A Role for REM Sleep in Recalibrating the Sensitivity of the Human Brain to Specific Emotions

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Although the impact of sleep on cognitive function is increasingly well established, the role of sleep in modulating affective brain processes remains largely uncharacterized. Using a face recognition task, here we demonstrate an amplified reactivity to anger and fear emotions across the day, without sleep. However, an intervening nap blocked and even reversed this negative emotional reactivity to anger and fear while conversely enhancing ratings of positive (happy) expressions. Most interestingly, only those subjects who obtained rapid eye movement (REM) sleep displayed this remodulation of affective reactivity for the latter 2 emotion categories. Together, these results suggest that the evaluation of specific human emotions is not static across a daytime waking interval, showing a progressive reactivity toward threat-related negative expressions. However, an episode of sleep can reverse this predisposition, with REM sleep depotentiating negative reactivity toward fearful expressions while concomitantly facilitating recognition and ratings of reward-relevant positive expressions. These findings support the view that sleep, and specifically REM neurophysiology, may represent an important factor governing the optimal homeostasis of emotional brain regulation.

Keywords: emotion, reactivity, REM, sleep

Introduction

Long-held maternal wisdom suggests that sleep can help ameliorate our emotions, the old adage that "if troubled, get to bed, you'll feel better in the morning." Clinical evidence supports this anecdotal view; nearly all affective psychiatric and neurological mood disorders express co-occurring abnormalities of sleep, commonly involving rapid eye movement (REM) alterations (Benca et al. 1992; Nofzinger et al. 1993; Turek 2005; Armitage 2007; Harvey 2008), implying an intimate relationship between sleep and emotion. A growing collection of experimental findings has continued to substantiate a role for sleep in emotion processing. For example, sleep deprivation has been shown to disrupt the encoding and consolidation of emotional memories (Walker and Stickgold 2006; Sterpenich et al. 2007) and disproportionately amplify neural and autonomic reactivity to negative emotional events (Yoo et al. 2007; Franzen et al. 2009). Moreover, REM sleep in particular has been implicated in the consolidation of negative emotional episodic experiences (Wagner et al. 2001, 2006; Nishida et al. 2009), whereas manipulations of REM have been shown to alter the evaluation of affective stimuli, particularly those of negative valence (Wagner et al. 2007; Lara-Carrasco et al. 2009).

Building on this empirical and clinical literature, several conceptual frameworks have proposed a preferential role for REM sleep neurophysiology in modulating affective brain processes, ranging from basic emotional reactivity to episodic memory processing (Levin and Nielsen 2009; Walker 2009a, 2009b; Walker and van der Helm 2009). Based on the marked reduction in aminergic neurochemistry and reactivated limbic anatomy during REM (Hobson and Pace-Schott 2002) these theories have suggested that REM may offer an ideal neurobiological medium within which to depotentiate prior negative experiences, restoring optimal postsleep affective reactivity (Levin and Nielsen 2009; Walker 2009a, 2009b; Walker and van der Helm 2009).

Despite such a proposed association, limited knowledge exists regarding the beneficial advantage of sleep (rather than a lack thereof) in regulating specific categories of emotions. Considering that emotion responses represent fundamental processes governing not only our personal and professional lives but also our social (one-to-one) and societal (group) interactions, understanding biological factors that modulate emotion regulation, such as sleep, becomes particularly germane (Adolphs 2003; Barrett et al. 2007). To date, studies examining the interaction between sleep and emotion reactivity have focused principally on subjective measures of mood and how such measures change due to a loss of sleep. For example, using a sleep restriction paradigm (5 hours per night), Dinges et al. (1997) have reported a progressive increase in emotional disturbance across a 1-week period on the basis of questionnaire mood scales, indicating increasing complaints of emotional difficulties. Sleep loss also can induce amplified negative affective reactions to disruptive daytime experiences while reducing positive emotional benefits associated with rewarding or goal-enhancing activities (Zohar et al. 2005).

At an objective level of measurement, both the speed and accuracy rating of emotional face drawings has been reported to deteriorate (slowed and becoming less accurate, respectively) following 1 night of sleep deprivation (Pallesen et al. 2004). Using functional magnetic resonance imaging, Yoo et al. (2007) have recently demonstrated that 1 night of sleep deprivation amplifies amygdala reactivity in response to negative emotional stimulus viewing associated with a loss of top-down functional connectivity with autonomic brain stem activating centers. Franzen et al. (2009) have also reported significantly larger pupillary response (an index of autonomic reactivity) under conditions of sleep deprivation during passive viewing of negative pictures, relative to both positive and neutral stimuli.

