at all Less than 15 minutes 16-30 minutes 31-45 minutes 46-60 minutes
13) Did you have a phone call, text message or email wake you during the night?	Yes ☐ No ☐