Examining the Causal Effects of Sleep Deprivation on Emotion Regulation and Its Neural Mechanisms

Maheen Shermohammed, Laurel E. Kordyban, and Leah H. Somerville

Abstract

■ Cognitive reappraisal (CR) is a strategy used to regulate emotions that is thought to be effective but effortful, relying on higher-order cognitive control systems to engage in active regulation. Sleep deprivation is believed to impair the functioning of these control systems, suggesting that it may impede the ability to implement CR effectively. This study tested the causal effects of sleep deprivation on emotional reactivity and the neurobiological systems underlying CR. We employed a within-subject crossover design in which participants underwent fMRI scanning twice, once when fully rested and once after a night of total sleep deprivation. During scans, participants passively viewed or used CR to downregulate their emotional response to negative and neutral images. Contrary to hypotheses, both self-reported negative affect ratings and neural responses to the images indicated no difference in the way participants implemented CR when sleep deprived and when fully rested. Meanwhile, neural regions that showed distinct reactivity responses to negative relative to neutral images lost this specificity under deprived conditions. Negative affect ratings and heart rate deceleration, a physiological response typically evoked by aversive pictures, exhibited a similar blunting. Together, these results suggest that, although sleep deprivation may reduce the discrimination between emotional reactivity responses to negative and neutral stimuli, it does not impact CR the way it is presently studied. ■

INTRODUCTION

Cognitive reappraisal (CR) is a form of emotion regulation that involves reinterpreting the content of an emotional stimulus in a way that changes its meaning and emotional impact (Gross, 2014). CR is regarded as an especially potent emotion regulation strategy, more effectively modulating the experiential, physiological, and neurobiological components of an emotional response than attempts to suppress or passively experiencing the affect (Goldin, McRae, Ramel, & Gross, 2008; Gross, 1998). Furthermore, the tendency to use CR in daily life is associated with fewer depressive symptoms, better interpersonal functioning, and greater psychological well-being (Gross & John, 2003).

Because of these perceived assets, CR has been the subject of great empirical attention. However, the effectiveness of this regulation strategy has been primarily tested in laboratory environments, free from the challenges that may encumber emotion regulation abilities in the real world. One common such challenge is lack of sleep, a condition faced by almost half of Americans on a regular basis (Swanson et al., 2011). Sleep loss may be especially relevant to emotion regulation processing. Psychopathologies that critically implicate dysregulated emotion are consistently associated with disrupted sleep. Sleep disturbance can promote the development and worsening of depression and post-traumatic stress disorder symptoms (Baglioni, Spiegelhalder, Lombardo, & Riemann, 2010; Germain, Buysse, & Nofzinger, 2008; Perlis, Giles, Buysse, Tu, & Kupfer, 1997; Ford & Kamerow, 1989) and frequently coincides with the occurrence of anxiety disorders such as generalized anxiety, panic disorders, and eating disorders (Smith, Huang, & Manber, 2005; Lauer & Krieg, 2004; Latzer, Tzischinsky, Epstein, Klein, & Peretz, 1999; Mellman & Uhde, 1989). These clinical associations motivate a better understanding of how sleep may interact with the efficacy of emotion regulation strategies and the strength of emotional responses. The current study sought to evaluate the neurobiological mechanism behind this interaction by examining the effects of sleep deprivation (SD) on CR and emotional reactivity.

CR has been particularly well studied in the brain. It is believed to draw on domain-general cognitive control systems in the prefrontal and temporoparietal cortices to modulate activation in limbic regions, like the amygdala (Buhle et al., 2014; Ochsner & Gross, 2005). SD, meanwhile, has been shown to perturb the functioning of these same cognitive and affective circuits. First, it impairs executive functions, which rely on similar cognitive control systems. SD causes deficits in short-term and working memory and decreases the ability to focus or sustain attention (Krause et al., 2017; Ma, Dinges, Basner, & Rao, 2015; Goel, Rao, Durmer, & Dinges, 2009; Durmer & Dinges, 2005). These functional impairments from SD are associated with reductions in brain activation in lateral prefrontal and posterior parietal cortical regions (Ma et al., 2015; Lythe, Williams, Anderson, Libri, & Mehta, 2012; Mu et al., 2005; Chee & Choo, 2004; Drummond et al., 1999).

Harvard University

Second, lack of sleep can heighten affective responding. It is associated with increases in negative emotions and mood as well as rises in depressive and anxiety symptoms in otherwise healthy populations (Prather, Bogdan, & Hariri, 2013; Babson, Trainor, Feldner, & Blumenthal, 2010; Kahn-Greene, Killgore, Kamimori, Balkin, & Killgore, 2007; Sagaspe et al., 2006; Zohar, Tzischinsky, Epstein, & Lavie, 2005; Caldwell, Caldwell, Brown, & Smith, 2004; Dinges et al., 1997; Cutler & Cohen, 1979). The affective reactivity changes accompanying SD are paralleled by exaggerated amygdala reactivity to emotional stimuli (Greer, Goldstein, & Walker, 2013; Motomura et al., 2013; Gujar, Yoo, Hu, & Walker, 2011; Yoo, Gujar, Hu, Jolesz, & Walker, 2007). Additionally, obtaining sleep can be restorative, reducing subjective negative affect and amygdalar responding to previously viewed negative stimuli (van der Helm et al., 2011).

To our knowledge, two previous studies have directly tested the effects of sleep on CR in a community sample of young adults. Mauss, Troy, and LeBourgeois (2013) tested how individual differences in self-reported sleep quality were associated with CR-induced changes in affect in response to sad films and found that poorer sleep quality was correlated with decreases in CR efficacy. However, a separate study testing reappraisal of negative images found that self-reported sleep duration or quality were not related to CR ability or associated neural activation (Minkel et al., 2012). The conflicting results of these studies remain unresolved, motivating further investigation. Furthermore, although findings from Mauss et al. (2013) may suggest that sleep impairs CR, it is just as likely that a person's inability to effectively reappraise their emotions impairs their sleep (Kahn, Sheppes, & Sadeh, 2013). Indeed, there is evidence that individuals who do not tend to use CR as an emotion regulation strategy are more vulnerable to the effects of lack of sleep on neural markers of sustained attention to negative stimuli (Cote, Jancsar, & Hunt, 2015). An experimental manipulation of sleep would be capable of resolving these competing explanations.

In this study, we experimentally manipulated sleep by inducing 24 hr of SD. Although one night of total SD does not impose the same impacts as a persistent sleep disorder or clinical insomnia, it nonetheless has been shown to be sufficient to influence emotional and cognitive functioning (Babson et al., 2010; Goel et al., 2009; Sagaspe et al., 2006; Caldwell et al., 2004; Van Dongen, Maislin, Mullington, & Dinges, 2003). We employed a within-subject crossover design to examine participants both under SD and rested wakefulness (RW). Under both conditions, participants passively viewed and attempted to use CR to regulate their emotional response to aversive images while undergoing fMRI scanning. Analyses first validated the effectiveness of the sleep manipulation and then measured the degree to which deprivation modulated emotional reactivity and CR success. Our primary hypotheses were that lack of sleep would impair CR success and that it would do so by impairing the recruitment of prefrontal and parietal brain regions involved in CR while heightening amygdala activity.

METHODS

Participants

Thirty-six young adults participated in this study to completion. Data from one participant was excluded because of MRI scanner malfunction and from another because of noncompliance, leaving a final sample of $n = 34$ (aged 18–30 years, 17 women). Recruited participants were screened for the following exclusion criteria: history of sleep or neurological disorders, current use of antidepressant or hypnotic medication, current diagnosis of Axis I psychiatric conditions, engagement in shift work within the 3 months before participation, travel to time zones > 3 hr away in within the 3 months before participation, daily consumption of more than approximately 140 mg of caffeine (approximately 1 cup of brewed coffee), and any contraindications for MRI. In addition, participants were screened for irregular sleep habits, which include typical bedtime before 10 p.m. or after 2 a.m., sleep duration of less than 6.5 hr or greater than 9.5 hr, or highly variable bedtimes. These criteria are consistent with prior work implementing SD protocols (Goldstein-Piekarski, Greer, Saletin, & Walker, 2015; Chuah et al., 2010; Franzen, Buysse, Dahl, Thompson, & Siegle, 2009; Sagaspe et al., 2006) and ensured that confounds such as circadian lags and caffeine withdrawal did not compromise study measurements. Finally, participants were right-handed, nonsmokers, and proficient in English. All participants provided informed written consent for their participation. Research procedures were approved by the Committee on the Use of Human Subjects at Harvard University.