Although these studies importantly characterize the detrimental consequence of sleep loss on emotional behavior and brain function, the beneficial influence of sleep and specific types of sleep in modifying affective brain processes is less clear. In addition, the role of sleep in differentially modulating reactivity to distinctive types of emotion (e.g., fear, anger, and happiness) remains similarly unexplored. Using a nap paradigm, here we test the hypothesis that the reactivity to specific human emotions can be modified by intervening sleep, relative to an equivalent period of time awake. Furthermore, and motivated by recent neurobiological frameworks of REM sleepdependent emotion regulation (Levin and Nielsen 2009; Walker 2009a, 2009b; Walker and van der Helm 2009), we sought to test the hypothesis that a specific type of sleep-REMpreferentially contributes to these effects.

Materials and Methods

Participants

The 36 healthy subjects, divided equally between males and females, aged 18-30 years, were randomly assigned to either the Nap (n = 18, 11males, age 21.0 ± 0.56 [mean \pm SEM]) or the No-Nap (n = 18, 7 males, age 21.9 ± 0.59 [mean ± SEM]) groups. Subject exclusion criteria included a history of neurologic, psychiatric, or sleep disorders, past history of drug abuse, and current use of antidepressant or hypnotic medications. Subjects were abstained from caffeine and alcohol for the 72 h before and during the entire course of the study and kept a normal sleep-wake rhythm and average sleep duration (7-9 h of sleep per night, with morning wake time between 6:30 AM and 9 AM) 1 week prior to study participation, as verified by sleep logs. Total sleep the night before testing did not differ between the Nap and No-Nap groups (7.6 ± 0.19, $7.8 \pm 0.19 \text{ h}$, respectively [mean \pm standard error of the mean {SEM}], P =0.42), and mean rise times also did not differ significantly between groups (8:03 \pm 0.12, 8:23 \pm 0.11, respectively [mean \pm SEM], P = 0.40). The study was approved by the local human studies committee, with all subjects providing written informed consent.

Experimental Design

Subjects performed an emotional face recognition task (described below) at 12 PM (±30 min; Test1) and were then randomly assigned to either the Nap or the No-Nap group. Following completion of Test1, subjects in the Nap group obtained a 90 min sleep opportunity, monitored using polysomnography (PSG), whereas those in the No-Nap group stayed awake. Both groups then repeated the emotional face task later the same day at 5 PM (±30 min; Test2), allowing adequate time for dissipation of potential sleep inertia effects. Participants were allowed to go about their normal daily activities during the waking interval between Test1 and Test2, with the exception that the No-Nap group was instructed not to sleep during the day, which was confirmed by postexperimental questionnaire. Similarly, beyond the experimentally recorded midday nap, those in the Nap group were also instructed not to nap before or after the noon sleep session, also confirmed by postexperimental questionnaire.

Prior to each of the 2 tests, subjects completed the Positive and Negative Affect Scale (PANAS), a standard psychological tool measuring participants' internal subjective perception of mood state across an array of positive (e.g., happy, energetic, and excited) and negative (e.g., distressed, scared, and guilty) emotional items, resulting in a summed score of positive and negative mood items (Watson et al. 1988). Subjects also completed the Stanford Sleepiness Scale, a standard measure of subjective alertness ranging across a 7-point scale (1 being most alert) (Hoddes et al. 1973). Participants in the No-Nap group indicated a trend toward reduced levels of sleepiness from Test1 to Test2 ([mean \pm SEM]: 2.4 \pm 0.18 and 2.06 \pm 0.19, respectively; P < 0.08). Those in the Nap group demonstrated a nonsignificant reduction in levels of sleepiness from Test1 to Test2 ([mean ± SEM]: 2.50 ± 0.17 and 2.19 ± 0.22 , respectively; P = 0.31).

Emotional Face Task

The experimental task involved rating 4 different affective face categories: fearful, sad, angry, and happy. Black and white photographs of the same male individual expressing fearful, happy, sad, angry, and neutral face expressions were taken from the Ekman "Pictures of facial affect" set (http://www.paulekman.com/researchproducts.html), a validated stimulus set of human emotional expressions. Each of the 4 emotional pictures were morphed to the neutral face of the same individual by employing a series of 8 equal gradient steps using a face morph software tool (Gryphon Morph 2.5), resulting in 10 separate images for each of the 4 emotions; incrementally increasing in their relative degree of affect intensity (Harmer et al. 2001; Hornak et al. 2003; Heberlein et al. 2008). Each emotion was presented in a separate block of trials, and within this block, the 10 pictures were presented in a random order on a 14.1" laptop computer screen (central screen location, at half-screen height) at a standard distance from the participant. Subjects were required to make an emotional strength rating for each face slide on a scale from 1 to 4, with 1 being most neutral and 4 most emotional, using a standard computer keyboard. For example, for the emotion happy, the scale was as follows: 1—definitely neutral; 2-more neutral than happy; 3-more happy than neutral; 4—definitely happy.

