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Sleep restriction alters children's positive emotional responses, but effects are moderated by anxiety

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Background: An abundance of cross-sectional research links inadequate sleep with poor emotional health, but experimental studies in children are rare. Further, the impact of sleep loss is not uniform across individuals and pre-existing anxiety might potentiate the effects of poor sleep on children's emotional functioning. **Methods:** A sample of 53 children (7–11 years, *M* = 9.0; 56% female) completed multimodal, assessments in the laboratory when rested and after two nights of sleep restriction (7 and 6 hr in bed, respectively). Sleep was monitored with polysomnography and actigraphy. Subjective reports of affect and arousal, psychophysiological reactivity and regulation, and objective emotional expression were examined during two emotional processing tasks, including one where children were asked to suppress their emotional responses. **Results:** After sleep restriction, deleterious alterations were observed in children's affect, emotional arousal, facial expressions, and emotion regulation. These effects were primarily detected in response to positive emotional stimuli. The presence of anxiety symptoms moderated most alterations in emotional processing observed after sleep restriction. **Conclusions:** Results suggest inadequate sleep preferentially impacts positive compared to negative emotion in prepubertal children and that pre-existing anxiety symptoms amplify these effects. Implications for children's everyday socioemotional lives and long-term affective risk are highlighted. **Keywords:** Sleep; anxiety; emotion; emotional expression; emotional regulation.

Introduction

Poor sleep has deleterious effects on children's mental health, both acutely and over time. Longitudinal studies dependably find early sleep problems to herald the onset of affective problems and disorders (Kelly & El-Sheikh, 2014; Reynolds & Alfano, 2016; Shanahan, Copeland, Angold, Bondy, & Costello, 2014) with effects that cascade across development. For example, sleep problems beginning in infancy exert persistent negative effects on children's emotional regulation through the school-aged years (Williams, Berthelsen, Walker & Nicholson, 2017). Sleep problems in preschoolers predict higher rates of anxiety and depressive symptoms in middle childhood, which in turn predict greater emotional reactivity during the preadolescent years (Foley & Weinraub, 2017). In light of the public health epidemic of inadequate sleep in youth (Singh & Kenney, 2013), understanding the precise pathways through which early sleep generates (or potentially buffers against) affective risk is of paramount importance.

Among adults and to a lesser extent adolescents, a considerable body of experimental research has accumulated showing sleep deprivation to adversely impact emotional responding at subjective, behavioral, physiological, and neurobiological levels (Palmer & Alfano, 2017). Both increases in negative emotional states and decreases in positive affect are commonly found. While it is tempting to extrapolate these results to younger ages, robust developmental differences in both sleep and emotional regulation caution against such inferences. Sleep duration, timing, and structure undergo dramatic changes during the childhood years. Compared to a recommended minimum of 7 hr in adults, school-aged children (6–12 years) are recommended to receive between 9 and 12 hr of sleep per night (Paruthi et al., 2016). Concurrent alterations in underlying sleep architecture include a significant decrease in the amount and intensity of slow-wave sleep (SWS) from childhood to adolescence, the most restorative form of sleep (Colrain & Baker, 2011). The greater need for and depth of sleep that characterize early childhood are in turn linked with brain maturation and learning (Dang-Vu, Desseilles, Peigneux & Maquet, 2006).

Critically, emotional capacities mature in concert with these sleep-based developments. Underpinned by increasing rates of neural processing, accurate identification and understanding of emotional states are typically well-developed by the time children enter school (Banerjee, 1997; Herba, Landau, Russell, Ecker & Phillips, 2006). Emotion regulatory skills reflect an outgrowth of these earlier developments, and by the age of 10 years, most children can effectively regulate (e.g., modify) their emotions in context-appropriate ways (Saarni, 1984; Saarni, Mumme & Campos, 1998). While there is still much to be learned about when, why, and how children's emotional skills develop, deviations from a typical

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developmental course are known to pose long-term mental health risk (Cicchetti, Ackerman & Izard, 1995; Cole, Luby & Sullivan, 2008).

Despite intimate links between sleep and emotional development, experimental investigations in school-aged children are conspicuously rare. Yet, when children extend their sleep by as little as 30 min a night for one week, teacher ratings of emotional lability improve significantly (Gruber et al., 2012). Conversely, when children go to bed one hour later for just a few nights, they report fewer positive emotions and parents report their regulatory control of emotions decreases (Vriend et al., 2013). These subjective reports represent a critical first step, but extending beyond multi-informant reports is necessary to advance understanding of the precise mechanisms through which insufficient sleep elevates children's psychiatric risk. The current study therefore utilized multimodal in-laboratory assessment procedures to investigate the emotional effects of sleep loss at subjective, behavioral, and physiological levels.