CR Task

Building on prior work, we employed a task used frequently to target CR processes (Ochsner et al., 2004; Ochsner, Bunge, Gross, & Gabrieli, 2002). In this task, participants viewed negative and neutral images and were instructed to use CR to decrease their emotional response to half of the negative images (Figure 1). Before the MRI session, participants were thoroughly trained on the strategy of CR. They were given example reappraisals for sample negative images ("help is on the way," "it's just a scene from a movie," etc.) and generated their own reappraisals aloud to the experimenter over several practice trials until they demonstrated clear understanding of the goals of the task.

During fMRI scanning, a 2-sec instructional cue first informed participants whether they were to passively view

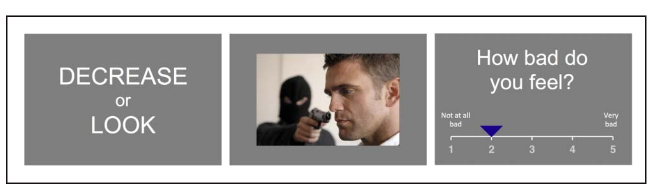

Figure 1. Schematic for trials in the CR task.

("look") or reappraise ("decrease") the image that followed. The image was displayed (8 sec), and then participants rated how negative they felt on a scale of 1 (*not at all bad*) to 5 (*very bad*) using a button response box held in the right hand (2 sec). Jittered fixation periods (2–8 sec) were presented between the image display and the rating scale and between the rating scale and the next trial. A total of 72 pictures (24 decrease-negative, 24 look-negative, 24 look-neutral) were presented over three scanning runs with 24 trials each. Images were from the International Affective Picture System (IAPS; Lang, Bradley, & Cuthbert, 1997) database,[1] and all included depictions of people. Two sets of negative images were constructed with the same average normative valence and arousal and assigned to the decrease-negative or look-negative condition, counterbalanced across participants. Run order was counterbalanced across participants. In addition to self-report ratings, heart rate (HR) was acquired as a measure of emotional response to each of the three picture conditions.

We did not include a condition instructing participants to reappraise neutral images, as prior work has found the instruction to be unclear to participants (e.g., Deveney & Pizzagalli, 2008; Jackson, Malmstadt, Larson, & Davidson, 2000). Though omission of this condition induces a differential expectancy across conditions in which the "look" cue reliably predicts a neutral image, prior work using a fully crossed 2 (look, decrease) × 2 (negative, neutral) design yielded highly similar behavioral and neural effects to those reported here (e.g., Ochsner et al., 2002, 2004).

Study Procedure

Participation in this study consisted of three visits. The first visit was an orientation, during which participants consented to study procedures and were given instructions as well as the opportunity to practice the CR task. Following the orientation, participants underwent fMRI scanning on two separate visits, once under RW and once after approximately 24 hr of SD. The order of the RW and SD visits were counterbalanced across participants (RW first = 16, SD first = 18). The orientation occurred at least 3 days before any subsequent visit, and the RW and SD sessions occurred at least 1 week apart to prevent any residual effects of SD. For the 3 days preceding each MRI session, participants were instructed to obtain full nights of sleep at their regular schedules and to refrain from taking naps or consuming alcohol or caffeine.

For the RW session, participants were instructed to arrive at the research facility in the morning, within 1 hr of the time they previously reported typically waking up. Participants were reminded of the tasks they would complete in the scanner and given a chance to practice them. Next, they completed mood and sleepiness assessments and were prepared for scanning. Mood assessments consisted of: the Positive and Negative Affective Scale, a 20-item questionnaire that yields positive and negative subscores (Watson, Clark, & Tellegen, 1988), and was used to assess changes in affect across visits; the state form of the State–Trait Anxiety Inventory (Spielberger, Gorsuch, & Lushene, 1970), a 20-item questionnaire that was used to assess changes in anxiety levels across visits; and a question asking participants to rate to what extent they felt stressed "right now" (using the same scale as the Positive and Negative Affective Scale). Sleepiness was assessed using the single-item Stanford Sleepiness Scale (Hoddes, Zarcone, Smythe, Phillips, & Dement, 1973) as well as the psychomotor vigilance task, a 10-min task in which participants pressed a button as quickly as possible every time they saw a visual target on the computer screen. The psychomotor vigilance task is highly sensitive to the increases in attentional lapses and slowing of RTs that accompany SD (Mueller & Piper, 2014; Dinges & Powell, 1985). After this task, participants were led to the MRI room and prepared for scanning. During scanning, participants were aware that their eyes were monitored through a live video feed to encourage wakefulness and to use during fMRI data analysis (see below).

For the SD session, participants arrived at the research facility in the evening, approximately 1 hr before their self-reported bedtime. The facility was a basement lounge with no windows. During the overnight period of this visit, participants were permitted to engage in nonstrenuous activities such as reading, watching movies, taking walks, working, and conversing. Participants were provided noncaffeinated snacks (such as chips, cereal, granola bars, juice, etc.) ad libitum throughout the overnight period. Between two to four participants engaged in the overnight session together, during which they were permitted to interact freely and were monitored by a researcher at all times. In the morning, participants were led through the same procedures as in the RW session. The start time of MRI scanning for the two sessions was well matched (mean difference in start time = 18 min, median = 22 min, *SD* = 29.74 min).

Sleep Measures for RW Session

Sleep behavior for the night before the RW scan was assessed using ambulatory actigraphy wrist monitoring (Actiwatch, Philips Respironics). The Actiwatch uses a motion sensor to predict sleep and wake times. These data were manually quality checked and combined with real-time sleep and wake information provided by participants (by pressing a button on the wrist monitor) to generate estimates of sleep duration. Technical difficulties with wrist monitors resulted in loss of actigraphy data for five participants. To supplement actigraphy estimates, on the morning of the RW visit, participants self-reported their bed and wake times for the night before.

Physiological Measures

Heart Rate

Previous research has shown that viewing aversive pictures elicits a brief, parasympathetically mediated deceleration in

HR, and the magnitude of this deceleration varies by stimulus intensity (Bradley, Codispoti, Cuthbert, & Lang, 2001; Campbell, Wood, & McBride, 1997). Furthermore, in prior work, we have found that this measure was sensitive to differences in emotional reactivity (Shermohammed et al., 2017). We therefore measured HR during the CR task as a physiological index of emotional responding to pictures.

This measure was acquired from the left ring finger using a wireless pulse oximetry sensor provided with the Siemens Physiological Monitoring Unit. For every participant, the resulting 400-Hz pulsatile signal was converted into a continuous beats-per-minute HR trace using Acq*Knowledge* software and was visually inspected for high-frequency noise, missing or biologically implausible values, and other poor quality epochs. Technical difficulties with the data collection hardware resulted in data loss for several scans. Any participant with at least three runs of HR data in both RW and SD sessions was included in these analyses, resulting in $n = 23$ usable data sets. Consistent with our previous protocol, the HR trace was first shifted 3.5 sec because of the specific shortcomings of using a pulse oximeter rather than an electrocardiography for stimulus-locked measurements (Shermohammed et al., 2017). Using the shifted trace, the average HR for the 4.5 sec following picture onset was computed, corrected for the average HR during the 2 sec preceding.

Eye Recordings

In addition to monitoring participants' eyes during fMRI scanning in real time, a video of the right eye was recorded for further evaluation. Each second of these videos was manually coded by an experimenter assessing whether the eye was open or closed. Classifications were subsequently used to exclude trials in which participants may have been too sleepy to engage in the CR task. These were defined as trials for which the participant's eye was fully closed for a second or more during the cue or picture period or in which no rating response was made. Such trials were excluded from behavioral analyses and were modeled separately in fMRI analyses. Technical difficulties with eye recording software resulted in data loss for three RW and two SD scanning sessions.

