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CLINICAL REVIEW

Sleep and emotion regulation: An organizing, integrative review

Cara A. Palmer*, Candice A. Alfano

Sleep and Anxiety Center of Houston, Department of Psychology, University of Houston, USA

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SUMMARY

A growing body of research suggests that disrupted sleep is a robust risk and maintenance factor for a range of psychiatric conditions. One explanatory mechanism linking sleep and psychological health is emotion regulation. However, numerous components embedded within this construct create both conceptual and empirical challenges to the study of emotion regulation. These challenges are reflected in most sleep–emotion research by way of poor delineation of constructs and insufficient distinction among emotional processes. Most notably, a majority of research has focused on emotions generated as a consequence of inadequate sleep rather than underlying regulatory processes that may alter these experiences. The current review utilizes the process model of emotion regulation as an organizing framework for examining the impact of sleep upon various aspects of emotional experiences. Evidence is provided for maladaptive changes in emotion at multiple stages of the emotion generation and regulation process. We conclude with a call for experimental research designed to clearly explicate which points in the emotion regulation process appear most vulnerable to sleep loss as well as longitudinal studies to follow these processes in relation to the development of psychopathological conditions.

An overview of sleep and emotion

Sleep plays a critical role in mental health and psychosocial adjustment across the life-span. Of particular concern is that inadequate or disrupted sleep is both a common symptom of and risk factor for a range of psychiatric disorders including, most commonly, anxiety and mood disorders [1,2]. In fact, inadequate sleep degrades several aspects of neurocognitive functioning, but its effects on psychological health are most robust [3]. Generally, sleep loss has been shown to increase the experience of negative emotions, reduce the occurrence of positive emotions, and alter the ways in which individuals understand, express, and modify these emotions [4,5]. Since inability to experience and control emotions in context-appropriate ways is a prominent feature of various forms of psychopathology [6], recent studies have increasingly aimed to identify emotion-related processes as explanatory mechanisms linking sleep and psychological risk. Experimental investigations continue to proliferate, revealing complex, interactive relationships across domains. Several review papers also have emerged that are focused on sleep and affective disorders [7], bidirectional associations between sleep and emotions [4,8], and the impact of sleep on emotion-related brain functions [9,10].

Some noteworthy challenges nonetheless exist in attempting to synthesize a rapidly expanding body of emotion-based sleep research. First, although the terms are often used interchangeably, emotion, affect, and mood represent distinct albeit overlapping constructs [11]. More precisely, an emotion is a multi-faceted response to internal or external stimuli that allows the individual to meet the demands of their environment through changes in their subjective experience, behavior, and physiology [12]. Affect, by comparison, is a superordinate term that encompasses various emotions but does not differentiate between discrete states. Instead, affect is typically classified as either positive or negative in valence and high or low in arousal level. Emotions can be further differentiated from mood which is more diffuse, long-lasting, and less likely to occur in response to a particular situation or stimuli. Although sleep deprivation has been shown to impact emotions, affect, and mood alike, more precise 'unpacking' of these terms is an essential first step in clarifying the role of sleep in emotion regulation.

A second, even more challenging issue centers on the seemingly ubiquitous use of the term 'emotion regulation' within this body of

Abbreviations: ACC, anterior cingulate cortex; CBT, cognitive behavioral treatment; ERP, event related potential; fMRI, functional magnetic resonance imaging; IAPS, International Affective Picture System; NREM, non-rapid eye movement sleep; PFC, prefrontal cortex; REM, rapid eye movement.

* Corresponding author. UH Health and Biomedical Sciences Building, #373 Houston, TX 77204, USA. Tel.: +1 713 743 1137; fax: +1 832 842 7001.
E-mail address: cara.palmer@times.uh.edu (C.A. Palmer).

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research. In fact, most studies do not explicitly examine regulatory processes related to emotion but rather focus on discrete emotions and/or overall emotional reactivity. Further, numerous facets of this construct exist and many activities that alter an emotional experience might be considered regulatory, whether intentional or not, and regulation can occur both before and after an emotion is experienced [13]. For example, emotion regulation can include the creation or modification of opportunities to experience an emotion, attending to specific features of a stimulus/situation over others, altering thoughts about a situation or feeling, and/or attempting to modify the actual emotion itself [14]. Emotion regulation is also influenced by an array of individual skills, such as the ability to correctly identify an emotional state as something that should be regulated, select an appropriate strategy, and effectively implement that strategy [15]. Using this conceptual framework it is clear that examinations of emotion regulation are useful only to the extent that distinction among specific components embedded within this construct are made. Commonly however, this complex process has been inadequately and imprecisely measured as part of sleep–emotion research, precluding meaningful comparison across studies and the development of a comprehensive theoretical model.

The current review aims to integrate and conceptualize available findings from studies focused on the impact of sleep on emotion-based outcomes among normal sleepers (i.e., non-clinical populations) using an organizing model of emotion regulation. We believe this is a critical step toward identifying constraining research gaps, designing more robust tests of putative mechanisms, and translating research findings into clinical action. Our review is purposely guided by the process model [14], the most widely cited framework available for understanding emotion regulation [16]. In the sections that follow we begin with a brief overview of sleep architecture and physiology as well as central neurobiological mechanisms involved in both emotion and sleep–wake regulation. We then provide a detailed description of the process model and its individual components. In subsequent sections, available research on sleep and emotion is reviewed and organized by specific components of the process model. This primarily includes adult-based outcomes as these studies occupy the major bulk of the literature. When available, relevant adolescent or child-based studies are included. We also consider other relevant emotion-based skills that likely contribute to individual differences in emotion regulation and additional factors to be considered when designing experimental studies. We conclude with a summary of findings and suggestions for future research.

