Sleep Deprivation Impairs the Accurate Recognition of Human Emotions

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Study Objectives: Investigate the impact of sleep deprivation on the ability to recognize the intensity of human facial emotions.
Design: Randomized total sleep-deprivation or sleep-rested conditions, involving between-group and within-group repeated measures analysis.
Setting: Experimental laboratory study.
Participants: Thirty-seven healthy participants, (21 females) aged 18–25 y, were randomly assigned to the sleep control (SC: *n* = 17) or total sleep deprivation group (TSD: *n* = 20).
Interventions: Participants performed an emotional face recognition task, in which they evaluated 3 different affective face categories: Sad, Happy, and Angry, each ranging in a gradient from neutral to increasingly emotional. In the TSD group, the task was performed once under conditions of sleep deprivation, and twice under sleep-rested conditions following different durations of sleep recovery. In the SC group, the task was performed twice under sleep-rested conditions, controlling for repeatability.
Measurements and Results: In the TSD group, when sleep-deprived, there was a marked and significant blunting in the recognition of Angry and Happy affective expressions in the moderate (but not extreme) emotional intensity range; differences that were most reliable and significant in female participants. No change in the recognition of Sad expressions was observed. These recognition deficits were, however, ameliorated following one night of recovery sleep. No changes in task performance were observed in the SC group.
Conclusions: Sleep deprivation selectively impairs the accurate judgment of human facial emotions, especially threat relevant (Anger) and reward relevant (Happy) categories, an effect observed most significantly in females. Such findings suggest that sleep loss impairs discrete affective neural systems, disrupting the identification of salient affective social cues.
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THE IMPACT OF SLEEP DEPRIVATION ON COGNITIVE BRAIN FUNCTION HAS RECEIVED INCREASING RESEARCH INTEREST OVER THE PAST HALF CENTURY, following the discovery of unique sleep stages.[1] This is perhaps not surprising considering the societal and medical ramifications of the deficits caused by sleep loss, which commonly include impaired sustained attention together with deficits in learning and memory.[2-4]

However, the impact of sleep deprivation on emotional processing has received considerably less research interest,[5] despite common subjective complaints of associated irritability and reported behavioral volatility.[6,7] This association is also pertinent considering that nearly all psychiatric and neurological mood disorders express co-occurring abnormalities of sleep, suggesting a potential intimate interdependence between sleep and affective brain function. Moreover, the implication of such a relationship becomes particularly germane in the context of interpersonal as well as professional interactions that are predicated on the basis of emotional judgments and decisions,[8] especially when considering the on-going erosion of obtained sleep time across many age ranges (National Sleep Foundation poll 2007: http://www.sleepfoundation.org/).

A commentary on this paper appears in this issue on page 281.

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To our knowledge, there have been few empirical reports investigating the impact of sleep loss on tasks of emotion processing, with the majority of studies utilizing subjective rating scales. Using a sleep restriction paradigm in combination with questionnaire mood scales, Dinges et al.[9] reported a progressive increase in emotional disturbance across a seven-day period. In addition, subjective descriptions in participants' daily journals indicated increasing complaints of emotional difficulties. Zohar et al.[6] examined the effects of sleep disruption on subjective emotional reactions to daytime work events in working medical residents. Sleep loss was shown to increase dysphoria and amplify negative emotional consequences of disruptive daytime events, while blunting the positive benefit associated with rewarding or goal-enhancing activities.

Using objective ratings tasks, several studies have now investigated the effects of sleep and sleep disruption on emotional processing. Pallesen and colleagues reported that the speed and accuracy for rating drawings of emotional facial expressions both deteriorate (slower and less accurate, respectively) following one night of sleep deprivation.[10] Complementing these findings, Wagner et al.[11] demonstrated that the speed of recognizing emotional facial expressions presented prior to sleep significantly improves the next day; a learning benefit that was positively correlated with the amount of intervening REM sleep. Another study by Wagner et al.[12] examined the effect of early versus late night sleep on the ratings of negative emotional pictures. Following sleep (especially late night), valence (representing pleasant or unpleasant) ratings of previously seen negative pictures were found to increase. Furthermore, Lara-Carrasco et al.[13] reported that late night REM sleep deprivation decreases participants' subjective reactivity to previously seen negative emotional pictures.