Analysis Strategy

Primary analyses evaluated how SD influenced responses during the reappraisal task. On one hand, SD could affect a participant's ability to use reappraisal effectively. If this was the case, SD should specifically reduce any differences between the decrease-negative and look-negative conditions, that is, the "reappraisal contrast." Another possibility is that SD could make participants more reactive to negative pictures in general. This would result in an exacerbation of any differences between the look-negative and look-neutral conditions, that is, the "reactivity contrast." We therefore conducted repeated-measures ANOVAs to test the effects of Sleep Session (RW or SD) and the Reappraisal Contrast (decrease-negative vs. look-negative) or Reactivity Contrast (look-negative vs. look-neutral) on the outcome variables: picture ratings, fMRI activation, and HR deceleration during the CR task. Because each of the ANOVAs only contain two of the three task conditions (decrease-negative, look-negative, look-neutral), we also report results from a paired *t* test with data merged across task conditions to assess the general effects of SD on outcome variables.

In addition, descriptive statistics and within-subject tests were employed to examine participant compliance, validate the effectiveness of the sleep manipulation, and assess changes in mood across visits. All statistical analyses were performed in R 3.2.3 (R Core Team, 2015).

fMRI Analysis

Acquisition and Preprocessing

Brain imaging was performed on a 3.0-T Siemens Prisma scanner, with a 32-channel head coil (Siemens Medical Systems) at the Harvard University Center for Brain Science-Neuroimaging. A T1-weighted high-resolution anatomical image of the brain was acquired using a multiecho multiplanar rapidly acquired gradient-echo sequence (176 sagittal slices; repetition time = 2200 msec; multi-echo times = 1.69, 3.55, 5.41, and 7.27 msec; flip angle = 7°; slice thickness = 1 mm; voxel size = 1 × 1 × 1 mm). Functional images were collected using an EPI T2*-weighted sequence sensitive to the BOLD response (87 axial slices per whole-brain volume, voxel size = 1.7 × 1.7 × 1.7 mm, repetition time = 2000 msec, echo time = 28 msec, flip angle = 80°, multiband acceleration factor = 3). Functional slices were oriented to a slightly greater tilt than the anterior–posterior commissure plane to minimize signal dropout due to sinus cavities.

Functional imaging data were preprocessed using the fMRI of the Brain Software Library (FSL; Version 5.0.4; Smith et al., 2004) tools implemented in Nipype (v. 0.11.0; Gorgolewski et al., 2011) using the Lyman interface (v. 0.0.7; www.cns.nyu.edu/~mwaskom/software/lyman/). Each functional scan was first realigned to its middle volume, spatially smoothed with a 6-mm FWHM Gaussian kernel, and high-pass filtered at 128 sec. Functional scans were coregistered to individual-subject anatomical images using bbregister (Freesurfer v. 5.3.1; Greve & Fischl, 2009). Subsequently, for analyses comparing across participants, statistical maps were first normalized to a Montreal Neurological Institute (MNI) brain template using linear and nonlinear warping methods through the Advanced Normalization Tools software (ANTS v. 1.9.x; Avants, Tustison, & Song, 2009).

First-level Modeling of CR Task

Preprocessed images were entered into a standard general linear model in FSL, which estimated fMRI responses to the cue period (collapsed over trial types), the three types of picture periods (decrease-negative, look-negative, and

look-neutral), and the rating period (collapsed over trial types). Regressors used boxcar functions convolved with the canonical double-gamma hemodynamic response function implemented in FSL. The model also included nuisance regressors for motion parameters, temporal derivatives for each regressor of interest, and temporal filter regressors with a cutoff of 128 sec. To remove additional noise, functional volumes with motion greater than 1 mm or whole-brain intensity values greater than 4.5 standard deviations away from the mean were censored from the model as additional regressors; one RW scan run had greater than 10% censored volumes and was excluded from analysis. No scan volume had greater than 5 mm of motion.

In addition, there were some trials for which there was indication that the participant may have been too sleepy to engage in the task (see Eye Recordings section). Cue, picture, and rating periods for these trials were modeled separately as regressors of no interest. If more than two trials of any task condition were flagged in a single scan run, that run was excluded (7 of 136 scan runs excluded). Parameter estimates from all runs of a given session were entered into a fixed-effects analysis in FSL. Resultant maps were normalized to an MNI template to compare across participants and sessions in subsequent analyses.

ROI Analysis

Unbiased, a priori ROIs were identified using a previous meta-analysis of 48 neuroimaging studies of reappraisal (Buhle et al., 2014). Eleven 6-mm spheres were centered on activation peaks from distinct regions reported for the reappraise > emotional baseline contrast in the meta-analysis, in addition to two 4-mm spheres in the bilateral amygdalae from the emotional baseline > reappraise contrast reported in the meta-analysis (see Table 1 for ROI coordinates). Mean parameter estimates were extracted for the picture period from each ROI and tested for effects of task and stress condition. *p* Values from these tests were corrected for 13 comparisons by controlling for the false discovery rate using the Benjamini–Hochberg method.

Whole-brain fMRI Analysis

To supplement ROI analyses, we also performed a random effects analysis focused on the picture period across the whole brain. We first wanted to corroborate established findings with this task irrespective of sleep condition. To do this, contrast maps from one-tailed *t* tests examining reappraisal (decrease-negative > look-negative) and emotional

Table 1. ROI Analyses for the Effects of SD on Reappraisal and Reactivity

					Main Effect			*Interaction with Sleep*	
		MNI Coordinates			*Reappraisal*	*Reactivity*	*Sleep*	*Reappraisal*	*Reactivity*
ROI	*Side*	*x*	*y*	*z*	*Corrected p*			*Corrected p (Uncorrected p)*	
Inferior frontal gyrus	R	60	24	3	<.001***	.012**	.343	.909 (.793)	.865 (.266)
Middle forntal gyrus	R	51	15	48	<.001***	.115	.042**	.909 (.619)	.890 (.434)
Medial frontal gyrus	R	9	30	39	.001***	.115	.338	.909 (.781)	.890 (.507)
Anterior cingulate gyrus	L	−3	24	30	<.001***	.115	.460	.909 (.824)	.890 (.606)
Superior frontal gyrus	L	−9	12	69	<.001***	.016**	.183	.909 (.840)	.972 (.921)
Middle forntal gyrus	L	−33	3	54	<.001***	.001***	.119	.950 (.950)	.258 (.035**)
Anterior insula	L	−36	21	−3	<.001***	.001***	.392	.909 (.747)	.258 (.040**)
Inferior frontal gyrus	L	−42	45	−6	<.001***	.034**	.574	.909 (.209)	.972 (.970)
Superior temporal gyrus	R	63	−51	39	.011**	.921	.784	.909 (.575)	.972 (.972)
Angular gyrus	L	−42	−66	42	<.001***	.627	.343	.909 (.603)	.890 (.510)
Middle temporal gyrus	L	−51	−39	3	<.001***	.115	.460	.909 (.679)	.865 (.240)
Amygdala	R	30	−3	−15	.704	.390	.001***	.909 (.635)	.890 (.616)
Amygdala	L	−18	−3	−15	.114	.994	.055*	.909 (.772)	.972 (.892)

Each ROI was subject to a separate ANOVA testing for the effect of Sleep Condition on reappraisal or reactivity. Both false discovery rate-corrected (correcting for the number of ROIs) and uncorrected *p* values are reported for each interaction. Main effects of Sleep are reported from a paired *t* test collapsed across picture type. Region labels were based on the Harvard–Oxford cortical and subcortical atlases, cross-referencing the study of Mai, Paxinos, and Voss (2008). R = right; L = left.

*$p < .1$.

**$p < .05$.

***$p < .005$.

reactivity (look-negative > look-neutral) from each session were first entered into separate fixed-effects analyses for each participant. The resulting map for each participant was then entered into a group-level mixed-effects analysis implemented in FEAT (fMRI Expert Analysis Tool; Woolrich, Behrens, Beckmann, Jenkinson, & Smith, 2004), producing maps of brain activity during the task irrespective of sleep status. Next, to test the primary question of the effects of sleep condition on reappraisal and emotional reactivity, paired t tests comparing the SD and RW sessions were computed for these contrasts. All contrast maps were corrected at a family-wise error (FWE) threshold of $p < .05$ using FSL's cluster-based correction and an initial threshold of $z > 3.1$.