This line of inquiry also requires acknowledgement that sleep's emotional impacts are not uniform across individuals. Examination of group-averaged responses to sleep deprivation is useful, but inherently assumes equal vulnerability across participants. Just as sleep need differs across individuals, so does its effects on functioning (Van Dongen et al., 2004; Van Dongen & Belenky, 2009). Emerging studies highlight the presence of anxiety as an important moderator of these effects (see Alfano, 2018). Increased limbic activity in response to emotional stimuli is associated with sleep deprivation generally, but the greatest levels of activation have been observed among those with high levels of trait anxiety (Goldstein et al., 2013). Correlational data suggest the presence of similar relationships during adolescence (Carlisi et al., 2017), but the moderating role of anxiety on sleep–emotion relationships has not been investigated in children.

With these research gaps in mind, we examined the impact of two consecutive nights of sleep restriction on emotional processing in prepubertal children. In addition to subjective reports of affect and arousal, emotional reactivity, expression, and regulation were examined via psychophysiological monitoring and facial expression analyses during in-laboratory assessments. Based on previous reports, we expected to observe greater negative affect and arousal in response to negative emotional stimuli, reduced positive affect, more blunted emotional expression, and reduced emotion regulatory abilities after sleep restriction compared to normal sleep. We expected these effects to be most pronounced among youth with high levels of anxiety.

Methods

Participants

Participants were 53 prepubertal children (Tanner stage 1 and 2) between the ages of 7–11 years recruited in Houston, TX, using flyers and postcard mailings. In order to recruit children with a range of affective symptoms, materials specifically targeted children 'who get sad or nervous sometimes'. To be eligible, children were required to live with a primary caretaker, speak English, and have an IQ greater than 85. Participants were ineligible if they had any psychiatric disorder, a chronic medical condition that might affect sleep, were diagnosed with or suspected to have a sleep disorder, used any medication or over the counter supplement that might impact sleep, and/or experienced current or past suicidal ideation.

A total of 61 children were enrolled in the study and completed the initial assessment. However, eight families were removed due to scheduling problems, detection of significant psychiatric concerns, sleep disturbances, and/or low IQ. Demographics for the final sample along with actigraphy-derived sleep variables during a baseline week are provided in Table 1.

Procedures

All study procedures were approved by the Institutional Review Board of the University of Houston. Interested parents first completed a detailed phone screen to assess basic eligibility. Appropriate families were invited to complete an in-person assessment during which consent/assent was obtained. Families completed a sleep interview to rule out the presence of any sleep disorders and structured psychiatric interviews. All interviews were completed by trained doctoral students or postdoctoral fellows and reviewed with a licensed clinical psychologist. Children and parents completed a series of questionnaires, and child IQ was assessed with the Wechsler Abbreviated Scale of Intelligence (Wechsler, 2011).

On the following Friday, children's sleep was monitored at-home via unattended polysomnography (PSG). Children were prepared for PSG at home and given bed and wake times of 21:00 and 07:00 (10 hr in bed). PSG recordings confirmed the absence of sleep disorders and served to standardize sleep

Table 1 Demographic variables, anxiety symptoms, and baseline sleep characteristics for the study sample ($N = 53$)

	M (*SD*)/ *n* (%)	Range
Age in years: *M* (*SD*)	9.08 (1.34)	7–11
Female: *n* (%)	30 (56.6)	
Race: *n* (%)		
Caucasian	32 (60.4)	
African-American	16 (30.2)	
Asian-American	2 (3.8)	
Biracial/Other	3 (5.7)	
Hispanic/Latino Ethnicity: *n* (%)	15 (28.3)	
Yearly household income: *n* (%)		
<$20K	3 (5.7)	
$20–$60K	18 (34.0)	
$60–$100K	17 (32.1)	
>$100,000	15 (28.3)	
Actigraphy sleep during baseline week		
TST: *M* (*SD*)	612.8 (47.5)	499.80–718.80
SE%: *M* (*SD*)	94.7 (3.9)	82.67–99.67
WASO: *M* (*SD*)	29.0 (22.7)	1.83–87.67
RCADS anxiety scores: *M* (*SD*)	24.49 (17.89)	0–70
25th percentile	10.25	
50th percentile	19.25	
75th percentile	35.50	

RCADS, Revised Children Anxiety and Depression Scales; SE, sleep efficiency; TST, total sleep time in minutes; WASO, wake after sleep onset in minutes.

duration before the first emotional assessment. The following morning children returned to the laboratory for a baseline emotional assessment (5 hr after waking). Children also began wearing actigraphs for nine consecutive nights. On the following Friday night, families were called and reminded to restrict the child's sleep to 7 hr that night (from 23:00 to 06:00) and not allow daytime napping the next day.