Neurobiological underpinnings of sleep and emotion

At a neurobiological level, emotion regulation involves the interaction of subcortical brain structures of the limbic system (e.g., amygdala) that generate emotional responses to stimuli with control centers (e.g., prefrontal cortex) that regulate emotional responses and behavior [17]. Given that the brain structures and neurochemicals involved in the regulation of emotion also govern sleep [9], and nearly all affective disorders co-occur with sleep abnormalities [1,2], an intimate relationship between these two domains of functioning is intuitive.

To begin to understand the complexities of these relationships however, it is first necessary to consider some basic sleep processes. Sleep is comprised of two main types – rapid eye movement (REM) and non-rapid-eye movement (NREM) sleep (which is further divided into three stages: NREM 1–3, each reflecting different depths of sleep). REM sleep is uniquely marked by activation of emotion-related brain regions (e.g., amygdala, hippocampus) and inhibition of aminergic neurotransmitters including norepinephrine and serotonin [18]. REM sleep occupies a central role in theories of emotional memory. According to the "sleep to forget, sleep to remember" model [5], REM sleep periods both strengthen the declarative component of emotional experiences via activation of the same emotion-related brain structures and attenuate their affective tone via inhibition of aminergic neurotransmitters, resulting in successful reactivation and neural integration of emotional events. However, a more tentative but competing model proposes a relationship whereby REM sleep rouses emotional reactivity, reinforcing the salience of emotional events [19,20]. As evidence to support both models exists, more research is needed to determine how REM sleep, precisely, may alter the specific processes involved in emotions and their regulation.

An organizing framework of emotion and emotion regulation

Arguably, one of the most fundamental distinctions when considering emotion regulation as a construct is the distinction between emotion generation and emotion regulation. Emotion generation occurs when an individual encounters an emotion-eliciting stimulus, attends to and appraises that stimulus, and then generates an emotional response (see Fig. 1). This has been referred to as the modal model of emotion regulation [21], as these features are present across many theories of emotion [15,22]. Responses are typically multi-faceted in that they involve simultaneous changes in subjective experience, behavior, and physiology [23]. Principally, emotional responses are adaptive in that they allow the individual to adjust to environmental demands. For example, many negative emotions promote responses that minimize potential harm (e.g., feeling fear prompts physiological responses that help avoid danger, such as increasing blood flow to the extremities to assist a quick escape). Likewise, positive emotions can prompt action tendencies that build social, physical, and psychological resources (e.g., joy promotes playful behavior which helps build social relationships and physical capacities) [24]. Yet emotional responses can also be maladaptive in terms of their intensity (the response is too large or small given the situation), duration (the emotion lasts too long or not long enough), frequency (experiencing an emotion too often or too seldom), and/or type (the emotion experienced is inappropriate for the current context) [6].

Emotion regulation can be distinguished from emotion generation in that it involves heterogeneous actions that influence what emotions we have, when we have them, and how we have them [14]. The process model [11,14] is rooted in the premise that emotion regulation strategies occur along a timeline of an unfolding emotional response, and highlights five different processes that may occur to alter the course of an emotion (see Fig. 2). These five processes are distinguished by the time points in the emotion-generative process where these emotion regulation strategies

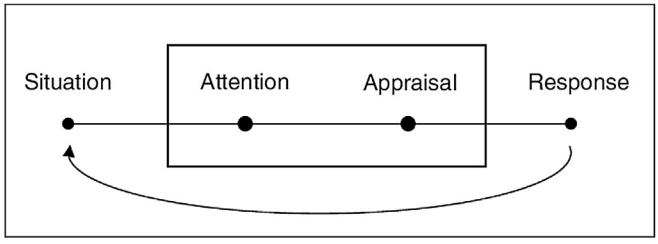

Fig. 1. The modal model of emotion.
Adapted from Gross JJ. Emotion regulation: conceptual and empirical foundations. In: Gross JJ (ed) *Handbook of Emotion Regulation*, 2nd Edition. New York: Guilford; 2014. Figure 1.2. Reprinted with permission of Guildford Press.

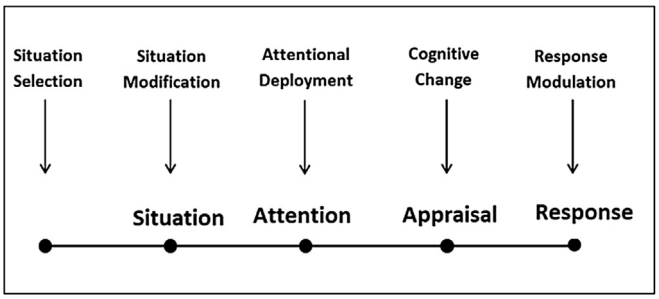

Fig. 2. The process model of emotion regulation.
Adapted from Gross JJ. Emotion regulation: conceptual and empirical foundations. In: Gross JJ (ed) *Handbook of Emotion Regulation*, 2nd Edition. New York: Guilford; 2014. Figure 1.3. Reprinted with permission of Guildford Press.

have the most impact. Further, regulation can occur explicitly (with intent, such as evading a difficult coworker to avoid frustration) or implicitly (without the intent of altering an emotion or without conscious awareness, such as automatically allocating attention away from a distressing stimulus) [25]. Further, regulation of an emotional response can be a goal in and of itself or it can serve as a helpful means of meeting some other goal (e.g., managing anxiety to improve performance). The process model is the most widely cited framework for organizing emotion regulation strategies [16], in part because of its comprehensive focus on strategies that occur throughout the emotion generation experience (i.e., both before and after an emotion occurs).

The first point in the process model, situation selection, can influence whether or not an individual encounters an emotion-eliciting situation. This occurs when an individual seeks out or avoids a situation that may result in desired or undesired emotional states. For example, one might ask a close friend to dinner in attempt to create a positive emotional experience or they might avoid seeing a friend who routinely elicits frustration. The second point in the process model, situation modification, refers to attempts to alter or change aspects of the current physical environment once an emotion-eliciting situation is already occurring (e.g., using humor in a tense situation). Like situation selection, modification of a situation creates or inhibits opportunities to experience certain emotions by influencing exposure to emotion-eliciting stimuli. The selection or modification of emotional situations alters the emotion generation process at its earliest point (before encountering an emotional situation or emotional stimulus).