RESULTS

Compliance and Sleep Manipulation Check

Participants complied with instructions to obtain a full night of sleep before the RW session, as evidenced by self-reported sleep duration estimates (7.58 ± 0.75 hr), although these estimates were higher than those estimated by actigraphy (6.62 ± 1.15 hr). Participants also complied with instructions on the night before the SD scan, getting 0 hr of sleep as confirmed by experimenter monitoring.

As expected, the SD manipulation successfully induced sleepiness and impairment on the psychomotor vigilance task. One participant did not complete the self-reported sleepiness ratings during the RW visit, leaving a final sample of $n = 33$ for this measure. As expected, compared with RW, during SD participants rated themselves as sleepier, $t(32) = -11.33$, $p < .001$ (Figure 2A). Psychomotor vigilance task RTs were first log-transformed to mitigate skew. Participants exhibited significantly slower RTs on the psychomotor vigilance task under SD compared with RW, $t(33) = -5.54$, $p < .001$ (Figure 2B).

Changes in Baseline Affective Measures in Response to SD

One participant did not complete the self-reported stress rating during the RW visit, leaving a final sample of $n = 33$ for this measure. As expected, SD resulted in an increase in self-reported stress (RW: mean = 1.30, *SEM* = 0.11; SD: mean = 2.09, *SEM* = 0.17), $t(32) = 3.88$, $p < .001$; an increase in anxiety (RW: mean = 32.18, *SEM* = 1.35; SD: mean = 41.94, *SEM* = 1.71), $t(33) = 6.82$, $p < .001$; an increase in negative affect (RW: mean = 12.12, *SEM* = 0.44; SD: mean = 14.59, *SEM* = 0.59), $t(33) = 4.43$, $p < .001$; and a decrease in positive affect (RW: mean = 24.41, *SEM* = 1.28; SD: mean = 19.73, *SEM* = 1.25), $t(33) = -3.44$, $p = .002$.

Effects of SD on Emotional Reactivity and CR

To evaluate the general effectiveness of the task manipulation, we first evaluated main effects of Picture Valence and Reappraisal Instruction on affect ratings (Table 2). As expected, the negative pictures were rated significantly more negatively than the neutral pictures, $F(1, 99) = 744.85$, $p < .001$. A significant main effect of Picture Condition, $F(1, 99) = 135.84$, $p < .001$, indicated that, consistent with prior work, participants successfully

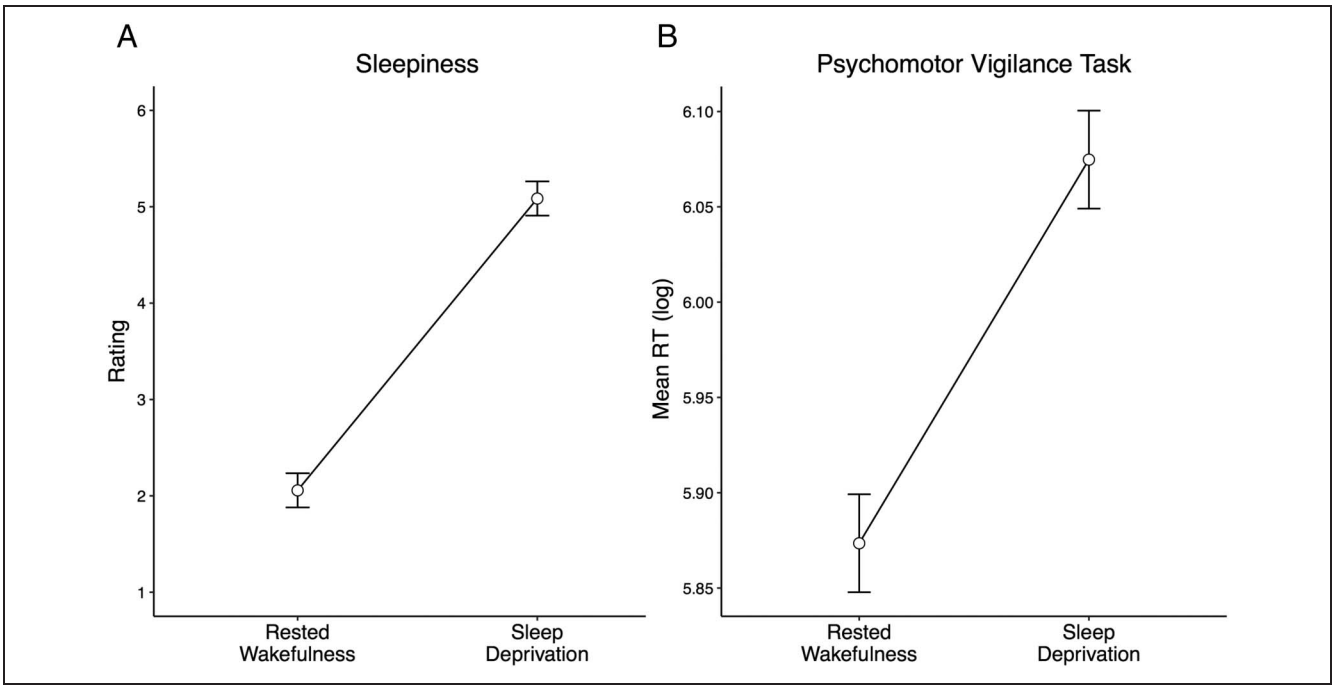

Figure 2. SD successfully induced sleepiness, as assessed by self-report on the Stanford Sleepiness Scale (A) and slower RTs on the psychomotor vigilance task (B). Error bars represent within-subject *SE*.

Table 2. Negative Affect Ratings by Condition

Sleep Session	*Picture Type*	*Mean Rating*	*SE*
RW	Decrease-negative	2.30	0.053
RW	Look-negative	3.23	0.085
RW	Look-neutral	1.19	0.074
SD	Decrease-negative	2.39	0.077
SD	Look-negative	3.12	0.075
SD	Look-neutral	1.32	0.048

Negative affect ratings were acquired on a 1–5 scale, with higher values indicating greater negative affect.

reduced their negative reaction to negative pictures using reappraisal strategies compared with passive viewing.

The critical tests evaluated whether SD modulated reappraisal success and reactivity levels (Figure 3). Evaluating interactions with Sleep Condition revealed a trending interaction between Sleep Condition and Picture Type on emotional reactivity, $F(1, 99) = 2.86, p = .094$, such that participants exhibited marginally attenuated emotional reactivity under SD. Although reappraisal success was nominally lower under SD than during RW, this interaction was not statistically significant, $F(1, 99) = 1.93, p = .167$. Finally, a paired t test collapsed across picture type showed no effect of Sleep Condition on the overall negativity of affect ratings, $t(33) = 0.89, p = .378$.

Effects of SD on Neural Signatures of Emotional Reactivity and CR

ROI Analysis

Parallel to the behavioral analyses above, separate ANOVAs were conducted on each ROI testing for main effects of Task Condition and interactions between Task Condition and Sleep Condition on fMRI responses. Results are summarized in Table 1. Consistent with meta-analytic evidence localizing the neural correlates of reappraisal, all cortical ROIs exhibited greater activation during reappraisal than while passively viewing negative images. Contrary to our predictions, no ROI showed a significant interaction between Sleep Condition (RW, SD) and Reappraisal Condition, even before correcting for multiple comparisons.

With respect to emotional reactivity, which is measured using a comparison of look-negative versus look-neutral picture types, there was a main effect of Picture Type in the left anterior insula, left inferior frontal gyrus, left middle frontal gyrus, right inferior frontal gyrus, and left superior frontal gyrus; each of these regions exhibited greater activation when participants were viewing negative compared with neutral pictures. Like the reappraisal contrast, no interactions between Sleep and Reactivity Condition survived correction for multiple comparisons. However, to provide the most comprehensive description of the data, we also report uncorrected results for this analysis. Without correction, there was a significant interaction between Sleep and Reactivity Condition in the left anterior insula and left middle frontal gyrus. In both of these ROIs, differences in activation due to emotional reactivity during RW were blunted during SD.