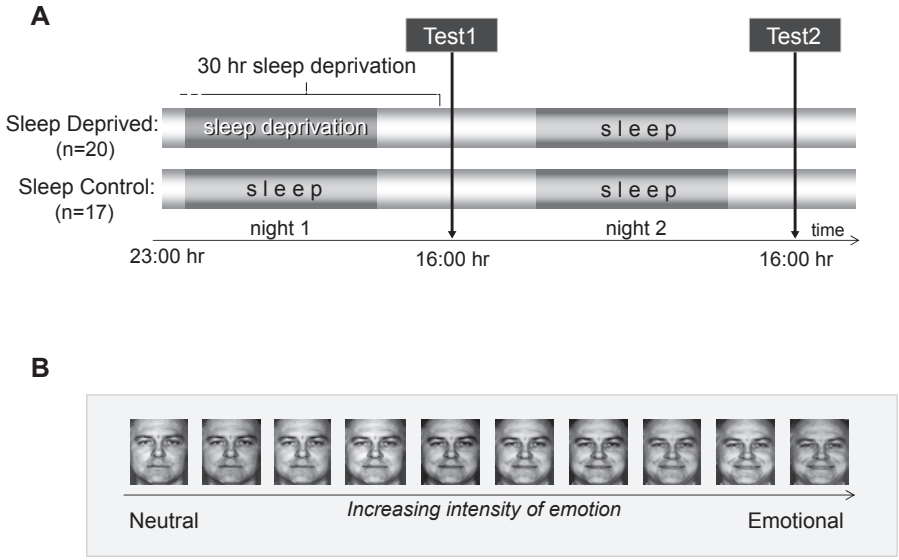

Figure 1—(A) Experimental design: Participants in each group performed the emotional face recognition task twice; once on Day 2 (16:00) and once on Day 3 (16:00). The experimental manipulation occurred across the night before the first test session (Test1). Participants in the sleep control group were awake across Day 1 and slept normally across Night 1 before Test1 on Day 2. Participants in the total sleep deprivation group were similarly awake across Day 1, but were subsequently kept awake across Night 1, and across Day 2 accumulating 30 h of total sleep deprivation prior to Test1. Following Test1, both groups had a normal night of sleep (Night 2), and repeated the same task a second time on Day 3 (Test2). **(B)** Example of the emotional face stimuli gradient used for the affective category HAPPY.

At a physiological level, using functional MRI (fMRI), Yoo et al.[14] demonstrated that one night of sleep deprivation significantly amplifies the human amygdala reaction to increasingly negative and aversive picture stimuli. In addition, this amygdala potentiation was associated with a loss of top-down medial prefrontal connectivity, yet an increased coupling with autonomic activating regions of the locus coeruleus. Most recently, Franzen et al. demonstrated significantly larger pupillary responses to negative emotional pictures compared to positive or neutral stimuli in participants who were sleep deprived,[15] further suggesting an autonomic physiology dysregulation caused by sleep deprivation.

While these studies collectively indicate that sleep loss disrupts aspects of emotional processing, it remains unclear how sleep deprivation impacts the recognition of unique and different types of emotions, which rely on dissociable neural systems.[16] Furthermore, following sleep deprivation, it is unknown whether such impairments can be reversed by recovery sleep, and if so, how quickly. Using a face recognition task, here we examine the impact of one night of total sleep deprivation and subsequent sleep recovery on the ability to identify specific facial emotions.

METHODS

Participants

Thirty-seven healthy participants (21 females) aged 18–25 y (mean 19.7 [SD ± 0.91]) were randomly assigned to the sleep control (SC; $n = 17$, 10 females) or total sleep deprivation group (TSD; $n = 20$, 11 females). Participants abstained from caffeine and alcohol for the 72 h prior to and during the study, and kept a normal sleep-wake rhythm with average sleep duration (7–9 h per night, morning wake time between 06:00-09:00) for the same amount of time. Compliance to this sleep schedule was verified with sleep logs. Exclusion criteria were a history of neurologic, psychiatric or sleep disorders, past history of drug abuse, and current use of antidepressant or hypnotic medications.

Experimental Design

The core experimental protocol is described in Figure 1A, with participants performing an emotional face recognition task (details below) once at 16:00 (± 30 min) on Day 2 and once at 16:00 (± 30 min) on Day 3. The experimental manipulation, differentiating the 2 conditions, occurred across the night before the first test session (Test1). Specifically, participants in the sleep control group were awake across Day 1 and slept normally at home across Night 1 (obtaining a mean of 7.9 h [SD ± 1.6] based on sleep log diaries), before returning for the first test session on Day 2. Participants in the total sleep deprivation condition were similarly awake across Day 1, but were subsequently kept awake in the sleep laboratory under full supervision across Night 1 and across Day 2, accumulating a mean of 30.9 h (SD ± 1.4) of total sleep deprivation prior to Test1. During this time, subject activities were limited to using the internet, short walks, reading and playing board games, providing a standardized regimen of waking activity across the deprivation period.