For each block, subjects were first informed which emotional category they would be viewing-fearful, sad, angry, or happy. Next, subjects were acquainted with the range of emotional gradient by having the 10 face slides appear in random order on the screen, 1 at a time and for 1-s intervals, without requiring any response. This allowed subjects to appreciate and become familiarized with the full spectrum of emotion intensity prior to rating. Following this familiarization phase, an instructional screen notified subjects that they would now be rating each of the individual faces for a specified emotional category. Each of these blocks contained 10 face picture trials, and each trial consisted of a 2-s face stimulus presentation, followed by the response screen instructing subjects to rate the face using the above-described 1-4 ranking system, and no longer contained the face stimuli. Following the keyboard response, the next trial began. After rating all 10 pictures, subjects repeated the same process for the remaining 3 emotional categories.

The second session of testing was identical to the first, including the re-presentation of the same individual, with the exception that at the second session subjects did not perform the familiarization phase prior to the actual rating phase. Within subjects, the order presentation of the 10 faces was rerandomized between the familiarization and first test sessions and further rerandomized between the first and the second test sessions. Additionally, the order presentation of the emotion categories was similarly randomized within subjects, across sessions, and across subjects.

Data Analysis

Behavioral response data were assessed at 3 different levels 1) mean ratings across the 10 trials at Test1 and at Test2 for each emotion separately, 2) the change in emotional reactivity across the time delay, quantified by subtracting the mean responses (per emotion) at Test1 from Test2, and 3) a more fine-grained analysis evaluating separated responses across the increasing affective gradient of picture trials (per emotion) at Test1 and Test2. For this latter analysis, a moving average approach was implemented across the picture gradient, averaging the rating scores of 2 successive picture trials at a time. Thus, the 10 picture trials resulted in a total of 9 data points for each subject, containing the average score of trials 1-2, then 2-3, 3-4, and so on up to trials 9-10. Comparisons principally focused on within-subject, between-test measures of performance due to the known intersubject variability in emotional reactivity and mood disposition (Davidson

Statistical analyses were calculated using between- and within-group analysis of variance (ANOVA) models together with post hoc withinand between-group comparisons calculated using paired and unpaired 2-tailed t-tests, respectively. All analyses were performed using the software program JMP v8.0 (SAS), with P < 0.05 considered significant. An initial omnibus repeated-measures multivariate ANOVA (MANOVA) was conducted with condition (Nap and No-Nap) and emotion (fearful, sad, anger, and happy) as within-subject factors. Significant interactions for these ANOVAs were decomposed using appropriate simple effects analyses and pairwise contrasts (described in more detail later).

Sleep Recording

PSG recording was performed in accordance with standardized techniques (Rechtschaffen and Kales 1968) using digital electroencephalography (EEG), electromyogram, and electrooculogram signals acquired with a Grass Colleague system (sampling rate: 100 Hz, high-and low-pass filter: 0.3 Hz and 35 Hz, respectively, notch filter: 60 Hz). A mastoid referenced PSG electrode montage was utilized and composed of EEG sites F3 and C3 (referenced to A2), and F4 and C4 (referenced to A1). Each sleep epoch of the PSG record was scored according to standard criteria using C3 and C4 channels (Rechtschaffen and Kales 1968), blind to subjects' behavioral task performance. Digital PSG records were scored visually, epoch by epoch, as non-rapid eye movement (NREM) stages 1–4, REM sleep, awake, or movement time. Slow-wave sleep (SWS) consisted of stage 3 and stage 4 NREM sleep combined.

Results

Effect of Wake and Sleep on Emotional Face Ratings

Analyses first focused on a repeated-measures ANOVA (MAN-OVA) using the mean rating across all 10 faces. At a group level, there were significant main effects of condition ([Nap and No-Nap]; $F_{1,136} = 4.76$, P < 0.04), emotion ([fearful, sad, anger, and happy]; $F_{3,136} = 13.2$, P < 0.001), a test session × emotion interaction ($F_{3,136} = 3.47$, P < 0.02), and no main effect of test session. Within the Nap group, there was a significant main effect of emotion ($F_{3,68} = 8.40$, P < 0.001), a test session × emotion interaction ($F_{3,68} = 4.02$, P < 0.001), and no main effect of test session. In the No-Nap group, there were significant main effects of emotion ($F_{3,68} = 5.96$, P < 0.002), test session ($F_{1,68} = 5.91$, P < 0.02), and a near significant test session × emotion interaction ($F_{3,68} = 2.25$, P < 0.09).