Finally, we examined the main effect of Sleep irrespective of Task Condition to assess the general effects of SD on neural activation in each ROI. There was a significant effect of Sleep Condition on activation in the right amygdala and the right middle frontal gyrus as well as a trending effect in the left amygdala. For each of these ROIs, SD resulted in reduced overall activation compared with RW. Statistics from this analysis in each ROI are reported in Table 1.

Whole-brain Analysis

We supplemented targeted ROI analyses with exploratory whole-brain comparisons at whole-brain $p < .05$ FWE thresholding. Consistent with prior work (Buhle et al., 2014), group analyses (where participants' RW and SD sessions were collapsed) revealed that reappraisal (decrease-negative > look-negative) recruited an extensive network of lateral and medial prefrontal regions, as well as areas in the posterior temporal and parietal cortex (Figure 4). Emotional reactivity (look-negative > look-neutral) also recruited regions consistent with our previous findings (Shermohammed et al., 2017), including the bilateral anterior insula. Contrary to expectations, group analyses of emotional reactivity did not yield activation in the amygdala; however, examining emotional reactivity only during RW sessions resulted in activation in the right amygdala.

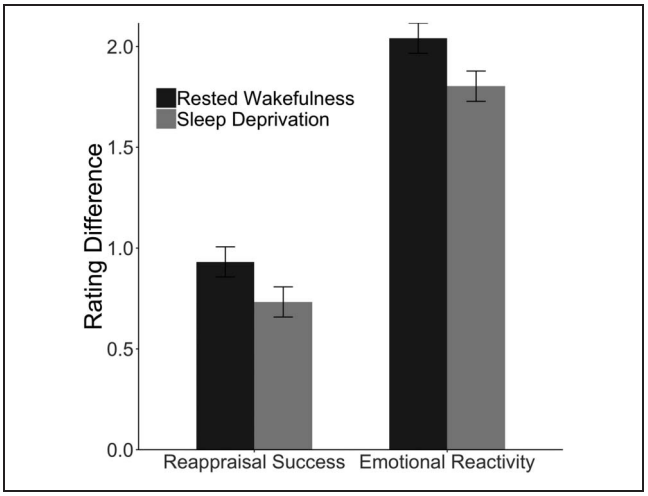

Figure 3. Reappraisal success and emotional reactivity under RW and SD. Reappraisal success is defined as the difference in self-reported affect ratings for look-negative > decrease-negative pictures. Emotional reactivity is defined as the difference in self-reported affect ratings for look-negative > look-neutral pictures. Error bars represent within-subject *SE*.

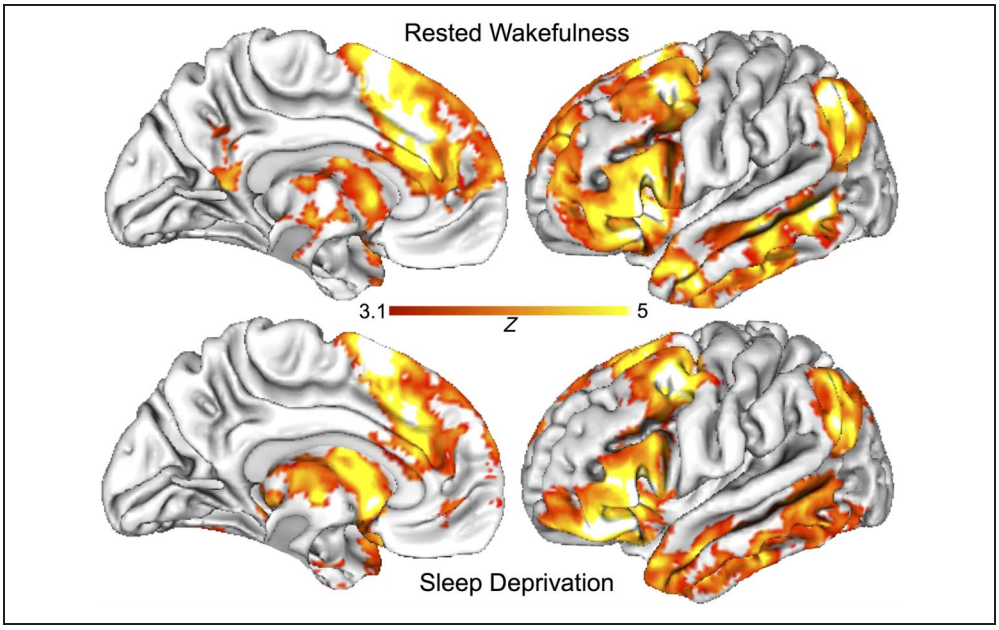

Figure 4. Whole-brain fMRI analyses examining reappraisal (decrease-negative > look-negative) under RW (top) and SD (bottom). This contrast revealed the extensive network of prefrontal, temporal, and posterior parietal regions expected from previous work (Buhle et al., 2014). There were no differences in reappraisal-related brain activation between sleep conditions. Images are $p < .05$, FWE-corrected.

Examining the effects of sleep condition on emotional reactivity revealed activation differences bilaterally in the insula and middle temporal gyrus, as well as regions in occipital and parietal cortices (Table 3). In previous work, these regions have coded for negative affect, exhibiting greater activation for negative compared with neutral picture viewing (Shermohammed et al., 2017). Participants in this study exhibited the same pattern under RW. However, SD disrupted this pattern; it either extinguished any reactivity differences (in the case of the precuneus and the right middle temporal gyrus) or resulted in greater activation to neutral compared with negative pictures (in the case of the left middle temporal gyrus). There were no effects of Sleep Condition for the Reappraisal Contrast.

Effects of SD on HR Changes in Response to Pictures

Baseline-corrected HR provided a physiological index of emotional responding. A paired t test collapsed across picture type showed that, in general, this HR measure was lower under SD compared with RW, $t(22) = 2.62$, $p = .016$. There was no effect of Reappraisal on HR, $F(1, 66) = 0.004$, $p = .948$, and no interaction between Reappraisal and Sleep Condition, $F(1, 66) = 0.151$, $p = .699$.

There was, however, a significant interaction between Emotional Reactivity and Sleep Condition on baseline-corrected HR, $F(1, 66) = 4.28$, $p = .042$. Compared with neutral pictures, participants exhibited decreased HR in response to negative pictures under RW. However, there was no such valence difference under SD; instead, participants exhibited decreased HR in response to both negative and neutral pictures relative to the preceding baseline cue period. Thus, SD appears to have extinguished the valence specificity of the HR deceleration response that is typically observed for negative pictures.

DISCUSSION

This study employed a manipulation of SD to test its causal effects on emotional reactivity, CR, and their underlying neural processes. SD resulted in expected increases in sleepiness, impairments in cognitive functioning, and elevations in baseline negative affect, state anxiety, and stress. Findings from the CR task were also highly consistent with previous work. Participants self-reported greater negative affect in response to negative pictures compared with neutral pictures, and these affect ratings were attenuated when

Table 3. Brain Regions Recruited during Emotional Reactivity for RW > SD

		Voxel		MNI Coordinates		
Region	*Side*	*Extent*	*Max Z*	*x*	*y*	*z*
Middle temporal gyrus	R	1155	6.16	60	−46	14
Middle temporal gyrus	L	1123	6.08	−58	−48	8
Precuneus	L	1028	5.66	−8	−60	42
Parietal lobule	L	522	4.83	−54	−34	50
Insula	R	355	5.26	34	26	0
Insula	L	351	4.99	−40	18	−4
Lateral occipital cortex	L	270	4.65	−30	−72	20

Brain regions that exhibited greater activity during emotional reactivity (look-negative > look-neutral) at $p < .05$, FWE-corrected during RW than SD. No brain regions were significantly more activated during SD than RW during this contrast. Reported are peak coordinates. R = right; L = left.

participants were instructed to use CR. Furthermore, CR recruited a network of prefrontal, temporal, and posterior parietal brain regions that was strongly convergent with meta-analytic evidence from prior work (Buhle et al., 2014).