Following Test1, both groups returned home to sleep the following night (Night 2), and repeated the same task a second time on Day 3 (Test2). This offered an evaluation of recovery sleep on task performance in the deprivation group, and an evaluation of test performance consistency and repeatability in the control group. Across this recovery night (Night 2), participants in the deprivation group obtained a mean of 13.5 h (SD ± 3.2) sleep, while those in the control group obtained a mean of 8.1 h (SD ± 1.3), based on sleep log diaries. Prior to each of these two tests, all participants completed the Stanford Sleepiness Scale; a standard measure of subjective alertness ranging across a 7-point scale (1 being most alert[17]). As expected, participants in the sleep deprivation group indicated significantly higher levels of sleepiness (lower scores) at Test1 (mean 5.4, SD ± 0.9) than following the recovery night of sleep at Test2 (mean 2.0, SD ± 0.9; $t_{19} = 2.09$, $P < 0.001$). In contrast, the control group did not differ in their sleepiness ratings on Test1 (mean 2.4, SD ± 1.1) compared to Test2 (mean 2.8, SD ± 1.6; $t_{16} = 2.12$, $P = 0.37$).

Although there is now substantive evidence for the restoration of certain brain and body functions following total sleep deprivation, ranging from 1 to 14 days of recovery,[2,18] there is currently less knowledge on recovery rates for the restitution of

mood and emotional brain reactivity following acute sleep deprivation. Therefore, in the event that a single night of recovery sleep may not have been sufficient to restore task performance, we also tested participants in the TSD group a third time (Test3; not shown in Figure 1) following a more conservative recovery period of three weeks (mean 22.9 [SD ± 5.1] days).

Task

The experimental task involved evaluating three different affective face categories: Sad, Angry and Happy. Black and white photographs of the same male individual expressing happy, sad, angry, and neutral faces 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 3 emotional pictures were morphed to the neutral face of the same individual using a series of 8 equal gradient steps using a face-morph software tool *(Morph 2.5),* resulting in 10 separate images for each of the 3 emotions, incrementally increasing in their relative degree of affect intensity (Figure 1B). 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-inch 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 being 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—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, one 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 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. Following the keyboard response, the next trial began. After rating all 10 pictures, subjects repeated the same process for the remaining two 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. The order of presentation for each emotional category was randomized across participants, and, within participants, randomized across each of the 2 sessions.

Behavioral response data were assessed at 2 different levels: (1) mean ratings across the 10 trials at Test1 and at Test2, for each emotion separately, and (2) 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 sliding window approach was implemented across the picture gradient, averaging the rating scores of two 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 trial 9-10. Comparisons principally focused on within-subject, between-test measures of performance, due to the known inter-subject variability in emotional reactivity and mood disposition.[19]

Statistical analyses were calculated using within- and between-group analysis of variance (ANOVA) models, together with post hoc within- and between-group comparisons calculated using paired and unpaired two-tailed *t*-tests, respectively. All analyses were performed using the software program JMP v8.0 (SAS).

RESULTS

Emotions Combined

Before evaluating each emotion separately, we first combined data across the three affective categories to examine the overall influence of sleep deprivation on emotional face rating. For the total sleep deprivation group, marked differences in affective face judgment emerged. Specifically, under conditions of sleep deprivation at Test1, ratings were significantly blunted (lower) compared to performance following recovery sleep at Test2 (Figure 2, upper left panel bar graphs; paired *t*-test, $t_{19} = 2.09$, $P < 0.005$). Moreover, when separated across the affective spectrum, it was apparent that this recognition deficit escalated as the emotional gradient increased (Figure 2, upper left panel line graphs; significance values provided in figure), with the exception of the most extreme picture slides. Therefore, rather than imposing a consistent impairment on the processing of basic face perception, sleep deprivation was associated with a more selective deficit, disrupting the ability to identify expressions of moderate and strong emotional salience, and not neutral affect.