Post hoc analyses further elucidated these dissociable influences within and across groups (Fig. 1, significance values displayed within figure). A significance amplification of anger ratings developed across the day in the No-Nap group, yet this intensification was blocked in the Nap group, with a betweengroup comparison further confirming significance (Fig. 1). Ratings of fearful expressions were also significantly different between groups, demonstrating a marked reduction in the Nap group, yet a converse increase in ratings toward fear expressions for the No-Nap group. Counter to the rating reductions in

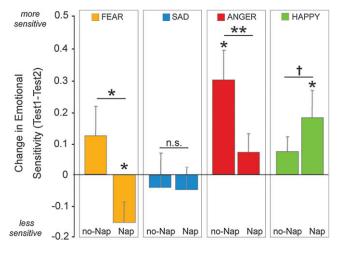


Figure 1. Change in emotional reactivity. Difference in mean ratings between the 2 test sessions in the No-Nap and Nap groups across all 4 emotions (fear, sad, anger, and happy). Within (symbol above individual bars) and between (line across bars) comparisons reflect significance at † <0.08, * <0.05, and ** <0.01. Error bars represent SEM.

response to these negative emotions following sleep, a significant increase in the rating of happy expressions occurred at Test2 in the Nap group, yet showed no significant change in the No-Nap group. No within- or between-group differences were identified in response to sad emotion expressions.

Mean rating values for Test1 and Test2 (from which the subtracted difference measure was calculated for each emotion), together with the data separated across the emotional gradient response curves for each group, are provided in Figures 2 and 3 (significant comparisons provided within figures). The 2 groups did not differ significantly in their baseline (Test1) performance across the 4 emotions (unpaired t-test, all P > 0.13). Analyses of the gradient response curves demonstrated that the changes reported between groups for the mean values were most pronounced in the moderate range of the emotional picture gradient where expressions were more ambiguous (and arguably most typical of daily life) rather than the extremes (Figs 2 and 3).

Effects of Wake and Sleep on Mood Scale Changes

In addition to the objective measure of emotional stimulus ratings, subjects also completed the PANAS, a standard psychological tool measuring participants' internal subjective perception of mood state, which yields a summed score of positive and negative mood items (each of which are considered independent) (Watson et al. 1988).

For the positive mood score dimension, there was no main effect of condition ([Nap and No-Nap]; $F_{1,31} = 0.56$, P = 0.45), a nonsignificant trend toward a main effect of test session ([Test1 and Test2]; $F_{1,31} = 3.26$, P = 0.08), with lower ratings at Test2 session, and no condition \times test session interaction ($F_{1,31} = 0.64$, P = 0.43). For the negative mood score dimension, there was no effect of condition ($F_{1,31} = 1.12$, P = 0.29), a significant main effect of test session ($F_{1,31} = 11.81$, P < 0.002), again with ratings being lower at the second test session, and no condition \times test session interaction ($F_{1,31} = 0.02$, P = 0.86). Test session values and further discussion of the PANAS mood data are provided in Supplementary Materials.

Sleep Stage Sleep Contribution to Emotional Task Performance

PSG values for the Nap group are provided in Table 1. To examine the sleep stage contributions to the change in emotional face ratings and motivated a priori by the growing connection between REM sleep and affective processing (Benca et al. 1992; Nofzinger et al. 1993; Armitage 2007; Harvey 2008; Walker 2009a, 2009b), the Nap group was separated according to those who achieved REM (n = 8, REM group) and those who did not (n = 10, no-REM group). Sleep stage values for each subgroup are described in Table 2. Focusing on the mean rating score for each emotion category at each test, there was an overall main effect of condition ([REM and no-REM]; $F_{3.68} = 4.02$, P < 0.02), a main effect of emotion ($F_{3.68} = 4.83$, P < 0.02) 0.01), and within each group, a significant main effect of emotion (both P < 0.01), and no main effect of test session. Only in the REM group was there a significant test session × emotion interaction ($F_{3,28} = 3.99$, P < 0.02). Post hoc tests (described in Fig. 4) demonstrated that those who achieved REM expressed a significant reduction in ratings toward fearful expressions, yet a concomitant and significant increase in the rating of happy face stimuli (Fig. 4). Between-subgroup tests on the change in emotion rating (displayed in Fig. 4) for each of