Despite the success of these manipulation checks, the effects of SD on the CR task were limited. Negative affect ratings in response to negative compared with neutral pictures, an index of emotional reactivity, showed a small but nonsignificant decrease under deprivation. However, the crucial test of the effects of sleep on CR revealed similar reductions in negative affect when participants used reappraisal under RW and under SD. In the brain, we conducted a priori analyses of ROIs consistently shown to be involved in reappraisal. We found overall reductions of neural activation in the right middle frontal gyrus and bilateral amygdalae in response to SD. However, these effects were not specific to reappraisal and instead were observed for all task conditions. Indeed, we found no evidence for neurobiological effects of the sleep manipulation on emotional reactivity or CR in a priori regions known to be involved in reappraisal. With CR in particular, we did not find evidence for modest effects even under more liberal statistical criteria.

These findings ran contrary to our predictions. First, with respect to basic emotional reactivity, we expected to observe an increase in negative affect ratings in response to negative pictures. We expected this because sleep loss has been associated with elevated negative affect and heightened amygdala responding to affective stimuli (Motomura et al., 2013; Prather et al., 2013; Chuah et al., 2010; Yoo et al., 2007; Zohar et al., 2005). However, the present findings are at least partially consistent with another theoretical account that suggests that the heightened sensitivity to affective stimuli associated with sleep loss may be accompanied by a decrement in specificity, which would in turn result in indiscriminate emotional responding to potentially nonemotional stimuli (Goldstein & Walker, 2014). This model is supported by previous work showing that SD impairs the discrimination between threatening and nonthreatening cues and increases negative evaluation of neutrally valenced stimuli (Goldstein-Piekarski et al., 2015; Simon et al., 2015; Tempesta et al., 2010). One previous correlational study found a similar weak trend between poor self-reported sleep quality and decreased subjective emotional reactivity in the present task (Minkel et al., 2012).

A specificity-focused account is also supported by additional evidence in the present work. In the brain, we observed marked effects of SD on emotional reactivity in the precuneus and the right middle temporal gyrus, as well as weak effects in the left middle frontal gyrus and the left anterior insula. Similar to the pattern observed with self-report, clear differences in activation in these regions due to emotional reactivity under RW were blunted under deprivation. Finally, we examined a physiological index of emotional responding to images, HR deceleration. This measure reflects a parasympathetic orienting response akin to fear bradycardia, and its magnitude increases with stimulus intensity (Bradley et al., 2001; Campbell et al., 1997). Under RW, we observed the expected pattern of a prominent deceleration of HR in response to negative but not neutral pictures. However, SD abolished such valence differences, producing a deceleration in response to neutral pictures as well. Together, these findings provide preliminary evidence that sleep loss may lessen the degree to which someone is able to discriminate between negative or salient stimuli and neutral or nonsalient stimuli.

The lack of SD effects on CR presents another puzzle. CR is believed to draw on general cognitive control systems to regulate affective responding (Buhle et al., 2014; Ochsner & Gross, 2005). SD has reliably been shown to reduce neural activity in these systems and to impair executive functions that rely on them, like working memory and attention (Krause et al., 2017; Ma et al., 2015; Lythe et al., 2012; Goel et al., 2009; Durmer & Dinges, 2005; Mu et al., 2005; Chee & Choo, 2004). We therefore expected that sleep loss would hinder the effective mobilization of these regions to down-regulate negative affect. However, we saw no evidence of such sleep-related impairments in self-reported, physiological, or neural indices of CR. One interpretation of these findings is that the ability to implement CR could be robust to the effects of SD.

We cannot rule out the possibility that participants were simply not sleep deprived enough to exhibit CR impairment. After all, staying awake for an entire night is likely not common behavior among healthy adults and is not comparable to the sleep debt characteristic of those with diagnosable sleep disorders. It is possible that the more ecologically reflective mild sleep restriction that accumulates over time may actually be more potent. However, Van Dongen et al. (2003) systematically characterized the level of cognitive impairment under different amounts of SD and restriction and found that one night of total SD caused similar levels of impairment as 2 weeks of sleeping 4–6 hr a night. Furthermore, the reliably observed cognitive deficits that motivated our hypotheses were largely observed in studies that also employed a single night of total SD, as this is the most common method of experimentally manipulating sleep levels (Ma et al., 2015; Goel et al., 2009). Finally, participants averaged 6.5 hr of sleep in the RW control condition. Although this amount of sleep is consistent with typical young adult sleep patterns in the United States (and likely reflects participants' sleep levels in studies not focused on sleep per se), it nonetheless falls short of the recommended sleep duration of 8–9 hr per night. Thus, while reflecting typical sleep behavior, participants' sleep in the control condition may be considered less than the theoretically ideal differential sleep levels between the two conditions.

It is also important to remember that, although the task we employed to measure CR is widely used, its scope is limited relative to what is involved in implementing reappraisal within daily life. This task was designed to assess a participant's ability to generate and effectively implement at least one reappraisal of an affective image.

In daily life, a person must choose to use CR in the first place and subsequently may generate a wide range of reappraisals that vary in content. It is possible that lack of sleep may modulate these other components of CR rather than the aspect of CR ability that this task is constructed to measure. Indeed, previous work has suggested that people may be less inclined to choose CR as a strategy when a negative situation is of high intensity, which SD may promote (Sheppes, Scheibe, Suri, & Gross, 2011). However, this explanation does not resolve the inconsistency between the results of this study and that of Mauss et al. (2013), who found a negative relationship (albeit correlational) between sleep quality and regulation success on a different task also designed to assess CR ability.

One key difference between this study and that of Mauss et al. (2013) is the use of emotionally evocative pictures (from the IAPS set) compared with sad movie clips to induce an emotional response. Previous work has found that SD reliably increases baseline negative affect and anxiety (Reddy, Palmer, Jackson, Farris, & Alfano, 2017; Goldstein & Walker, 2014; Minkel et al., 2012; Dinges et al., 1997), and the few studies that have assessed emotional responding to stimuli in daily life have found the same pattern (Gordon & Chen, 2014; Zohar et al., 2005). However, these emotional changes are not reflected in participants' response to IAPS pictures; rather, as in this study, evidence of changes in emotional reactivity has been weak or mixed (Palmer & Alfano, 2017; Reddy et al., 2017; Minkel et al., 2012). Such findings beg the question of what real-world phenomena these emotional picture ratings generalize to. It may be the case that the fuller, richer emotional experience provided by a sad movie clip is needed to accurately assess the effects of sleep loss on emotions that we experience in daily life.

Observations that lack of sleep impairs executing functioning and heightens affective responding have often been cited as evidence that emotion regulation is impaired as well (Goldstein & Walker, 2014; Gruber & Cassoff, 2014). This study served as a critical test of this assumption, experimentally manipulating sleep to examine behavioral and neurobiological responses to a form of emotion regulation that has been hailed as particularly effective, using a widely employed laboratory task. We found no evidence of impairment of CR in response to SD. Perhaps just as likely as providing evidence that CR could be robust to SD, these results may evince the limitations of this task in reflecting real-world CR ability.

Acknowledgments

We thank Kate McLaughlin, Randy Buckner, Elizabeth Phelps, and Charles Czeisler for helpful discussion; Gina Falcone, Hyun Young Cho, Asi Graham, Katya Kabotyanski, Amma Ababio, and Biniam Andargie for their help conducting this study; and Erik Kastman, Gian Klobusicky, and the Center for Brain Sciences for technical support and code. Research reported in this publication was supported by the National Science Foundation (DGE1144152 to M. S.) and the National Institutes of Health Shared Instrumentation grant (S10OD020039).

Reprint requests should be sent to Leah H. Somerville, Department of Psychology and Center for Brain Science, Harvard University, Northwest Building, 52 Oxford Street, Room 290, Cambridge, MA 02138, or via e-mail: somerville@fas.harvard.edu.

Note

1. IAPS images used: 2038, 2095, 2100, 2102, 2104, 2120, 2205, 2214, 2305, 2357, 2375.1, 2383, 2385, 2393, 2441, 2455, 2480, 2487, 2490, 2493, 2512, 2575, 2579, 2590, 2595, 2661, 2683, 2691, 2700, 2702, 2703, 2710, 2749, 2750, 2799, 2811, 2840, 2870, 2900, 3160, 3180, 3220, 3280, 3300, 3350, 3500, 4605, 4621, 6211, 6212, 6250, 6311, 6312, 6313, 6530, 6555, 6561, 6821, 6840, 7493, 9007, 9070, 9331, 9341, 9404, 9423, 9424, 9429, 9584, 9903, 9905, 9927.