On the final night of actigraphy (Saturday), parents and children completed a second night of sleep restriction (SR) in the laboratory including PSG monitoring. Families arrived at 21:00 and were continually monitored by study staff to ensure children remained awake until bedtime. Children were permitted to sleep for 6 hr (from 0:00 to 06:00). In the morning, children were provided breakfast and were monitored by study staff until the second emotional processing assessment (5 hr after waking). This assessment included identical procedures to the baseline assessment using matched, counterbalanced stimuli. Caffeine was monitored and prohibited on both PSG nights and during the hours between waking and both emotional assessments. Afterward, families were given instructions for helping their child return to a regular sleep schedule and financially compensated for their time. See Figure 1 for a diagram of the full study protocol.

Questionnaires

Positive affect and negative affect schedule for children (10-item PANAS-C; Ebesutani et al., 2012) is a child-adapted version of the adult measure that lists 5 positive and 5 negative descriptors, rated on a 5-point Likert scale (1 'very slightly or not at all' to 5 'extremely'). The measure has strong psychometric properties in children ages 6–18 years (Ebesutani et al., 2012). Participants completed the PANAS-C based on their current feelings at the start of both assessments with reliability estimates ranging from $\alpha = .88$–$.91$ for positive affect and $\alpha = .46$–$.82$ for negative ratings. Of note, the lower estimates for negative affect were partially related to a floor effect for negative items.

Revised Children's Anxiety and Depression scale (RCADS; Chorpita et al., 2000) is a widely used, validated 47-item child-reported questionnaire designed to assess a range of anxious and mood symptoms based on DSM criteria. The RCADS possesses strong psychometric properties among children ages 6–18 years (Piqueras, Martín-Vivar, Sandin, San Luis & Pineda, 2017). For the current study, we used raw total anxiety symptom scores ($\alpha = .94$).

Sleep patterns

Actigraphy and sleep diaries. An actigraph is a device that resembles a wrist watch and records movement. Data can be collected over extended periods and downloaded for analysis estimating wake versus sleep periods. MicroMotion Logger actigraphs (Ambulatory Monitoring Inc., Ardsley, NY) were used in the current study. Participants wore the watches 24 hr a day and were instructed to press an event marking button on the watch to indicate when they got into and out of bed each evening/morning. Families completed daily sleep diaries in conjunction with actigraphy which were used to clarify any irregularities. No child in the current study was observed to take daytime naps. Consistent with most pediatric sleep research (Meltzer et al., 2012), activity data were collected in 1-min epochs using the zero-crossing mode (which counts the number of times per epoch that the signal crosses a threshold, typically set at or close to zero) and scored with the Sadeh algorithm (Sadeh et al., 1994).

Emotional assessment tasks

Two matched, randomly counterbalanced sets of emotional stimuli were used in the current study. Both emotional assessments were conducted 5 hrs after a set wake time, in the same room, using the same equipment. Assessments began with a 5-min resting baseline recording of heart rate (HR) and respiratory sinus arrhythmia (RSA). Participants were seated in front of a 22″ computer monitor next to a research assistant who delivered instructions and recorded subjective ratings. Participants were recorded throughout the assessments using a 1080p high-definition webcam mounted to the computer monitor. HR and RSA were collected using a BioPac MP150 unit and Acqknowledge 4.4 acquisition software (Biopac, Goleta, CA Inc.). All physiological and video recordings were time synchronized with presented stimuli using Observer XT software (Noldus, Inc.).

Affective images. Participants were presented with a series of computerized positive ($n = 5$) and negative ($n = 9$)[1] images selected from the International Affective Picture System (IAPS; Lang, Bradley, & Cuthbert, 2005).[2] To ensure matching across the two assessments, images were matched based on both content and published norms for arousal and valence ratings (Lang et al., 2005). All images were displayed on the computer screen for 6 sec preceded by a fixation cross for 3 sec.

Emotional movie clips. Children watched a series of age-appropriate emotional movie clips (3 positive and 3 negative) ranging in duration from 80 to 190 sec. In each, the emotional content developed and intensified throughout the clip. Across the two assessments, each movie clip was matched to a clip of similar length and emotional content, randomly counterbalanced. More information about all movie clips can be found in a supplemental file (S1). Prior to each movie, participants were provided with instructions to look at the screen the entire time