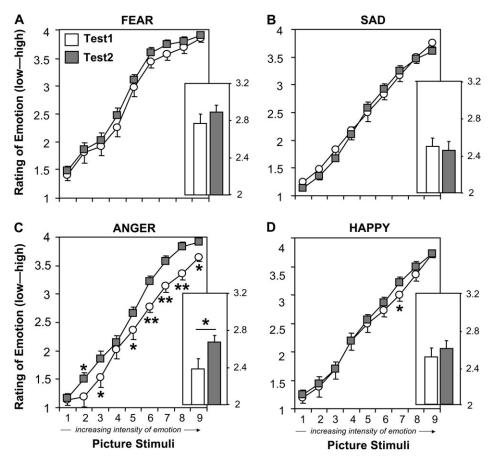


Figure 2. Test session ratings across the increasing affective gradient for each emotion in the No-Nap group together with corresponding means. Response curves at Test1 (clear circles) and Test2 (filled squares) for the rating of the face stimuli plotted across the emotional intensity gradient from low to high (left to right). Average ratings at Test1 (clear bars) and Test2 (filled bars) for each of the 4 emotions (i.e., mean across the response curves) are provided in lower right bar graphs, from which the subtracted difference and hence change in emotional sensitive scores were derived (Fig. 1). Paired t-test comparisons between Test1 and Test2 are represented at the statistical levels of *P < 0.05, **P < 0.01, uncorrected for multiple comparisons. Error bars represent SEM.

these 2 emotions were also significant (both P < 0.04). No significant differences in the change in ratings toward anger expressions were evident between the 2 subgroups (P = 0.87).

As indicated in Table 2, beyond the factor of REM sleep, the REM and no-REM subgroups differed on the basis of total sleep time (TST) but no other sleep parameter. To investigate whether this difference in TST had a significant or stronger contribution to the emotional changes than that of REM, we repeated our statistical analyses, but on the subgroup separation around the group mean TST (low/high, < or > 62 min, n =10 and n = 8, respectively), rather than no-REM/REM separation (also n = 10 and n = 8, respectively). That is, does total sleep time of the nap (high/low) alternatively explain the observed differences in emotional rating rather than the presence or absence of REM? Within the low TST, there was no main effect of test session ($F_{1,36} = 0.56$, P = 0.46), a significant main effect of emotion ($F_{3.36} = 4.70$, P < 0.01), but no test session × emotion interaction ($F_{3.36} = 2.18$, P = 0.14). For the high TST group, there was no main effect of test session ($F_{1,28} = 0.13$, P = 0.72), a significant main effect of emotion ($F_{3,28} = 3.74$, P < 0.03), but no test session × emotion interaction ($F_{3,28} = 1.92$, P = 0.15). Therefore, although the REM and no-REM groups did differ on the basis of TST (with the REM group experiencing a longer sleep period), this metric of TST did not demonstrate a test session by emotion category interaction (unlike the REM group). Corresponding figures for this TST data analyses are

provided in Supplementary Materials (Supplementary Figure 1), as are equivalent subgroup separation analyses on the basis of stage 2 NREM and SWS.

Sleep Stage Sleep Contribution to Mood Scale Changes

In addition to the changes in emotion rating, we also examined changes in PANAS mood scale ratings for the REM and no-REM groups. For the positive mood score dimension, there was no main effect of condition ([REM and no-REM]; $F_{1,15} = 0.56$, P =0.45), a nonsignificant trend toward a main effect of test session ([Test1 and Test2]; $F_{1.15} = 3.26$, P = 0.08), showing decreased ratings at the second test, and no condition x test session interaction ($F_{1,15} = 0.64$, P = 0.43). For the negative mood score dimension, there was no effect of condition ($F_{1,15}$ = 1.12, P = 0.29), a significant main effect of test session ($F_{1,15} =$ 11.81, P < 0.002), similarly demonstrating reduced ratings at the second test, and no condition x test session interaction $(F_{1.15} = 0.02, P = 0.86)$. Test session values for the PANAS mood data are provided in Supplementary Material.

Discussion

A central component of human affective brain processing is the evaluation of facial expressions, which represent nonverbal social cues, capable of communicating information that can alter our judgment and perception of other people, as well as

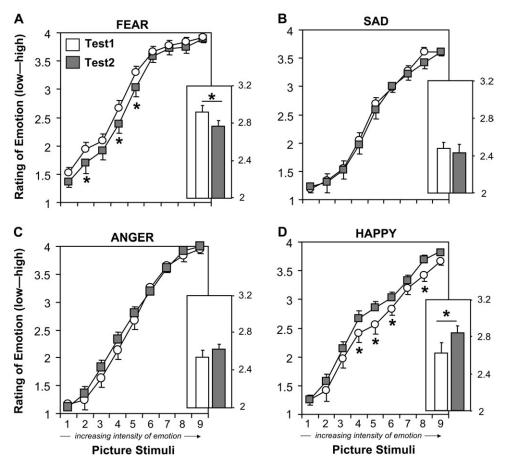


Figure 3. Test session ratings across the increasing affective gradient for each emotion in the Nap group together with corresponding means. Same data display as in Figure 2, but for the Nap group. Paired t-test comparisons between Test1 and Test2 at each data point are also represented at the statistical levels of *P < 0.05, **P < 0.01, uncorrected for multiple comparisons. Error bars represent SEM.