The third point in the process model, attentional deployment, refers to the way individuals direct (or redirect) their attention toward or away from emotionally-laden content. A common attentional strategy is distraction, which includes the deployment of attentional resources away from a negative aspect of a situation. Importantly, attention can be altered externally (e.g., looking away from a bad car crash on the other side of the road) or internally (e.g., thinking about a positive memory). Once an individual is in the midst of an emotional situation, attentional deployment can disrupt emotion generation by altering which aspects of that situation are most salient.

Cognitive change, the fourth point in the model, involves regulatory strategies aimed at changing the appraisal or meaning of an emotion eliciting-situation. One common form of cognitive change, reappraisal, can center on external stimuli (e.g., "He overreacted because he had a tough day at work"), or internal feelings (e.g., "I probably feel down because I just watched a sad movie"). Broadly, adaptive use of cognitive change alters the emotion generated by appraising an emotion-eliciting stimulus as less negative or more positive. These first four points in the model occur early on in the emotion-generative process, allowing for modification of the emotional trajectory by influencing emotion responses before they have been fully generated (i.e., antecedent-focused strategies).

The fifth and final point in the model, response modulation, involves direct alteration of experiential, behavioral, and/or physiological responses to an emotional stimulus and occurs after an emotion has been fully generated, in turn providing fewer opportunities for alteration and necessitating greater efforts to modulate. Response modulation can include a range of adaptive (e.g., going for a run) and maladaptive (e.g., consuming alcohol) behaviors. Response modulation influences emotion generation by altering the emotional response directly as it is unfolding. However, before regulation occurs at any of these points in the process model, an individual may go through several stages that influence the regulatory strategy eventually implemented. This may include the identification of an emotion as something that needs to be regulated, the selection of an appropriate strategy, and the successful implementation of that strategy [15].

Taken as a whole, the series of processes and responses that unfold along the emotion regulation continuum is vast. At a fundamental level, regulation of emotion is distinct from generation of an emotional response, although it is often difficult to adequately disentangle these processes in research [26]. For this reason, we first review available studies at the intersection of sleep and emotion generation with a focus on studies where regulatory processes were not explicitly examined. In subsequent sections, we utilize the framework described above to discuss sleep research in which emotion regulatory processes were investigated. Due to a paucity of research examining explicit attempts to regulate emotion, we also include a discussion of research investigating processes that can subsequently alter emotions experienced, regardless of whether or not a goal to regulate emotion was present. Finally, we discuss how sleep is related to various factors impacting emotion regulation through the identification, selection, and implementation stages.

Sleep and emotion generation

A majority of findings on sleep and emotion generation derive from correlational designs and self-reported assessments of emotion. Inadequate sleep, either in duration, continuity, or quality, is routinely linked with greater negative and fewer positive emotions [27,28]. Results are similar in both lab-based and real-world settings. For example, following a night of poor sleep, couples report and display less adaptive emotions during a lab-based dyadic discussion [29]. Among medical residents, shorter sleep duration and greater sleep fragmentation are related to more negative and fewer positive emotions in the workplace [30].

Experimental studies that partially restrict or deprive sleep, though fewer in number, also result in alterations in emotional responding reliably characterized by subjective decreases in positive affect and increased negative affect/mood [see [4] for a comprehensive review]. A common methodology used to examine emotion generation as a function of sleep includes affective ratings in response to emotional images from the International Affective Picture System (IAPS) [31]. Specific outcomes vary considerably however, with adult participants rating neutral images more negatively [32], all affective images more positively [33], or no differences in ratings [34] when sleep deprived or sleep restricted. To some extent, such differences might be explained by divergent sleep paradigms, deprivation of NREM versus REM sleep stages, specific images selected for inclusion, and/or the gender composition of samples [32,33,35]. Contextual considerations too, such as whether assessment procedures take place inside a functional magnetic resonance imaging (fMRI) scanner [33] could contribute

meaningfully to individual outcomes. Further, while some studies have assessed individual emotional reactivity in response to IAPS images [35], other studies have assessed appraisal of images [32–34] rather than how the images made participants feel personally.

Emotional appraisal is an important component of the emotion generation process and one of several determinants of which emotions are actually experienced [11]. Evidence from the emotional memory literature suggests that sleep plays a salient role in the appraisal of previously encountered stimuli. For example, one study found that irrespective of circadian influences, a normal period of nighttime sleep maintained negative appraisals of previously viewed IAPS images whereas a period of daytime wake resulted in attenuated appraisals [19]. REM sleep in particular is most commonly linked with consolidation of emotional memories and preservation of their affective tone [20,35,36] suggesting this sleep stage functions to retain memory for threat-related information. This interpretation holds potential implications for how individuals appraise situations that are repeatedly encountered. Alternatively, other evidence in line with the "sleep to forget, sleep to remember" model [5] suggests that periods of normal sleep, particularly REM sleep, decrease the emotional tone attached to previous emotional experiences [37]. The basis of discrepancies observed across studies is unclear but may relate to differences in the intensity of the emotional experience [20,38]. Specifically, whereas one night of normal sleep may be sufficient to reduce negative appraisals of low intensity stimuli, highly intense stimuli may require more sleep to be successfully processed [20]. Research investigating the impact of naturally occurring sleep on the appraisal of and reactivity to negative stimuli of various intensities across multiple nights is therefore warranted.

Other studies have utilized partial sleep restriction protocols in an effort to more accurately simulate real world sleep loss. Results from such studies show both increases in negative emotions and decreases in positive emotions in both adults and adolescents [39–41]. For example, across one week of sleep restriction (4–5 h per night), adults reported cumulative negative emotional changes [40]. Youth (13–17 y) whose sleep was restricted to 6.5 h (compared to 10 h) across five nights reported more negative mood [41]. Further, restricted sleep (4 h) in children (11–15 y) resulted in greater negative emotions in response to negative images compared to optimized (10 h) sleep [42].