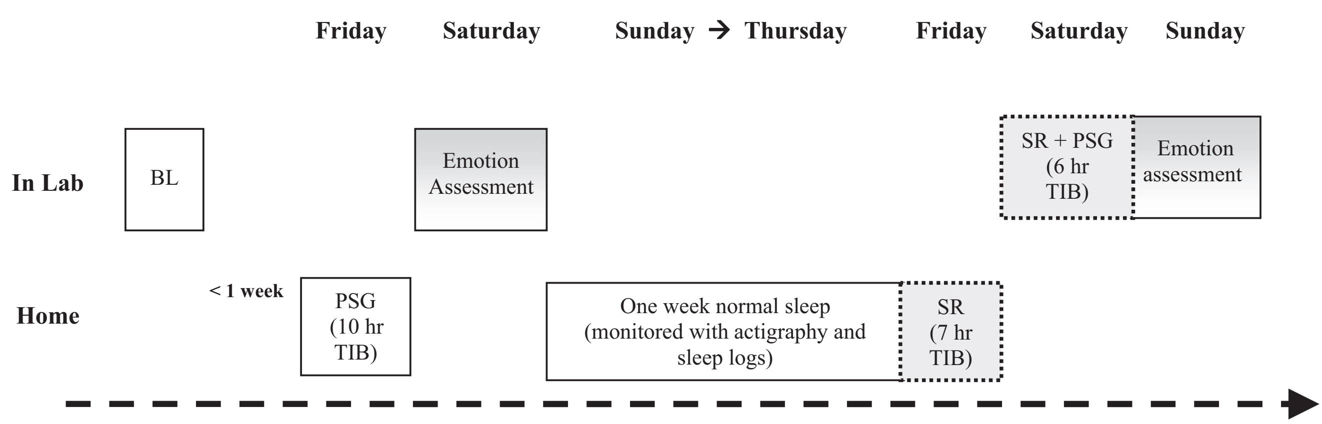

Figure 1 Study protocol. BL, baseline assessment; PSG, polysomnography; TIB, time in bed; SR, sleep restriction

and to suppress all facial expressions ("If you have any feelings while you watch the movie, please do not let those feelings show. Pretend there is someone watching you and you do not want them to know how you are feeling."). Participants viewed a 1-minute neutral clip (as in Gross & Levenson, 1995) between each movie during which they were asked to try and clear their mind of thoughts and feelings.

Subjective measures of emotion and emotion regulation

Emotional ratings. After each IAPS image and movie clip, children provided ratings of arousal using the Self-Assessment Manikin (SAM; Bradley & Lang, 1994), a widely used nonverbal pictorial scale that measures the pleasure (valence) and arousal associated with a person's affective reaction to a wide variety of stimuli. Children also rated the valence of each IAPS image using the SAM. Arousal and valence were reported on a 9-point Likert-type scale with higher values indicating greater arousal/negative valence. Average scores were calculated for positive and negative stimuli. After each movie clip, participants also were asked to rate how difficult it was to suppress their expressions from 0 (not hard at all) to 10 (very hard).

Objective measures of emotion

Emotional expression. Children's facial expressions were recorded and analyzed using FaceReader 4.0 software during both tasks (Noldus, Leesburg, VA Inc.). Photography-grade lighting equipment was installed in the assessment room to ensure adequate and consistent lighting conditions. FaceReader detects the face using the Viola-Jones algorithm (Viola & Jones, 2001) and models the face using the Active Appearance method (Cootes, Edwards & Taylor, 1998). Activation values are calculated for every single frame (30 frames per second) for six basic emotions. Summary scores for valence and arousal (i.e., intensity) are provided. The program shows good reliability with human coding, with agreement rates ranging from 84.8% to 95.9%. To account for individual differences in facial features/expression, all participants were individually calibrated during the resting baseline period. For the current study, scores for each frame were averaged across the last minute of each movie clip (corresponding with the most intense emotional content) and for each 6 sec image. Although we did not exclude children who wore glasses from participating in our study, they were excluded from emotional expression analyses.

Psychophysiological assessment. HR and RSA were monitored during the movie task. HR provides an index of emotional reactivity, whereas RSA is thought to index emotion regulation. Data were collected according to established guidelines using two ECG Ag-AgCl electrodes. ECG was analyzed during resting baseline and during the last minute of each movie clip. Segments of data containing excessive artifacts or ectopic or missing beats were excluded. RSA was calculated using a Fast Fourier Transformation to extract high-frequency components of the signal and estimate high-frequency HR variability (HF-HRV). Frequency bands were adjusted for each participant to account for age-related changes in respiration, and HF-HRV values were log transformed for analyses.

Analytic plan

All analyses were conducted in SPSS version 25. Paired samples *t*-tests were used to examine changes in self-reported affect and emotional outcomes. Repeated-measures analyses of covariance (RM-ANCOVA) examined changes in physiology during movies, controlling for change in resting baseline physiology. Finally, a series of moderated repeated-measures analyses were conducted with total RCADS anxiety scores as a moderator using the MEMORE macro with 5,000 samples and percentile bootstrapped 95% confidence intervals (Montoya, 2019). Significant interactions were probed using percentiles, as recommended by Hayes (2018). For moderation models involving covariates, RM-ANVOCAs with a median split were used. Given the number of comparisons, we utilized a p-value $<.01$ as the criterion for statistical significance.