Table 1							
PSG sleep stage values for the Nap group (mean \pm SEM)							
	Sleep time (min)	%					
Total nap time	62 ± 6.83						
Stage 1	15.03 ± 2.41	28.51 ± 2.29					
Stage 2	17.06 ± 2.65	28.34 ± 3.23					
SWS	25.39 ± 3.09	37.77 ± 3.90					
REM	4.53 ± 1.40	5.38 ± 1.64					

Note: Mean duration (in minutes), percent (%), and standard error (SEM) of total nap time; NREM sleep stages 1 and 2 together with SWS (NREM stage 3 and stage 4); and REM sleep.

our actions toward them (Vuilleumier and Pourtois 2007). Indeed, the human face has been suggested to be the most salient environmental cue to another person's emotional state, influencing aversive and affiliative feelings and behaviors, guiding reproductive activity, and even shaping the extent and complexity of social networks (Ekman and Davidson 1994). Therefore, understanding factors that modulate our evaluation of these instructional signals is particularly relevant. Here we report that 1 such biological factor capable of modulating the evaluation of human facial emotion is that of brain state, both wake and sleep.

Brain State Effects

Across the day, those in the No-Nap group expressed a significant, but selective, increase in ratings of fear and anger

	REM group		no-REM group		P value	
	Sleep time	%	Sleep time	%	Sleep time	%
Total nap time Stage 1 Stage 2 SWS REM	$\begin{array}{c} 18.3 \; \pm \; 2.31 \\ 21.9 \; \pm \; 2.19 \\ 34.6 \; \pm \; 4.04 \end{array}$	$\begin{array}{c} 0.22 \ \pm \ 0.05 \\ 0.26 \ \pm \ 0.04 \\ 0.4 \ \pm \ 0.09 \end{array}$	43.7 ± 3.17 12.5 ± 2.57 13.2 ± 2.72 18.1 ± 3.88 0.0 ± 0.00	0.3 ± 0.07	<0.01 0.24 0.16 0.19 <0.001	0.25 0.63 0.71 <0.001

Note: Mean duration (in minutes), percent (%), and standard error (SEM) of total nap time and sleep stages. SWS (NREM stage 3 and stage 4); REM sleep. Unpaired *t*-test comparisons described in far right columns.

expressions. Although the biological factors instigating this change across the day remain unknown, 1 potential contribution may be an alteration in prefrontal regulatory control of emotional processing, particularly in mesial and ventral portions (Dolan et al. 1996; Blair et al. 1999; Calder et al. 2004; Sotres-Bayon et al. 2004); regions which modulate subcortical limbic and basal ganglia networks associated with these negative emotions (Phan et al. 2002; Sotres-Bayon et al. 2004; Quirk and Beer 2006; Dolan 2007). Previous neuro-imaging studies have demonstrated that portions of the prefrontal lobe, including the medial and orbitofrontal, are among those most significantly impaired in their activity

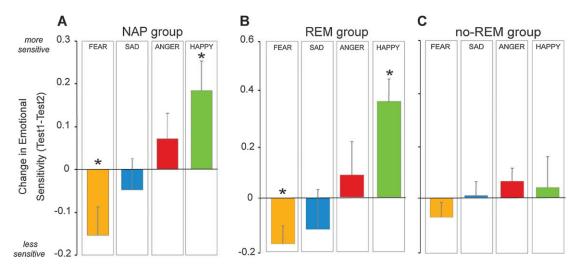


Figure 4. Differential impact of REM on the change in emotion reactivity. Difference in mean ratings between the 2 test sessions and across all 4 emotions (fear, sad, anger, and happy) for (A) the Nap group overall (recomposed from Fig. 1), (B) only for those in the Nap group who obtained REM sleep, and (C) only for those in the Nap group who did not obtain REM sleep. Within-group comparisons (symbol above individual bars) reflect paired t-test significance (relative to null) at * <0.05 and ** <0.01, with between-group tests reported in main text. Error bars represent SEM.

following extended durations of wakefulness (beyond 16 h; Harrison et al. 2000; Thomas et al. 2000, 2003; Muzur et al. 2002). This susceptibility of the prefrontal lobe may still be sufficient to produce identifiable changes in the evaluation and judgment of emotional expressions across a waking interval not considered to reflect sleep deprivation.