REFERENCES

Avants, B. B., Tustison, N., & Song, G. (2009). Advanced normalization tools (ANTS). *Insight Journal*, *2*, 1–35.

Babson, K. A., Trainor, C. D., Feldner, M. T., & Blumenthal, H. (2010). A test of the effects of acute sleep deprivation on general and specific self-reported anxiety and depressive symptoms: An experimental extension. *Journal of Behavior Therapy and Experimental Psychiatry*, *41*, 297–303.

Baglioni, C., Spiegelhalder, K., Lombardo, C., & Riemann, D. (2010). Sleep and emotions: A focus on insomnia. *Sleep Medicine Reviews*, *14*, 227–238.

Bradley, M. M., Codispoti, M., Cuthbert, B. N., & Lang, P. J. (2001). Emotion and motivation I: Defensive and appetitive reactions in picture processing. *Emotion*, *1*, 276–298.

Buhle, J. T., Silvers, J. A., Wager, T. D., Lopez, R., Onyemekwu, C., Kober, H., et al. (2014). Cognitive reappraisal of emotion: A meta-analysis of human neuroimaging studies. *Cerebral Cortex*, *24*, 2981–2990.

Caldwell, J. A., Jr., Caldwell, J. L., Brown, D. L., & Smith, J. K. (2004). The effects of 37 hours of continuous wakefulness on the physiological arousal, cognitive performance, self-reported mood, and simulator flight performance of F-117A pilots. *Military Psychology*, *16*, 163–181.

Campbell, B. A., Wood, G., & McBride, T. (1997). Origins of orienting and defensive responses: An evolutionary perspective. In P. J. Lang, R. F. Simons, & M. Balaban (Eds.), *Attention and orienting: Sensory and motivational processes* (pp. 41–67). Mahwah, NJ: Erlbaum.

Chee, M. W. L., & Choo, W. C. (2004). Functional imaging of working memory after 24 hr of total sleep deprivation. *Journal of Neuroscience*, *24*, 4560–4567.

Chuah, L. Y. M., Dolcos, F., Chen, A. K., Zheng, H., Parimal, S., & Chee, M. W. L. (2010). Sleep deprivation and interference by emotional distracters. *Sleep*, *33*, 1305–1313.

Cote, K., Jancsar, C., & Hunt, B. (2015). Event-related neural response to emotional picture stimuli following sleep deprivation. *Psychology & Neuroscience*, *8*, 102–113.

Cutler, N. R., & Cohen, H. B. (1979). The effect of one night's sleep loss on mood and memory in normal subjects. *Comprehensive Psychiatry*, *20*, 61–66.

Deveney, C. M., & Pizzagalli, D. A. (2008). The cognitive consequences of emotion regulation: An ERP investigation. *Psychophysiology*, *45*, 435–444.

Dinges, D. F., Pack, F., Williams, K., Gillen, K. A., Powell, J. W., Ott, G. E., et al. (1997). Cumulative sleepiness, mood disturbance, and psychomotor vigilance performance decrements during a week of sleep restricted to 4–5 hours per night. *Sleep*, *20*, 267–277.

Dinges, D. F., & Powell, J. W. (1985). Microcomputer analyses of performance on a portable, simple visual RT task during sustained operations. *Behavior Research Methods, Instruments, & Computers*, *17*, 652–655.
Drummond, S. P. A., Brown, G. G., Stricker, J. L., Buxton, R. B., Wong, E. C., Gillin, J. C., et al. (1999). Sleep deprivation-induced reduction in cortical functional response to serial subtraction. *NeuroReport*, *10*, 3745–3748.
Durmer, J. S., & Dinges, D. F. (2005). Neurocognitive consequences of sleep deprivation. *Seminars in Neurology*, *25*, 117–129.
Ford, D. E., & Kamerow, D. B. (1989). Epidemiologic study of sleep disturbances and psychiatric disorders. An opportunity for prevention? *JAMA*, *262*, 1479–1484.
Franzen, P. L., Buysse, D. J., Dahl, R. E., Thompson, W., & Siegle, G. J. (2009). Sleep deprivation alters pupillary reactivity to emotional stimuli in healthy young adults. *Biological Psychology*, *80*, 300–305.
Germain, A., Buysse, D. J., & Nofzinger, E. (2008). Sleep-specific mechanisms underlying posttraumatic stress disorder: Integrative review and neurobiological hypotheses. *Sleep Medicine Reviews*, *12*, 185–195.
Goel, N., Rao, H., Durmer, J. S., & Dinges, D. F. (2009). Neurocognitive consequences of sleep deprivation. *Seminars in Neurology*, *29*, 320–339.
Goldin, P. R., McRae, K., Ramel, W., & Gross, J. J. (2008). The neural bases of emotion regulation: Reappraisal and suppression of negative emotion. *Biological Psychiatry*, *63*, 577–586.
Goldstein, A. N., & Walker, M. P. (2014). The role of sleep in emotional brain function. *Annual Review of Clinical Psychology*, *10*, 679–708.
Goldstein-Piekarski, A. N., Greer, S. M., Saletin, J. M., & Walker, M. P. (2015). Sleep deprivation impairs the human central and peripheral nervous system discrimination of social threat. *Journal of Neuroscience*, *35*, 10135–10145.
Gordon, A. M., & Chen, S. (2014). The role of sleep in interpersonal conflict: Do sleepless nights mean worse fights? *Social Psychological and Personality Science*, *5*, 168–175.
Gorgolewski, K., Burns, C. D., Madison, C., Clark, D., Halchenko, Y. O., Waskom, M. L., et al. (2011). Nipype: A flexible, lightweight and extensible neuroimaging data processing framework in Python. *Frontiers in Neuroinformatics*, *5*, 13.
Greer, S. M., Goldstein, A. N., & Walker, M. P. (2013). The impact of sleep deprivation on food desire in the human brain. *Nature Communications*, *4*, 2259.
Greve, D. N., & Fischl, B. (2009). Accurate and robust image alignment using boundary-based registration. *Neuroimage*, *48*, 63–72.
Gross, J. J. (1998). Antecedent- and response-focused emotion regulation: Divergent consequences for experience, expression, and physiology. *Journal of Personality and Social Psychology*, *74*, 224–237.
Gross, J. J. (2014). Emotion regulation: Conceptual and empirical foundations. In J. J. Gross (Ed.), *Handbook of emotion regulation* (2nd ed., pp. 3–20). New York: Guilford Press.
Gross, J. J., & John, O. P. (2003). Individual differences in two emotion regulation processes: Implications for affect, relationships, and well-being. *Journal of Personality and Social Psychology*, *85*, 348–362.
Gruber, R., & Cassoff, J. (2014). The interplay between sleep and emotion regulation: Conceptual framework empirical evidence and future directions. *Current Psychiatry Reports*, *16*, 500.
Gujar, N., Yoo, S.-S., Hu, P., & Walker, M. P. (2011). Sleep deprivation amplifies reactivity of brain reward networks, biasing the appraisal of positive emotional experiences. *Journal of Neuroscience*, *31*, 4466–4474.
Hoddes, E., Zarcone, V., Smythe, H., Phillips, R., & Dement, W. C. (1973). Quantification of sleepiness: A new approach. *Psychophysiology*, *10*, 431–436.
Jackson, D. C., Malmstadt, J. R., Larson, C. L., & Davidson, R. J. (2000). Suppression and enhancement of emotional responses to unpleasant pictures. *Psychophysiology*, *37*, 515–522.
Kahn, M., Sheppes, G., & Sadeh, A. (2013). Sleep and emotions: Bidirectional links and underlying mechanisms. *International Journal of Psychophysiology*, *89*, 218–228.
Kahn-Greene, E. T., Killgore, D. B., Kamimori, G. H., Balkin, T. J., & Killgore, W. D. S. (2007). The effects of sleep deprivation on symptoms of psychopathology in healthy adults. *Sleep Medicine*, *8*, 215–221.
Krause, A. J., Simon, E. B., Mander, B. A., Greer, S. M., Saletin, J. M., Goldstein-Piekarski, A. N., et al. (2017). The sleep-deprived human brain. *Nature Reviews Neuroscience*, *18*, 404–418.
Lang, P. J., Bradley, M. M., & Cuthbert, B. N. (1997). International Affective Picture System (IAPS): Technical manual and affective ratings. *NIMH Center for the Study of Emotion and Attention*, *1*, 39–58.
Latzer, Y., Tzischinsky, O., Epstein, R., Klein, E., & Peretz, L. (1999). Naturalistic sleep monitoring in women suffering from bulimia nervosa. *International Journal of Eating Disorders*, *26*, 315–321.
Lauer, C. J., & Krieg, J.-C. (2004). Sleep in eating disorders. *Sleep Medicine Reviews*, *8*, 109–118.
Lythe, K. E., Williams, S. C. R., Anderson, C., Libri, V., & Mehta, M. A. (2012). Frontal and parietal activity after sleep deprivation is dependent on task difficulty and can be predicted by the fMRI response after normal sleep. *Behavioural Brain Research*, *233*, 62–70.
Ma, N., Dinges, D. F., Basner, M., & Rao, H. (2015). How acute total sleep loss affects the attending brain: A meta-analysis of neuroimaging studies. *Sleep*, *38*, 233–240.
Mai, J. K., Paxinos, G., & Voss, T. (2008). *Atlas of the human brain* (3rd ed.). San Diego, CA: Academic Press.
Mauss, I. B., Troy, A. S., & LeBourgeois, M. K. (2013). Poorer sleep quality is associated with lower emotion-regulation ability in a laboratory paradigm. *Cognition and Emotion*, *27*, 567–576.
Mellman, T. A., & Uhde, T. W. (1989). Sleep panic attacks: New clinical findings and theoretical implications. *American Journal of Psychiatry*, *146*, 1204–1207.
Minkel, J. D., McNealy, K., Gianaros, P. J., Drabant, E. M., Gross, J. J., Manuck, S. B., et al. (2012). Sleep quality and neural circuit function supporting emotion regulation. *Biology of Mood & Anxiety Disorders*, *2*, 22.
Motomura, Y., Kitamura, S., Oba, K., Terasawa, Y., Enomoto, M., Katayose, Y., et al. (2013). Sleep debt elicits negative emotional reaction through diminished amygdala-anterior cingulate functional connectivity. *PLoS One*, *8*, e56578.
Mu, Q., Nahas, Z., Johnson, K. A., Yamanaka, K., Mishory, A., Koola, J., et al. (2005). Decreased cortical response to verbal working memory following sleep deprivation. *Sleep*, *28*, 55–67.
Mueller, S. T., & Piper, B. J. (2014). The Psychology Experiment Building Language (PEBL) and PEBL Test Battery. *Journal of Neuroscience Methods*, *222*, 250–259.
Ochsner, K. N., Bunge, S. A., Gross, J. J., & Gabrieli, J. D. E. (2002). Rethinking feelings: An fMRI study of the cognitive regulation of emotion. *Journal of Cognitive Neuroscience*, *14*, 1215–1229.
Ochsner, K. N., & Gross, J. J. (2005). The cognitive control of emotion. *Trends in Cognitive Sciences*, *9*, 242–249.
Ochsner, K. N., Ray, R. D., Cooper, J. C., Robertson, E. R., Chopra, S., Gabrieli, J. D. E., et al. (2004). For better or for worse: Neural systems supporting the cognitive down- and up-regulation of negative emotion. *Neuroimage*, *23*, 483–499.