Previous studies using experimental sleep paradigms to assess emotion-based outcomes have reported moderate to large size effects, with larger effects reported for physiological outcomes. Based on these estimates, sample size calculations conducted with G*Power 3.1.6 software (Faul, Erdfelder, Lang & Buchner, 2007) indicated a sample size of $N = 30$ yields 80% power to detect a moderate effect size.

Results

Analyses of missing data

There were few missing data in our study with the exception of emotional expression data. Children who wore eyeglasses ($n = 8$) had to be excluded from these analyses as FaceReader software cannot reliably detect facial expression in these participants. FaceReader data for another 10 participants were removed from analyses following a rigorous manual checking procedure that detected artifact in analyses (e.g., if the child's head/face was partially turned away from the camera, if the child was covering part of their face with their hand). We compared those children with any missing emotional expression data to other children in the sample in terms of all demographic variables, baseline sleep variables, and anxiety symptoms. No significant differences were found with the exception of race ($X^2(3, 53)11.78$, $p = .008$). Despite our use of professional-grade lighting equipment, Black children were more likely to be missing some FaceReader data. This finding is consistent with other reports of automated facial detection analysis (see Abdurrahim, Samad & Huddin, 2018).[3]

Counterbalancing of emotional stimuli

To ensure there was no bias associated with the order of stimuli sets (A-B vs. B-A), we examined whether any of the outcomes of interest differed based on viewing order. No significant differences were detected for any outcome with the exception of one; SAM arousal ratings in response to negative IAPS images were higher on average when stimulus set B ($M = 3.9$, $SD = 1.27$) was viewed after stimulus set A ($M = 4.80$, $SD = 1.74$; $t(50)2.218$, $p = .031$). Rather than controlling for this difference statistically, we conservatively decided not to examine this outcome.

Sleep manipulation check

Based on actigraphy, total sleep time on the baseline PSG night ($M = 512.12$ min, $SD = 74.14$) was significantly longer than on the first ($M = 392.66$ min,

Table 2 Means and standard deviations of subjective and expressive emotional responses at baseline and after sleep restriction

	Baseline	SR
PANAS-C-positive affect	3.18 (1.18)	2.75 (1.22)*,ANX
PANAS-C-negative affect	1.22 (0.51)	1.17 (0.39)
iaps task		
Positive image SAM arousal	5.08 (2.25)	4.55 (2.45)^{†,ANX}
Negative image SAM arousal	4.35 (1.59)	3.90 (1.62)
Positive image SAM valence	2.65 (1.10)	2.75 (1.14)
Negative image SAM valence	6.93 (1.17)	6.76 (0.98)
Positive images expressive arousal	0.51 (0.10)	0.46 (0.09)*,ANX
Negative images expressive arousal	0.50 (0.10)	0.44 (0.11)*
Positive images expressive valence	−0.04 (0.18)	−0.09 (0.25)
Negative images expressive valence	−0.14 (0.17)	−0.13 (0.15)
Movie task		
Positive movies SAM arousal	4.65 (2.32)	3.91 (2.28)^{†,ANX}
Negative movies SAM arousal	4.97 (1.92)	5.00 (1.93)
Positive movies expressive arousal	0.34 (0.06)	0.32 (0.06)^{†,ANX}
Negative movies expressive arousal	0.34 (0.06)	0.33 (0.05)
Positive movies expressive valence	−0.12 (0.18)	−0.16 (0.23)
Negative movies expressive valence	−0.17 (0.19)	−0.15 (0.20)
Positive movies subjective suppression	2.83 (2.63)	1.61 (2.20)^{*,ANX}
Negative movies subjective suppression	3.46 (3.0)	2.73 (2.53)^{†,ANX}

IAPS, International Affective Pictures System; PANAS-C, Positive and Negative Affect Scale for Children; SAM, Self Assessment Manikin; SR, sleep restriction.
$^{†}p<.05$;
$^{*}p<.01$
^{ANX}Result moderated by anxiety symptoms.

SD = 59.12); $p < .001$) and second restriction nights (*M* = 329.17 min, *SD* = 26.86; $p < .001$). As a manipulation check, children also rated how difficult it was for them to wake in the morning from 0 (easy) to 10 (hard). Waking after the second SR night (*M* = 3.84, *SD* = 3.38) was significantly more difficult than the baseline night (*M* = 2.16, *SD* = 2.58; $t(49) = -2.99$, $p = .004$).

Changes in self-reported affect

Participants reported significantly lower positive affect after SR compared to baseline ($t(52) = 3.29$, $p = .002$). However, self-reported negative affect did not change significantly from baseline to after SR ($t(52) = 0.66$, $p = .51$; Table 2).

IAPS Task

Subjective arousal and valence. Compared to when rested, children reported marginally lower levels of arousal in response to positive images after SR ($t(50) = 2.13$, $p = .038$). Changes in valence ratings for positive ($t(50) = -1.24$, $p = .57$) and negative images ($t(50) = 1.24$, $p = .22$) were nonsignificant.