In contrast to the differences in task performance in the total sleep deprivation group, in the control group that slept each night prior to testing, there was neither a significant change in the overall mean rating at Test1 compared with Test2 (Figure 3, upper left panel bar graphs; paired *t*-test, $t_{16} = 2.12$, $P = 0.39$), nor when separated using the sliding window analysis across trials, from neutral to increasingly emotional (Figure 3, upper left panel line graphs; significance values provided in figure). Thus, general emotional recognition performance (across all 3 affective categories) was stable and consistent at the first (Test1) compared to second (Test2) assessments in participants that slept before both tests. We next evaluated the 3 emotions separately; *Happy*, *Angry* and *Sad* within the total sleep deprivation and sleep control groups.

Emotions Separated: Total Sleep Deprivation Group

Within the total sleep deprivation group, for Test1 and Test2, a repeated measures ANOVA investigating the effects of Test Session (Test1, Test2), Emotion (Happy, Angry, Sad) and their interaction, revealed a main effect of Test Session (Test1 sleep deprived vs. Test2 sleep recovered; $F = 7.81$; $P = 0.006$) a trend towards a significant main effect of Emo-

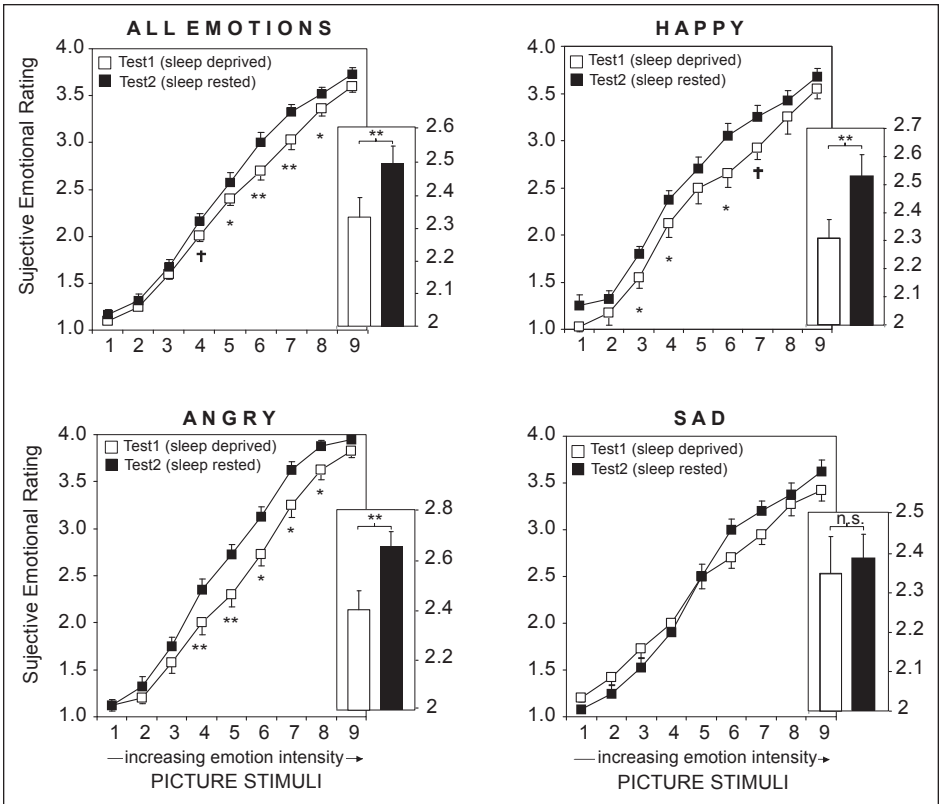

Figure 2—Emotional face recognition performance in the total sleep deprivation group. Upper left panel: Average rating of face stimuli across all three emotional categories (ANGRY, HAPPY, SAD) combined at Test1 (clear bar, when sleep deprived) and Test2 (filled bar, when sleep recovered), together with response curves at Test1 (clear squares, when sleep deprived) and Test2 (filled squares, when sleep recovered) for the rating of the faces stimuli when plotted across the emotional intensity gradient, from low to high (left to right). Remaining panels are mirror data for each of the emotions separately, labeled respectively on each panel.
†P < 0.08; *P < 0.05; **P < 0.01; n.s. Nonsignificant. Error bars represent standard error of the mean.

tion (F = 2.53; P = 0.084), and no Emotion by Test Session interaction (F = 1.25, P = 0.29). Analyses within each emotion revealed further significant differences within the total sleep deprivation group.