Experimental studies utilizing neurological and/or physiological measures of emotion provide evidence of the effect of sleep on arousal and neural activation following periods of extended wakefulness. Alterations in anterior cingulate cortex (ACC) and amygdala activity [43,44] have been observed, both of which are associated with emotion [17]. One study [44] found a remarkable 60% increase in amygdala activity among adults viewing negative emotional images after 35 h of sleep deprivation. Pupil diameter (i.e., a measure of emotional reactivity) increases when sleep-deprived subjects both anticipate and view negative IAPS images [45]. Increased reactivity to positive emotional stimuli also is observed in select striatal brain regions including the putamen and ventral tegmental area [33], which are associated with reward. Interestingly, a study selectively depriving participants of REM sleep found that behavioral and neural activity in response to threatening stimuli increased, but decreased in a group undergoing similar, but NREM sleep deprivation [46]. Together, these studies present unique information about emotion generation processes beyond subjective reports of emotional experience. Still, while conscious awareness of an emotion may derive from activation in particular neural regions, increased physiological arousal, and/or other internal processes, these changes alone do not necessarily produce subjective experiences of an emotion [47].

A number of studies, particularly those utilizing adolescent samples, provide evidence for greater decreases in positive emotions as compared to increased negative emotions following sleep loss. Among a sample of healthy adolescents (13–17 y), decreases in various positive emotions (e.g., happy, interested, cheerful) were reported after one night of restricted (4 h) compared to ideal (9.5 h) sleep whereas group differences in negative emotions (e.g., gloomy, mad, jittery) were not found (Reddy, Palmer, Jackson, & Alfano, manuscript in progress). Similar results for changes in positive but not negative emotions have been reported in studies of adolescents [48,49] as well as one study including children [50] and a few others of adults [48,51]. Collectively, these findings provide evidence for the effects of sleep loss on emotion generation more broadly, including a general 'affective imbalance' across a full range of emotions [33].

Sleep and emotion regulation

Because a majority of research has focused on sleep-related emotional responses without attention to possible modulatory efforts, differentiating between specific emotional processes is beset with a range of challenges. In most studies, the extent to which assessments of emotion may at least partially capture actual regulation cannot fully be known. Still, several studies find subjective sleep problems [52] and partial sleep restriction [39] to predict emotion regulation using broad, self-reported questionnaires. In child samples, parental reports also have been utilized [50]. In addition to problems of possible reporter bias (e.g., parents may not be able to accurately report on their child's regulation) and lack of differentiation among precise regulatory processes, sleep may also influence one's perceptions of successful and unsuccessful attempts to alter emotional experiences. At a neurobiological level, the effects of sleep deprivation include decreased connectivity between the medial prefrontal cortex (PFC) [44] and ventral ACC with the amygdala [41], suggesting global problems with monitoring and regulatory control. Other regions of the striatum (e.g., the caudate, putamen) implicated in motivation and emotion regulation also are highly sensitive to sleep [33]. Of challenge to understanding the precise impact of sleep on regulatory ability however is the fact that experimental paradigms rarely explicitly ask participants to regulate their emotions, making it impossible to disentangle reactivity from (conscious or unconscious) emotion regulation processes and to explicate the precise components of regulation disrupted. Below we organize and conceptualize available findings from the sleep–emotion literature within a process model framework by distinguishing how sleep may impact emotion regulation at each stage of the process model of emotion regulation.

1. Situation selection

Although experimental sleep research has not typically considered the extent to which certain behavioral choices might reflect emotion regulatory efforts, various findings illustrate how inadequate sleep may alter emotion at the situation selection level. First, although positive social relationships are a necessary component of experiencing positive emotions in daily life [53], insufficient sleep can directly undermine motivation to seek out and participate in rewarding social activities. Poor sleepers generally exhibit lower frequencies and less regularity of social activities than good sleepers [54] and correlational studies converge in linking sleep problems with poorer social well-being [28,55]. Daytime sleepiness represents one potent mechanism through which social experiences may suffer, even after controlling for the effects of comorbid depressive symptoms and relationship quality

[56]. Experimental research in this domain is more limited but a study utilizing a sleep deprivation protocol (72 h) found that motivation for social and leisurely activities progressively diminished with cumulative hours of wakefulness [57].

Situation selection in this case shadows neurobiological findings of altered neural reward circuitry [58], manifesting in both decreased motivation for and altered valuation of rewards. For example, subjective sleep quality is related to lower self-reported anticipation of rewards [59] and after a night without sleep, individuals are more willing to forgo larger rewards for smaller ones that require less effort [60]. Thus, even with awareness that participating in certain activities could positively alter one's emotions, diminished motivation to do so might ultimately function as a potent determinant of emotional experiences.

Less sleep might also increase the likelihood of experiencing negative emotions via situational decisions. Safety behaviors [61], or the overt or covert avoidance of negative outcomes, feature prominently in the insomnia literature and provide an apt example. Insomnia patients more so than good sleepers take time off of work, call in sick, cancel appointments and meetings, and skip out on social activities due to feelings of fatigue and sleepiness [62–64]. While selecting to avoid these situations might help the individual circumvent some level of negative emotionality in the short run, paradoxically, negative emotions are ultimately perpetuated through reinforcement of dysregulated schedules, physical inactivity, and reduced social engagement.

To summarize, sleep loss significantly alters behavior in ways that decrease the likelihood of situating oneself in positive emotional contexts. Prioritizing sleep over other important waking activities, reduced energy for and motivation to seek out enjoyable social activities, and low overall anticipation of reward for one's efforts might contribute to selecting situations that meet current emotional needs, but ultimately undermine the likelihood of positive emotional experiences over a longer term. Notably however, very little research has examined sleep in relation to the activation of an explicit goal to avoid or encounter an emotion-eliciting situation and, as a result, findings included here are primarily conceptualized in terms of implicit emotion regulation processes (i.e., acts done without the intent of selecting or avoiding emotion-eliciting situations).