Objective emotional expression. Expressive arousal decreased significantly after SR in response to positive ($t(34) = 3.08$, $p = .004$) and negative images ($t(36) = 2.81$, $p = .008$). No changes in expressive valence were observed for positive ($t(34) = 1.08$, $p = .29$) or negative images ($t(36) = -0.30$, $p = .77$).

Movies task

Subjective arousal. Children reported reduced arousal in response to positive movies when sleep restricted compared to when rested ($t(52) = 2.56$, $p = .013$) though this result just failed to meet our conservative significance criterion. Changes in arousal after SR during negative movies were nonsignificant ($t(52) = -0.14$, $p = .89$).

Ratings of expressive suppression. Participants indicated that it was significantly easier to suppress their emotional expressions during positive movies after SR ($t(52) = 3.56$, $p = .001$). A similar, albeit marginal result was observed for self-ratings of suppression during negative movies ($t(51) = 2.07$, $p = .04$).

Objective emotional expression. Facial expressions were examined during the last minute of each movie clip. A marginal decrease in expressive arousal was observed for positive movies after SR ($t(41) = 2.12$, $p = .04$). Changes in expressive arousal during negative movies were nonsignificant (t (41) = 1.27, $p = .21$) as were changes in valence for positive ($t(41) = 1.20$, $p = .24$) and negative movies ($t(41) = -.55$, $p = .58$).

Heart rate and respiratory sinus arrhythmia. RM-ANCOVAs (controlling for change in resting HR) revealed HR during positive movies did not differ significantly from baseline to SR ($F(1, 49) = 0.49$,

$p = .49$), but there was a marginal decrease in HR during negative movies ($F(1, 47) = 4.74$, $p = .035$). Controlling for changes in resting RSA, an increase in RSA during negative ($F(1, 48) = 8.15$, $p = .006$) and positive movies ($F(1, 49) = 7.50$, $p = .009$) was observed after SR (Tables 2 and 3).

Anxiety symptoms as a moderator of emotional outcomes

Child-reported anxiety symptoms based on the RCADS were examined as a potential moderator of significant and marginal effects reported above with the MEMORE macro for SPSS version 2 using 5,000 bootstrapped samples (Montoya, 2019). When covariates were included in models, RM-ANCOVAs were used. The same significance criterion ($p < .01$) was utilized for moderational analyses.

Affect ratings. Anxiety symptoms moderated changes in positive affect such that only youth with average (50^{th}%ile; effect = 0.36, SE = 0.14, $p = .01$, 95% CI [0.08, 0.64]) and high levels of anxiety symptoms (75^{th}%ile; effect = 0.48, SE = 0.15, $p = .002$, 95% CI [0.14, 1.09]) reported reductions in positive affect when sleep restricted.

IAPS task

Subjective arousal. Arousal in response to positive IAPS images decreased significantly after SR among youth with low (25^{th}%ile; effect = 0.96, SE = 0.33, $p = .005$, 95% CI [.30, 1.61]) and average (50^{th}%ile; effect = 0.67, SE = 0.26, $p = .01$, 95% CI [0.14, 1.20]) anxiety scores but not those with high anxiety symptoms.

Objective emotional expression. Anxiety symptoms moderated expressive arousal during positive images such that a marginal decrease in expressive arousal was found for children with high (75^{th}%ile; effect = 0.03, SE = 0.01, $p = .04$, 95% CI [0.001, 0.05]) but not average or low anxiety levels.

Table 3 Means and standard deviations of physiological responses at baseline and after sleep restriction during movies

	Baseline	SR
Negative movies HR	81.40 (10.72)	77.98 (10.55)†
Negative movies RSA	6.73 (1.17)	7.06 (1.06)*
Positive movies HR	80.58 (11.07)	78.02 (9.85)
Positive movies RSA	6.8 (1.21)	7.20 (1.11)*

HR, heart rate; RSA, respiratory sinus arrhythmia; SR, sleep restriction.
$^{\dagger}p < .05$;
$^{*}p < .01$

Movie task

Subjective arousal. Only youth with the highest levels of anxiety reported a significant decrease in arousal during positive movies after SR (75^{th}%ile; effect = 1.03, SE = 0.32, $p = .002$, 95% CI [0.39, 1.67]). Changes at average and low anxiety levels were nonsignificant.

Ratings of expressive suppression. Suppression of emotional expressions during positive movies was reported as significantly easier after SR among those with high (75^{th}%ile; effect = 1.50, SE = 0.38, $p = .0003$, 95% CI: [73, 2.27]) and average (50^{th}% ile; effect = 0.97, SE = 0.36, $p = .009$, 95% CI [0.26, 1.69]) but not low levels of anxiety. Similarly, perceived difficulty of suppression in response to negative movies decreased for those with high levels of anxiety only after SR (75^{th}%ile; effect = 1.07, SE = 0.39, $p = .009$, 95% CI: [0.28, 1.86]).