Rather than a maladaptive consequence of prefrontal impairment with continued waking, an alternative, adaptive explanation of the observed changes with progressive time awake may relate to alertness and fatigue. Overlaid on the 24-h circadian oscillation (termed "process C") is an increasing sleep pressure, which develops as a function of continued hours spent awake (termed "process S") (Borbely 1982; Borbely and Achermann 1999), associated with decreased alertness and attention (Durmer and Dinges 2005; Lim and Dinges 2008). Under such conditions, it may be "adaptive" for the brain to shift its recognition bias toward stimuli of greatest threatrelevant value (e.g., anger and fearful face signals), resulting in behavioral repertoires that are more conservative when attentional and basic alertness resources are more compromised. Tempering this possibility in the current study, however, were subjective sleepiness scores, which in both groups indicated increased subjective alertness at Test2 rather than decreased alertness. Therefore, although an adaptive hypothesis offers 1 framework within which to consider the changes observed in the No-Nap (wake) group, considerably more work is required to gain a deeper appreciation of the causal and mechanistic foundations underlying this effect.

In contrast to the No-Nap group, those participants in the Nap group expressed a different profile of performance change: a rating reduction (rather than increase) toward fearful expressions, a lack of amplified ratings toward anger expressions, a converse increase in ratings of happy face expressions, and no rating change toward sad expressions. Thus, an episode of sleep appears to bidirectionally, depending on the emotion category, remodulate the rating of affective face stimuli. One dimension that differentiates these emotion categories is the degree of autonomic arousal that each elicits. Fear and anger, emotion categories that displayed the largest sleep effect relative to the No-Nap group (and to a lesser degree happy), are associated with greater levels of induced physiological arousal than the emotion sad (Russell 1980; Lang et al. 1993). Thus, 1 organizing principal determining which types of emotion categories (and hence brain networks) are sensitive to the effects of sleep and wake may be the magnitude of associated autonomic reactivity.

Beyond alterations in emotional reactivity, an alternative hypothesis accounting for the observed group differences may be a change in basic visual perceptual processing rather than emotional reactivity. This intriguing possibility appears less parsimonious, however, when considering the selectivity of the effects. First, the differences identified in the sleep (Nap) group were specific for some emotions (fear, anger, and happy) and not for others (sad). A basic visual perceptual processing account may predict equivalent changes across all emotion categories. Second, the differential changes in direction that we observed, that is, rating some emotions more strongly (e.g., happy), others less strongly (e.g., fear and anger), are not well corroborated by changes in visual perceptual processing because it would predict a unidirectional change (either all increase or all decrease), which was not the case, even within each group. Third, within each emotion category, the changes observed were seen in a specific location across the morphed emotion intensity gradient (the moderate emotion range, not in the neutral or extreme emotion ranges), which does not appear easily accounted for by alterations in visual perceptual processing.

In addition to changes in emotion reactivity, dissociable influences on measures of mood were also observed. Within the No-Nap group, significant decreases in positive mood score occurred from Test1 to Test2, with a nonsignificant reduction in negative mood score. These findings are consistent with previous evaluations of both positive and negative mood scales across a full waking day (Buysse et al. 2007). In contrast, a highly significant postsleep decrease in negative mood ratings developed following sleep in the Nap group without a significant reduction (or increase) in positive mood score. These mood-based changes are therefore partially concordant with the alterations in emotional task reactivity, showing reductions in negative affect domains for both emotion reactivity and mood across a nap. However, they do not converge in the domain of positive affect where an increase in emotion reactivity toward the happy face expressions was identified in the Nap group without a corresponding increase in positive mood score. Therefore, although sleep and wake appear to modulate measures of mood and emotional reactivity, these changes do not appear to be entirely related to each other, supporting previous sleep-related alterations in different affect domains (Luo and Inoue 2000; Kaida et al. 2007). Such findings also fit with the conceptualization of mood and emotion representing related vet dissociable processes, the former reflecting an evaluation of internal state and the latter reflecting reactivity to evoking stimuli, and are often more short lived (Ekman and Davidson 1994). The differential impact of wake, sleep, and sleep stage physiology on mood and emotion processes represents a fertile area for future investigation, especially when considering the implications for clinical affective disorders.

An important limitation of the current design in the context of brain state effects, within which these results should be considered, is the lack of controlled waking activities in the No-Nap group during the 90-min period encompassing the sleep in the Nap group. One goal of the current study was to examine the influence of normal daily waking activities on the change in emotion reactivity in an endeavor to allow for an ecologically realistic impact of time awake. However, future such studies would ideally have 2 wake state conditions, one where subjects perform their normal routine daily activities and another under controlled laboratory conditions performing more standardized activities that more closely approximate conditions experienced by the Nap group.