Happy Faces: Under conditions of sleep deprivation there was a significant impairment in the ability to recognize happy facial expressions, being significantly lower (blunted) compared to performance following sleep recovery at Test2 (Figure 2, upper right panel bar graphs; paired t-test, t_{19} = 2.09, P < 0.01). Moreover, when separated across the affective spectrum, it was apparent that this recognition deficit emerged in the mid-spectrum range, as the expressions became emotionally ambiguous (Figure 2, upper right panel line graphs; significance values provided in figure).

Angry Faces: As with the emotion Happy, a marked and even stronger blunting in emotional recognition for the emotion Angry was observed under conditions of sleep deprivation at Test1 (Figure 2 lower left panel bar graphs; paired t-test, t_{19} = 2.09, P < 0.002). Furthermore, as the faces became progressively emotional, this impairment became increasingly amplified (Figure 2, lower left panel line graphs; significance values provided in figure).

Sad Faces: In contrast to the differences found for the facial expressions of Anger and Happy (both emotions of high autonomic arousal[20]), no significant impact of sleep deprivation was observed for the recognition of the emotion Sad (an emotion eliciting lower autonomic activation), with equivalent mean scores at Test1 and Test2 (Figure 2, lower right panel bar graphs; t_{19} = 2.09, P = 0.67). This was similarly true when separating responses across the affective gradient (Figure 2, lower right panel line graphs; significance values provided in figure).

Emotions separated: Control group

Within the control group, a repeated measures ANOVA investigating the effects of Test Session, Emotion, and their interaction, revealed no effect of Test Session (F = 0.487; P = 0.487), a main effect of Emotion (F = 5.28; P = 0.007), and no Emotion by Test Session interaction (F = 0.238, P = 0.79).

Evaluating the 3 emotions separately confirmed this lack of significant difference between Test1 and Test2 (paired t-tests $t_{16} \leq 2.12$ Happy: P = 0.41; Angry: P = 0.41; Sad: P = 0.85 as depicted in the bar graphs in Figure 3), and no significant differences were identified across the emotional gradient for any of the 3 emotions (Figure 3 line graphs; significance values provided in figure). Thus, emotional recognition performance remained consistent from Test1 to Test2 in participants who slept before both tests, supporting the observation that differences in the total sleep deprivation group could not be explained by repeated test exposure.

Sleepiness and Emotion Recognition

To further investigate whether subjective sleepiness was associated with affective face recognition, correlations were performed between the mean emotion ratings for each of the 3 categories (Sad, Angry, Happy) and participants' Stanford Sleepiness Scale scores, at both Test1 and Test2. Within the total sleep deprivation group, none of these 6 correlations were significant, all being $r^2 \leq 0.38$, P ≥ 0.10. Similarly, within the control group, all equivalent correlations were $r^2 \leq 0.21$, P ≥ 0.40, except for the emotion Anger at Test2, which resulted in an r^2 = 0.55, P = 0.03. However, this correlation did not survive a Bonferroni correction for multiple tests ([α / n tests = 0.05/6], resulting in a critical P-value of < 0.008). Therefore, with the exception of a statistical trend for one emotion category within the control group at one of the test sessions, the level of subjective sleepiness did not appear to demonstrate a strong, consistent relationship with emotion recognition task performance.

Considerations of Sleep Deprivation and Sleep Recovery

An alternate potential interpretation of the differences identified in the total sleep deprivation group may pertain to the effects of recovery sleep (Test2), rather than sleep loss (Test1).

That is, the differences observed in the total sleep deprivation group could be attributable to excess sleep on the recovery night, potentially amplifying emotional recognition at Test2, rather than sleep deprivation impairing emotional recognition at Test1. To investigate this possibility, subjects in the deprivation group returned to the laboratory for further testing approximately three weeks later. Contrary to the hypothesis of recovery sleep amplifying differences observed in the Test1-Test2 comparison, performance at this three-week session ("Test3") was similar to that following recovery sleep (Test2) for both the emotions Angry and Happy (Table 1), and was even statistically greater for Sad. Furthermore, performance at Test3 continued to show statistically significant, or trends towards significant, differences relative to Test1 (Table 1). Therefore, the comparative differences between Test1 (sleep deprived) and Test2 (sleep rested) appear to reflect a relative impairment in emotional processing at Test1 due to sleep deprivation, rather than an effect due to recovery sleep at Test2.