Objective emotional expression. A marginal decrease in expressive arousal during positive movies was found at high (75^{th}%ile; effect = 0.03, SE = 0.01, $p = .04$, 95% CI [0.001, 0.05]) but not low or average anxiety levels.

Physiological reactivity. Controlling for changes in baseline HR, anxiety symptoms did not moderate changes in HR during negative movies after SR. Similarly, anxiety did not moderate changes in RSA during negative or positive movies.

Discussion

Our study utilized a multimethod experimental approach to examine how insufficient sleep alters healthy children's experience, expression, and modulation of their emotions. We focused on the prepubertal years given a lack of research in this age group and suggestion that the transitional period into adolescence represents a critical 'window' for both sleep regulation and emotion regulation (McMakin & Alfano, 2015). Our findings are largely consistent with experimental studies in older age groups, but also reveal some differences. According to self-reports, children experienced significantly less positive affect after SR and reduced arousal in response to positive but not negative stimuli. Lack of sleep has been shown to degrade positive emotions in adults and adolescents, but increases in negative emotional states are also frequently observed (see Palmer & Alfano, 2017). The more polarized results in the current study are fitting of normative developmental changes in emotional reactivity, whereby positive stimuli produce greater arousal than negative stimuli during the childhood years (McManis, Bradley, Berg, Cuthbert & Lang, 2001; Vesker et al., 2018). In contrast, significant changes in children's valence ratings for either negative or positive stimuli were not observed from baseline to postsleep restriction. Thus, our collective findings suggest sleep loss meaningfully alters children's reactivity to positive affective information despite the absence of changes in the information's perceived attractiveness/pleasurability.

Objectively measured expressive arousal was significantly more blunted in response to both positive and negative images and marginally blunted during positive movies after sleep loss. Among adults, Minkel et al. (2011) also found expressive arousal decreases in response to emotional movie clips following sleep deprivation, with larger reductions observed during positive movies. Because emotional expression is a main vehicle for social communication (Sroufe et al., 1984), laying the foundation for positive social experiences and relationships, these findings may help to explain why children who sleep less on average have more peer-related problems (van Geel, Goemans & Vedder, 2016; Vaughn, Elmore-Staton, Shin & El-Sheikh, 2015). Thus, an important direction for future studies will be to examine how insufficient sleep might impair children's nonverbal communication in relevant social contexts.

We also compared children's ability to actively suppress their emotional expressions. Emotion regulation, or the processes by which one adjusts the content, intensity, expression, and timing of emotions (Gross, 2002), is undermined by deficient sleep (Palmer & Alfano, 2017). We selected suppression as a regulatory strategy based on the age of our sample (i.e., ability to use other strategies may have not yet have fully developed) and because our research has shown adolescent sleep problems are indirectly linked with anxiety disorders through suppression (Palmer et al., 2018). Children reported suppression to be significantly easier during positive movies and marginally easier during negative movies after SR. Subjective reports for positive movies were corroborated by a marginal reduction in expressive arousal. Although we did not systematically measure changes in attention, which might be presumed to mediate results, participants were closely monitored throughout assessments and reminded to look at the screen as needed. Since suppression reflects a downstream regulatory strategy employed after an emotional response has been generated (Gross, 2002) and children reported marginally reduced arousal during positive movies after SR, suppressing these responses likely posed less of a challenge. This interpretation fits with research showing suppression to specifically decrease the experience of positive emotions (Gross & John, 2003). In the real world, successful modification of facial expressions serves important everyday social goals, such as sparing someone hurt feelings, minimizing embarrassment, and sharing in joyful events and experiences. Inadequate sleep might therefore function as one pathway by which inadequate nighttime sleep 'spills over' into children's daily socioemotional lives.

RSA was examined as an objective index of emotion regulatory ability. In general, decreases in RSA during exposure to a stressor are indicative of a more flexible physiological response system that facilitates adaptive responses to emotional challenges (Porges, 1995, 2007). In the current study however, we observed increases in RSA after SR in response to all movies, suggesting suppression to be more taxing at an autonomic level when sleep is deficient. Although ours is the first study we are aware of to examine RSA following experimental SR in school-aged children, increases in HF-HRV (which is directly proportional to RSA) have been linked with greater child-reported sleep problems cross-sectionally (El-Sheikh & Buckhalt, 2015). In children at high risk for depression, greater decreases in RSA in response to emotional movie clips have been found to predict more adaptive emotion regulatory responses and fewer depressive symptoms (Gentzler, Santucci, Kovacs & Fox, 2009). In general, a lower level of RSA withdrawal is associated with the development of externalizing, internalizing, and academic problems in youth (Graziano & Derefinko, 2013). Thus, our findings highlight the potential contributory role of inadequate sleep in shaping early high-risk trajectories.