2. Situation modification

The fact that deprivation of sleep results in impaired decision making and poor impulse control [65,66] provides a window into some potential ways various situations might be inappropriately modified through the effects of inadequate sleep. Nuances in emotional expression and social communication for example provide a potent means of situation modification by allowing one's interests, beliefs, and desires to be communicated. The ability to self-monitor [65], appropriately interact with others [67], pick up on others' nonverbal cues [68], and accurately identify others' emotions [69,70] are diminished when sleep is disrupted. Dyadic research among couples suggest that individuals are less understanding and empathic of their partner in the face of inadequate sleep [29] and that after extended periods of sleep loss (55 h) blaming behavior and unwillingness to alleviate conflict become more common [71]. Broader links between sleep and the ability to relate to and empathize with others have been reported as well [66,72]. The multitude of ways such behaviors might negatively transform immediate social and professional contexts are apparent.

Impaired decision making, poor impulse control, and daytime sleepiness have additional implications for situation modification strategies in work settings. Fatigue is generally associated with more social loafing and less productivity [73] and one experimental study found that sleep deprivation produced less self-control and more deviant behaviors in the workplace [67]. The latter finding aligns with evidence that difficulty delaying gratification is a consequence of inadequate sleep [66]. Poor impulse control and a lack of concern for negative consequences may also give rise to maladaptive behaviors in the midst of a conflict (e.g., negative comments, name calling) as opposed to more adaptive, conflict resolution strategies. Together, these collective results suggest that individuals feeling frustrated, devalued, or burnt out in the workplace may be more prone to manage their emotions by modifying the work environment through the use of maladaptive (e.g., decreasing productivity) rather than more adaptive (e.g., setting up a meeting to discuss a possible pay raise) strategies. Problems restraining impulses create heightened physical risk as well, as evidenced by more workplace accidents and injuries when sleep is inadequate [67]. In this example, efforts to modify one's work situation (e.g., taking more risks in an attempt to get work done more quickly) may effectively create an even more negative situation into being (e.g., getting injured on the job and being unable to work). The range of ways in which impaired decision making, poor impulse control, and diminished regard for consequences may interfere with one's immediate and long-term professional goals is considerable.

3. Attentional deployment

Whereas situation selection or modification serves as a form of emotion regulation by shaping one's external situation, attentional deployment aims to regulate emotions without changing any aspect of the actual environment. Distraction (i.e., diverting attention away from something negative) is perhaps the most commonly studied attentional strategy, although it is worth noting that a broad range of methods and paradigms have been used [16,74]. Still, distraction has been shown to attenuate neurobiological activity in emotional brain regions in response to negative emotional content [75]. Sleep deprivation, in contrast, produces an opposing effect on these same structures [43,44] suggesting that distraction ability, efficacy, or both may be thwarted when sleep is inadequate.

Although no study has examined the use of distraction as an explicit means of regulating emotional responses in the context of sleep, sleep-related alteration of attention for emotional stimuli is a common finding. In particular, sleep deprivation may increase vigilance to negative or threat-related information. For example, one night of sleep deprivation resulted in difficulty inhibiting responses to negative but not positive stimuli in a Go/NoGo Task, with an increased hit rate and faster response time during trials where participants were supposed to inhibit responses [76]. While explicit instructions to attend to or distract from certain stimuli were not given in this study, the fact that differential outcomes were found for negative versus positive stimuli suggests, at the least, that poorer impulse control and/or fatigue do not fully account for these results. Conversely, another study [77] used three different word-based Stroop tasks to examine attentional bias (i.e., interference control and accuracy) but did not find sleep deprivation to produce different response times for threat-related words compared to neutral words. However, this task was self-paced, which may be less stressful and less cognitively demanding than tasks requiring a response in a predetermined time frame [78], and words also likely act as less potent emotional distractors than pictures [69]. For example, Chuah and colleagues [79] found that negative pictures were more distracting than neutral pictures during a delayed response working memory task, evidenced by impaired working memory and subjective reports of distractibility. In line with other findings [44], distraction in response to negative images

corresponded with increased amygdala activation and reduced functional connectivity with frontal cognitive control brain regions [79].

Several recent studies have utilized event related potentials (ERP) following sleep deprivation as a sensitive measure of attention to emotional stimuli. In one study, both positive and negative IAPS images produced significantly larger late positive potential amplitude than neutral images when participants were rested, whereas a night without sleep diminished any differences among the picture types via increased responses to neutral images (i.e., late positive potential responses to neutral pictures were as large as those evoked by emotional pictures) [80]. The authors interpreted these findings to reflect a general depletion of attentional resources via an inability to shift attention between emotional and non-emotional sources of information irrespective of valence. However, sleep-deprived participants in another study [81] evidenced larger late positive potential responses to positive and negative compared to neutral pictures, and greater responses to negative compared to positive pictures. Again, methodological differences between studies may be salient, such as response timing. The latter study showed that whereas early emotional processing (i.e., 100 ms following stimulus presentation) was not affected, biases in later processing (i.e., between 300 and 800 ms following stimulus presentation) were observed, suggesting that sleep deprivation may influence sustained attention for negative stimuli.

The effect of sleep on the processing of threat-related information is especially evident in research investigating attention to emotional faces. In particular, sleep deprivation creates difficulty in perceiving others' emotions, possibly due to deployment of attention to improper or irrelevant cues. Some studies have found general deficits in the recognition of emotions [82], but a preponderance of evidence suggests that attention to threatening faces is maintained while attention to non-threatening faces is impaired. For example, a night of total sleep deprivation resulted in diminished accuracy in recognizing positive and neutral but not negative faces [69]. In another sleep deprivation study greater neural reactivity (as evidenced by increased amplitude of the N170 using ERP) was observed in response to subtle threat-related negative faces (e.g., fear or anger), but decreased neural reactivity was observed in response to non-threatening faces (e.g., sadness) [68]. Participants accumulating sleep debt (4 h per night for 5 d) experienced increased neural activity in response to fearful faces, but not for happy faces [41]. Gujar and colleagues [83] found increases in ratings of anger and fear emotions in others across periods of wakefulness that were attenuated following a nap. Post-nap ratings of happy faces increased while sadness ratings remained stagnant. Notably the changes in fear and happiness ratings were most prominent in participants who obtained rapid eye movement (REM) sleep during the nap.