Sleep and Sleep Stage Effects

In addition to the overall nap condition effect, when separated on the basis of sleep stage, this profile of emotional modulation appeared to be expressed principally in those who obtained REM, displaying the most pronounced reactivity reductions toward fearful expressions yet the most significant enhancements toward happy face stimuli. The lack of increased reactivity toward angry face stimuli was similarly observed in both the no-REM and REM subgroups.

These findings add to a collection of studies demonstrating an interaction between sleep and emotional information processing. For example, a number of reports have described the selective consolidation of negative (unpleasant) emotional stimuli across periods containing sleep, a benefit that appears to be closely associated with REM (Wagner et al. 2001, 2006, 2007; Hu et al. 2006; Sterpenich et al. 2007; Payne et al. 2008; Nishida et al. 2009). Furthermore, sleep deprivation has been shown to specifically impair the initial encoding of positive emotional stimuli, although the ability for learning of negative information can persist (Walker and Stickgold 2006). It is interesting to speculate that the enhanced reactivity toward negative stimuli across continued waking periods might contribute to the previously described persistent ability for negative emotional memory formation. This learning-related literature can reciprocally offer insights into the profile of emotional change identified in the current study. Stimuli in our design were repeated at both test sessions, introducing the opportunity for learning-dependent contributions. The episode of sleep in the Nap group may enhance the consolidation of negative face stimuli, decreasing their novelty at repeat presentation, resulting in reduced ratings. Future designs using

different face stimuli at the 2 test sessions will allow for the further examination of such learning contributions.

Although the biological mechanisms orchestrating the observed changes in the current study remain unknown, a tenable contributing candidate may be the marked reductions in noradrenergic and serotonergic activities during REM (Saper et al. 2001; Pace-Schott and Hobson 2002), which form part of a network responsible for autonomic arousal control. As a result, reactivity to emotions most sensitive to aminergic transmission and associated limbic brain reactivity, notably threat-associated negative emotions (Phan et al. 2002), may decrease following such postsleep demodulation. Rather than 2 separate REM processes modulating negative and positive affect independently and in accordance with models proposing reciprocity between positive and negative emotion systems (Bradley 2000), the postsleep negative decrease may allow for a consequent disinhibition of reactivity toward reward-relevant positive emotions. Therefore, in concert with the restoration of prefrontal function, REM reactivation and potential resetting of activity and/or connectivity throughout these regions, which takes place in a brain state devoid of aminergic chemistry, may offer biological conditions conducive for redressing appropriate control processing throughout affective brain circuits (Levin and Nielsen 2009; Walker 2009a, 2009b; Walker and van der Helm 2009).

Our findings are in partial contrast to those reported by Lara-Carrasco et al. (2009), describing reduced, rather than exaggerated, arousal ratings toward negative pictures following REM deprivation. Several factors may contribute to these differences. First, our current study examined different types of negative emotions (fear, anger, and sad) and found selective effects for some, but not all, emotions. The study by Lara-Carrasco et al. (2009) focused on negative or positive stimuli in general but did not examine different types of affective categories. Second, we examined the benefit and presence of sleep, and specifically REM sleep, rather than the detrimental consequence of the absence of sleep, for which the latter, as Lara-Carrasco et al. (2009) note in their report, may lead to an emotional reactivity carryover effect in the morning.

Additionally, our current data do not, by themselves, discount the contribution of other parameters, such as sleep time, NREM sleep characteristics, or circadian alterations in modulating affective processes (Benca et al. 1992; Nofzinger et al. 1993; Armitage 2007; Harvey 2008; Walker 2009a, 2009b). Furthermore, we note that the REM sleep subgroup analyses alone are not sufficient to implicate an exclusive, causative role for REM in alterations of emotional reactivity. Studies that experimentally manipulate REM sleep parameters, although holding others constant, will be necessary in this respect, offering more nuanced insights into the role of specific sleep parameters in emotional regulation.

In summary, here we demonstrate that the reactivity to specific human emotions is not static across a daytime waking interval being associated with a dynamic increase in ratings of expressions commonly associated with threat-related value (fear and anger, not sad). Furthermore, an intervening period of sleep can block (anger) and reverse (fear) this negative emotion enhancement, yet increase ratings of reward-relevant, positive expressions, with the latter 2 effects being observed only in those participants who obtained REM sleep. These data add to a growing collection of findings indicating a regulatory role for sleep in the optimal homeostasis of emotional brain function (Benca et al. 1992; Nofzinger et al. 1993; Armitage

2007; Harvey 2008; Walker 2009a, 2009b), which if disrupted may have detrimental contributions to clinical symptomotology in affective disorders (Turek 2005).

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Supplementary Material

Supplementary material can be found at http://www.cercor.oxfordjournals. org/.

Notes

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