Palmer, C. A., & Alfano, C. A. (2017). Sleep and emotion regulation: An organizing, integrative review. *Sleep Medicine Reviews*, *31*, 6–16.
Perlis, M. L., Giles, D. E., Buysse, D. J., Tu, X., & Kupfer, D. J. (1997). Self-reported sleep disturbance as a prodromal symptom in recurrent depression. *Journal of Affective Disorders*, *42*, 209–212.
Prather, A. A., Bogdan, R., & Hariri, A. R. (2013). Impact of sleep quality on amygdala reactivity, negative affect, and perceived stress. *Psychosomatic Medicine*, *75*, 350–358.
R Core Team. (2015). *R: A language and environment for statistical computing*. Vienna: R Foundation for Statistical Computing.
Reddy, R., Palmer, C. A., Jackson, C., Farris, S. G., & Alfano, C. A. (2017). Impact of sleep restriction versus idealized sleep on emotional experience, reactivity and regulation in healthy adolescents. *Journal of Sleep Research*, *26*, 516–525.
Sagaspe, P., Sanchez-Ortuno, M., Charles, A., Taillard, J., Valtat, C., Bioulac, B., et al. (2006). Effects of sleep deprivation on Color-Word, Emotional, and Specific Stroop interference and on self-reported anxiety. *Brain and Cognition*, *60*, 76–87.
Sheppes, G., Scheibe, S., Suri, G., & Gross, J. J. (2011). Emotion-regulation choice. *Psychological Science*, *22*, 1391–1396.
Shermohammed, M., Mehta, P. H., Zhang, J., Brandes, C. M., Chang, L. J., & Somerville, L. H. (2017). Does psychosocial stress impact cognitive reappraisal? Behavioral and neural evidence. *Journal of Cognitive Neuroscience*, *29*, 1803–1816.
Simon, E. B., Oren, N., Sharon, H., Kirschner, A., Goldway, N., Okon-Singer, H., et al. (2015). Losing neutrality: The neural basis of impaired emotional control without sleep. *Journal of Neuroscience*, *35*, 13194–13205.
Smith, M. T., Huang, M. I., & Manber, R. (2005). Cognitive behavior therapy for chronic insomnia occurring within the context of medical and psychiatric disorders. *Clinical Psychology Review*, *25*, 559–592.
Smith, S. M., Jenkinson, M., Woolrich, M. W., Beckmann, C. F., Behrens, T. E. J., Johansen-Berg, H., et al. (2004). Advances in functional and structural MR image analysis and implementation as FSL. *Neuroimage*, *23(Suppl. 1)*, S208–S219.
Spielberger, C. D., Gorsuch, R. L., & Lushene, R. E. (1970). *Manual for the State–Trait Anxiety Inventory*. Palo Alto, CA: Consulting Psychologists Press.
Swanson, L. M., Arnedt, J. T., Rosekind, M. R., Belenky, G., Balkin, T. J., & Drake, C. (2011). Sleep disorders and work performance: Findings from the 2008 National Sleep Foundation Sleep in America poll. *Journal of Sleep Research*, *20*, 487–494.
Tempesta, D., Couyoumdjian, A., Curcio, G., Moroni, F., Marzano, C., De Gennaro, L., et al. (2010). Lack of sleep affects the evaluation of emotional stimuli. *Brain Research Bulletin*, *82*, 104–108.
van der Helm, E., Yao, J., Dutt, S., Rao, V., Saletin, J. M., & Walker, M. P. (2011). REM sleep de-potentiates amygdala activity to previous emotional experiences. *Current Biology*, *21*, 2029–2032.
Van Dongen, H. P. A., Maislin, G., Mullington, J. M., & Dinges, D. F. (2003). The cumulative cost of additional wakefulness: Dose–response effects on neurobehavioral functions and sleep physiology from chronic sleep restriction and total sleep deprivation. *Sleep*, *26*, 117–126.
Watson, D., Clark, L. A., & Tellegen, A. (1988). Development and validation of brief measures of positive and negative affect: The PANAS scales. *Journal of Personality and Social Psychology*, *54*, 1063–1070.
Woolrich, M. W., Behrens, T. E. J., Beckmann, C. F., Jenkinson, M., & Smith, S. M. (2004). Multilevel linear modelling for fMRI group analysis using Bayesian inference. *Neuroimage*, *21*, 1732–1747.
Yoo, S.-S., Gujar, N., Hu, P., Jolesz, F. A., & Walker, M. P. (2007). The human emotional brain without sleep—A prefrontal amygdala disconnect. *Current Biology*, *17*, R877–R878.
Zohar, D., Tzischinsky, O., Epstein, R., & Lavie, P. (2005). The effects of sleep loss on medical residents' emotional reactions to work events: A cognitive-energy model. *Sleep*, *28*, 47–54.