In sum, available research examining attention to emotional content in association with sleep loss indicates a failure to use attentional strategies to effectively regulate one's emotional responses. Although individuals tend to utilize distraction when emotional information is highly intense [84], inadequate sleep is likely to mitigate such attempts vis-à-vis an interaction of different neural structures and processes. Specifically, disrupted sleep impairs attention to emotional information and may increase the salience of negative, threatening information. Theoretically, increased vigilance for negative information may actually reflect an adaptive response to sleep loss since assuming that an unfamiliar stimulus is threatening may allow the individual to recognize and react to potential threats more quickly. This theory is consistent with data suggesting that when time is limited, it is difficult to inhibit responses to negative stimuli [76]. However, some studies examining differences in reaction times to negative versus non-emotional or positive stimuli have failed to find differences [69,77]. Still, studies utilizing neurological measures suggest amplified reactivity to potentially-threatening stimuli [41,68] and ERP-based methods, which offer more sensitive examinations of the timing of neural responses, suggest sleep deprivation results in greater sustained attention and inability to direct attention away from negative information [81]. Under conditions of high sleep pressure, vigilance for potential threats may be heightened to compensate for global decrements in cognitive performance (e.g., slowed reaction time). Nevertheless, this increased vigilance may be maladaptive when experienced in excess or in non-threatening situations.

4. Cognitive change

The fourth point in the model, cognitive change, involves regulatory strategies aimed at generating an emotion in the absence of affective cues, or by using higher-order cognitive processes to change the appraisal or meaning of an emotion eliciting situation. One commonly researched type of cognitive change is reappraisal, or the process of reframing or reinterpreting an emotional event to make it less negative. Reappraisal of a negative situation appears to be highly effective in down-regulating subjective and physiological components of a negative emotional experience [13]. Accordingly, many cognitive behavioral treatment (CBT) programs for affective disorders teach patients how to utilize reappraisal techniques as a means of decreasing negative emotion.

Imaging studies of individuals engaged in cognitive reappraisal suggest increased activation in the PFC [17]. The effect of sleep on the same brain regions highlights the multiple mechanisms through which lack of sleep might interfere with successful reappraisal. Sleep deprivation shows a dose–response effect on generative cognitive tasks irrespective of circadian influence [85] suggesting that the basic formulation of relevant reappraisals may be disrupted. Indeed, poorer sleep quality over the course of a week is associated with lowered cognitive reappraisal ability, indexed by the extent to which participants were able to decrease feelings during sad movie clips [86]. However, another study found that individuals who tend to utilize cognitive reappraisal as an emotional regulation strategy (as measured by self-reports) were less vulnerable to effects of sleep deprivation on late positive potential responses (using ERP) to negative emotional stimuli [81]. Although actual reappraisal in response to the emotional stimuli was not assessed, this offers potential evidence that some degree of regulatory ability may remain intact.

Despite neurobiological evidence for the effects of sleep disruption on the cognitive control centers of the brain, little research has examined direct links between sleep and explicit attempts at cognitive reappraisal or actual cognitive reappraisal ability using experimental methods. One study found that sleep deprivation significantly reduces the tendency to think positively [66]. In a study utilizing two nights of partial sleep restriction (6.5 h followed by 2 h), adults and adolescents asked to engage in catastrophizing, a maladaptive form of cognitive appraisal, reported a greater likelihood of catastrophes coming true [48]. Only one study has examined the use of explicit cognitive reappraisal in relation to sleep. Healthy adolescents (13–17 y) were randomized to either one night of restricted (4 h) or idealized (9.5 h) sleep following a week of normal sleep (Reddy et al., manuscript in progress). The following day, participants were provided training in cognitive reappraisal techniques, and were asked to simply view and to reappraise IAPS images. The restricted and idealized sleep groups generated a similar number and type of reappraisal statements. Moreover, in both groups, ratings of reappraised as compared to viewed negative images were more positive, suggesting a similar

degree of emotion regulation ability between the groups. Although preliminary and specifically focused on adolescents, these results suggest that cognitive reappraisal ability may be somewhat resistant to sleep loss effects.

5. Response modulation

Response modulation involves the goal-directed alteration of an individual's experiential, behavioral, and/or physiological responses to an emotional stimulus. Response modulation occurs after an emotion has been fully generated; meaning that opportunities for alteration are likely to be fewer just as modulatory effort required is likely to be greater. The most commonly studied form of response modulation is expressive suppression, during which one attempts to hide visible signs of emotion [15]. Although suppression of negative emotion has been found to have a large effect on self-reported emotions [74], it is also associated with the presence of psychopathological symptoms [87] and increased activation in emotion-generative brain regions [88], indicating a general failure of this strategy to decrease the emotion that is actually experienced.

Research focused specifically on the regulation of emotions via suppression following sleep loss is sparse, though some evidence exists for general alterations in emotional expressiveness using sleep deprivation/restriction paradigms. Changes in emotion expression more broadly after disrupted sleep may influence and be influenced by response modulation. Based on speech analyses, adolescents and adults restricted to 2 h of sleep used less positive emotion words, more negative emotion words, and showed changes in the acoustic properties of their voice including increased sadness, low physiological activation, and stress/anxiety [89]. After one night of total sleep deprivation, adults were less emotionally expressive in response to both positive and negative emotional video clips [90]. However, neither study explicitly asked participants to modulate their expression. Thus, it is unclear whether differences in emotional expressiveness were a result of weakened regulatory ability, or were simply based on differences in reactivity (e.g., those who experienced less positive emotion displayed less positive emotion).