Importantly, most of the sleep-based alterations observed were moderated by pre-existing anxiety symptomatology. Reductions in positive affect and arousal during positive movies were specific to children with higher anxiety levels. In contrast, decreases in subjective arousal in response to positive images were found only among children with lower levels of anxiety. These opposing findings are most likely explained by the use of suppression during the movie task. When asked to hide their emotional expressions, highly anxious children indicated it was easier to suppress their emotions and were marginally more successful in doing so during positive movies. Anxious youth characteristically rely on avoidance-based emotion regulatory strategies, including suppression, aimed at preventing experience and expression of arousal (Carthy, Horesh, Apter & Gross, 2010; Southam-Gerow & Kendall, 2000). The use of emotional avoidance may be particularly appealing when anxious youth are tired based on pre-existing deficits in emotional understanding and regulatory skills (Suveg & Zeman, 2004). Unfortunately, suppression is a 'double-edged' sword, reducing arousal in the short term but increasing anxiety over time (Folk, Zeman, Poon & Dallaire, 2014).

Our study is not without other limitations. We examined positive and negative affect and emotions broadly in the current study but the extent to which alteration in specific emotions might drive observed emotional outcomes is unknown. Likewise, we examined only one emotion regulatory strategy and results cannot be extrapolated to other strategies (e.g., reappraisal, distraction). Missing data particularly for FaceReader analyses are also a limitation of our study that needs to be considered. We also acknowledge that the 'dosage' of sleep restriction utilized in the current study is more potent than that of some previous studies examining emotion-based outcomes in youth (e.g., Gruber et al., 2012) but less potent than others (e.g., McMakin et al., 2016). At present, sleep-based 'thresholds' for detecting emotional changes in children are not known and this is a critical question for future research. Finally, although we utilized two carefully selected and tested sets of counterbalanced emotional stimuli, the fact that the SR assessment always followed the rested assessment might raise questions about possible habituation effects. In this case, one would expect to see decreases in self-reported arousal (for all emotional stimuli) at the second assessment. Notably our findings were considerably more nuanced than this. One might also expect to observe decreases in RSA at a second assessment if habituation accounted for our results, yet increases in RSA during the movie task were observed after sleep restriction.

Conclusion

The present study is, to our knowledge, the first to evaluate the effects of partial SR on children's emotional processing via multimodal assessment. On the whole, children's positive emotions appear to take the greatest 'hit' when sleep is inadequate, detectable at multiple levels of analysis. The extent to which aspects of slow-wave sleep, which is more abundant in childhood and has recently been linked with positive affect (Finan et al., 2015, 2017) might mediate these effects is an interesting question for future research. Though less often studied than negative emotions, positive emotions are essential for promoting healthy social interactions, effective coping, alternative problem-solving approaches, and better overall adjustment (Fredrickson, 2001; Ramsey & Gentzler, 2015; Tugade & Fredrickson, 2002). Combined with the promotion of healthy sleep, preservation and enhancement of positive emotions might serve to shield youth against the adverse effects of periodic sleep problems, particularly youth at risk for anxiety disorders.

Supporting information

Additional supporting information may be found online in the Supporting Information section at the end of the article:

Table S1. Information about positive and negative movies clips used in the current study.

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Key points

- Childhood sleep problems presage later anxiety and depressive disorders but understanding of early mechanistic pathways underlying affective risk is lacking.
- Multimodal experimental sleep research in children is needed to clarify how insufficient sleep impacts emotional processing during the period when sleep and emotion regulatory systems are still developing.
- Two nights of partial sleep restriction adversely impacted subjective, physiological, and expressive responses to positive more so than negative emotional stimuli in prepubertal children.
- Children with high levels of anxiety symptoms were differentially impacted by sleep restriction compared to their less anxious peers.
- Along with the promotion of adequate sleep, preserving and enhancing children's positive emotional experiences might buffer against the affective risks associated with sleep problems, particularly in anxious youth.

Notes

1. Selection of specific IAPS images for inclusion was guided by the availability of normative arousal and valence ratings in child samples. We examined whether including the same number of negative and positive IAPS images would alter results but results remained similar.

2. Matched IAPS images used were as follows: 7010/7090, 8490/8496, 3500/3530, 7359/7380, 7040/7080, 7330/7390, 1120/1300, 1140/1710, 9421/3230, 9000/9001, 2057/2058, 9440/9490, 9594/9582, 2190/2290, 2703/2800, 5780/5781, 9900/9903.
3. Controlling for child race did not impact emotional expression outcomes and was therefore not included as a covariate.

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