In a novel study by Schwarz and colleagues [34], participants were instructed to respond to emotional stimuli with compatible or incompatible reactions after 8 h of sleep and after 4 h of sleep. Using facial electromyography, facial reactions to emotional stimuli were slower for the restricted group, but the inhibition of expressions themselves was not impaired. Thus, whereas global emotional expressiveness might be altered by sleep loss, ability to intentionally modulate expressions may be more resistant to the effects of sleep loss. Future investigation of expressiveness in contexts that require explicit attempts to suppress emotion can provide greater information about the influence of sleep on this regulatory strategy.

Extended model of emotion regulation

Gross [15] recently outlined an extended process model in which three stages of the emotion regulation cycle are described: identification of an emotion as something that should be regulated, selection of an emotion regulation strategy, and the effective implementation of that strategy. Description of the full model is beyond the scope of this review but several specific points bear mention with regard to their relevance for sleep–emotion research. First, the emotion-generative cycle requires that an emotional response is detected and identified as requiring regulation. Identification therefore requires emotional awareness, which entails mindfulness of one's current emotional experience and the context in which it is occurring [91]. Although research on sleep and emotional awareness in healthy populations is sparse, good sleep quality may facilitate mindfulness [55,92], a nonjudgmental attentiveness to present experiences that promotes better emotion regulation [93].

The emotions that one desires to feel (i.e., their emotional goals) will ultimately serve to determine whether an emotion needs to be regulated in the first place. The intimate ways in which emotional goals and sleep intersect to impact emotion regulation remain relatively unexplored, but in situations where certain emotions are required (e.g., emotional labor), better self-reported sleep quality is related to a better match between the emotion needed to be felt and what is actually felt [94]. Still, it is unclear if this is because the emotion goal itself has changed or the ability to achieve that goal. In fact, not much is known about the ways emotional goal-setting might change as a result of sleep, but when sleep drive is high, desire to sleep often conflicts with other goals or obligations [95].

Triggered by the identification of an emotional response, the selection of a strategy represents a subsequent step in the emotion regulatory process. Some regulatory strategies are generally considered to be adaptive, such as cognitive reappraisal, whereas others, such as rumination and suppression, are typically associated with maladaptive outcomes and psychopathology [87]. At least to some extent, choice of a regulatory strategy is dependent upon the availability of personal resources and/or the specifics of the emotional context. So, for example, although reappraisal is generally considered adaptive, distraction may be more effective when emotional stimuli are especially intense [84]. Moreover, strategies that are more taxing and resource-dependent (e.g., cognitive reappraisal) may be less appealing when higher-order cognitive skills are depleted [65]. On the whole however, research examining the ways in which selection of emotion regulatory strategies might be impacted by sleep is unavailable.

Finally, the implementation stage is concerned with actually implementing the selected strategy in context-appropriate ways. Difficultly implementing specific strategies effectively, similar to their selection, has been implicated in various forms of psychopathology. For example, in a study where participants were instructed to use cognitive appraisal to enhance or suppress their emotional responses, depressed patients experienced greater difficulty in contexts where maintenance or up-regulation of positive affect was expected [96]. Thus, failure at the implementation stage may occur for any number of reasons including abnormalities in neural networks involved in regulating affect, a general lack of skill in translating a chosen strategy into practice, and/or a mismatch between the functionality of the strategy selected and the situational context.

It is also largely beneficial for an individual to be able to respond flexibly across contexts and to utilize strategies that meet the demands of the immediate environment [97]. Evidence of diminished cognitive flexibility during extended waking periods suggests that sleep loss might disrupt this process. A night of total sleep deprivation results in failures to incorporate new information or match an approach to a task [98] and resultant neurological changes (including increased activation in the nucleus accumbens, decreased activation in the anterior insula following losses, and lower activation of the orbitofrontal cortex) point toward weakened ability to learn from prior mistakes [99]. As a next step, research that expands experimental paradigms to include emotion-focused tasks and explicit instructions to implement emotion regulatory strategies will be better positioned to address these questions.

Critical points and suggested directions for research

Embedded within the recent proliferation of studies aimed at uncovering emotional mechanisms linking sleep and psychological risk are differing experimental designs, paradigms, and approaches aimed at addressing similar questions. The current review examined and organized available findings from this rapidly emerging body of research within the framework of Gross's process model of emotion regulation with the goal of guiding future studies. Specifically, we attempted to organize findings according to specific points in the emotion-generative process whereby sleep might impose the greatest impact on emotional outcomes. However inasmuch as emotion generation is a dynamic, ongoing process [11], the extent to which any of these emotion-based findings fits neatly into one category is unknown. As just one example, suppressing an emotional response may be a form of response modulation, but it can also modify the current situation (e.g., to avoid potential conflict). Thus, it is important to note that many findings included in our review are subject to alternative interpretations in terms of their ordering and placement in the emotion regulation process.

Insight into some of the ways in which inadequate sleep impacts human emotion is afforded by these studies, but remaining gaps in understanding are far more substantial. A consistent finding across all studies includes the experience of decreased positive and increased negative emotions following sleep loss, with growing evidence for more profound decrements in positive emotional responses. The latter finding maps onto neurobiological data showing regions of the striatum such as the caudate and putamen, areas associated with reward and motivation, to be highly sensitive to insufficient sleep [33].

Some methodological issues regarding the assessment of emotion generation are nonetheless noteworthy. Namely, many studies do not adequately disentangle the effects of sleep on emotion generation and emotion regulation. The extent to which assessments of emotion may at least partially capture voluntary or involuntary regulatory efforts directed at altering one's emotional experience cannot fully be known in the absence of directed inquiry. Despite wide-spread interest in and reference to the construct of emotion regulation within the sleep literature, emotion regulation as defined by Gross [14] has in fact rarely been examined. In reviewing available findings we found only a few studies that have attempted to directly examine emotion regulation in relation to sleep. Several studies using self-reported emotion regulation questionnaires [39,52] suggest that sleep disruption predicts poorer emotion regulation. Degree of correspondence between retrospective reports and real-time use of regulatory strategies is nonetheless unclear.

Many of the studies cited refer to more implicit regulation strategies or behaviors and cognitions that impact emotion indirectly. Since little research has examined explicit attempts to modulate emotion, a primary question for future work is whether sleep impacts regulation *ability* versus simply the *tendency* to engage in actions or thoughts that alter emotion responses. However, in one study explicitly instructing adolescents to use cognitive reappraisal, adolescents receiving 4 h or 9.5 h of sleep evidenced similar reappraisal ability when viewing negative IAPS images (Reddy et al., manuscript in progress). In another study participants receiving 4 h or 8 h of sleep were able to effectively modulate their emotional expressions when asked [34]. It may be that one night of partial sleep restriction does not significantly impact the use of emotion regulation strategies as compared to several cumulative nights of poor sleep, and providing instructions to regulate may minimize sleep-related individual differences in regulation as it would naturally occur. Whether spontaneous use of emotion regulation might produce similar results remains to be known.

Specific points in the process model merit rigorous experimental investigation as it is unclear whether certain aspects of regulation might be particularly vulnerable to sleep loss. Evidence of reduced motivation and perceived reward as a consequence of a lack of sleep [58,59] suggests that volition to improve one's emotions may be compromised, in turn influencing subsequent regulatory decisions (e.g., situation selection and modification). Understanding how sleep impacts the selection of both adaptive and maladaptive regulatory behaviors represents an additional critical area of inquiry. Such research necessarily requires examination of one's goals, since the emotions one desires to experience will influence chosen regulatory strategies. The precise ways in which sleep intersects with these processes and others awaits investigation.

Some points with regard to the assessment of sleep are important as well. Studies differ vastly in their approaches to measuring sleep ranging from naturalistic (at-home) subjective sleep patterns, to one or several nights of sleep restriction, to total sleep deprivation protocols. Other studies have focused more specifically on restricted REM versus NREM sleep stages. In lieu of the value of experimental paradigms, a common naturally-occurring form of sleep loss in the general population is characterized by irregular sleep–wake schedules including restricted sleep during the week and extended (i.e., recovery) sleep periods on weekends [100,101]. This pattern of sleep notably results in sleep architecture alterations including 'rebound REM' sleep on weekend nights [100,102]. As the prototypical backdrop for the development of emotional problems, simulations of this sleep pattern could potentially provide more generalizable experimental findings regarding emotion generation and regulation. Similarly, there is some indication that sleep quality rather than quantity might better predict certain emotional outcomes including regulation [52]. Thus, more studies investigating the effects of normal (i.e., typical) sleep on emotional constructs are needed along with research investigating the effect of the diurnal timing of assessments (i.e., based on hours of wakefulness).

There is marked variability in susceptibility to disrupted sleep as well [103]. Sleep need varies significantly between individuals [104], and preliminary research suggests that sleep's top-down influences on emotion via the PFC may be stronger for some individuals [105]. Therefore, research incorporating the assessment of individual differences that alter susceptibility to the impact of sleep on emotional functioning is needed. For example, there is increasing evidence that sleep loss may be most problematic for emotion in females compared to males [106,107]. Commonly, research interested in sleep–emotion relationships has utilized young adult samples. Because both sleep patterns and emotional functioning vary across the life-span, age may also be a potential moderator of the sleep–emotion relationship. Uncovering unique relationships occurring in infancy, childhood, adolescence, adulthood, and older adulthood hinges upon the use of developmentally-sensitive measures of both sleep and emotional processes. Understanding these processes in adolescence seems especially important given notable amounts of insufficient sleep [108], and increased risk for various forms of psychopathology that emerge during this time [109,110].

Conclusions

The inability to obtain sufficient sleep can result in significant emotional consequences and place individuals at risk for a range of psychiatric disorders. Research to date indicates that sleep has a pervasive impact on emotional functioning, including deficits in

emotion generation and regulation via a multitude of neurobiological, behavioral, and cognitive processes. The current review integrates a broad body of literature on sleep and emotion. Specifically, through behavioral tendencies and neurological changes, sleep appears to impact both emotion generation and emotion regulation via several potential mechanisms including situation selection, situation modification, attentional deployment, cognitive change, and possibly response modulation. Preliminary evidence also suggests that sleep may affect the ability to identify an emotion as problematic, choose an appropriate emotion regulation strategy, and implement that strategy in an effective way. Still, much remains to be understood about the sleep–emotion relationship including the causal role of sleep in influencing explicit attempts to regulate emotion, and how these links might mediate the development of psychopathology. Increased experimental research and longitudinal research following these processes over time are necessary to explicate how sleep disturbance might contribute to specific emotional deficits and in turn the development of psychopathology.

Practice points

- Inadequate sleep produces more negative and less positive emotions, with some evidence for greater decrements in positive emotions.
- Sleep deprivation can negatively impact emotion at various stages of the regulatory process, including the identification, selection, and successful implementation of various strategies.
- A focus on sleep quality in addition to sleep quantity may be critical for detecting emotional deficits.
- Decrements in motivation and perceived reward as a function of inadequate sleep may lead to unsuccessful emotion regulation strategies.

Research agenda

- Use methods that can clarify specific emotions and emotion regulation processes impacted by sleep.
- Use controlled, experimental designs, including sleep manipulations that more closely reflect typical sleep loss in the general population.
- Incorporate a broader range of emotion regulation strategies including assessments of positive emotion generation and regulation.
- Investigate the impact of individual and developmental differences in sleep–emotion relationships.

Conflicts of interest

The authors do not have any conflicts of interest to disclose.

* The most important references are denoted by an asterisk.

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