Taken together, these data suggest that one night of total sleep deprivation disrupts the recognition of some, but not all, emotional facial expressions, and within the moderate range of expressed emotion. Specifically, moderate affective expressions associated with high emotional arousal—Anger (threat relevant) and Happy (reward relevant)—demonstrated greater sensitivity to disruption under conditions of sleep loss than those of low arousal strength (Sad).

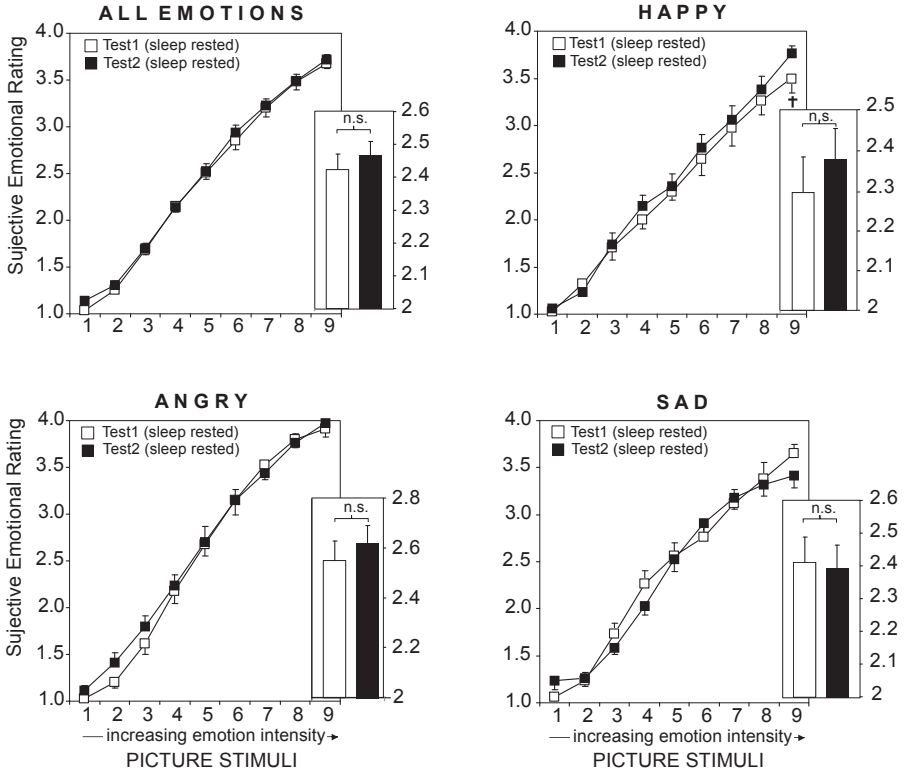

Figure 3—Emotional face recognition performance in the sleep control group. Upper left panel: Average rating of face stimuli across all three emotional categories (ANGRY, HAPPY, SAD) combined at Test1 (clear bar) and Test2 (filled bar) and response curves at Test1 (clear squares) and Test2 (filled squares) for the rating of the faces stimuli when plotted across the emotional intensity gradient, from low to high (left to right). Remaining panels are mirror data for each of the emotions separately, labeled respectively on each panel.
†P < 0.09; n.s. Nonsignificant. Error bars represent standard error of the mean.

Table 1—Average response scores (mean ± SEM) in the total sleep deprivation group across Test1, Test2, and Test3.

Emotion	Test1	Test2	Test3	Test1 vs. Test3	Test2 vs. Test3
Happy	2.31 ± .06	2.53 ± .08	2.48 ± .08	P < 0.07	P = 0.93
Angry	2.41 ± .08	2.66 ± .06	2.56 ± .06	P < 0.08	P = 0.22
Sad	2.35 ± .09	2.39 ± .06	2.54 ± .09	P < 0.01	P = 0.04

Gender Differences

Within the context of sleep disorders, emerging evidence suggests the presence of gender differences in the rates of depression, with females being particularly sensitive to the interaction of mood disorders and sleep abnormalities.[21,22] Considering this association, in an exploratory analysis, we reexamined our findings on the basis of gender. Consistent with previous clinical reports, female participants in the total sleep deprivation condition (n = 11) expressed marked and significant blunting in the recognition of both emotions that were impaired at the overall group level (Anger and Happy, with no significant effect observed for Sad, Table 2A). In contrast, these comparisons were nonsignificant in male participants under conditions of sleep deprivation. It should be noted, however, that mean values were somewhat similar between genders, yet the variance was greater in male participants. No significant gender differences were observed in the sleep rested control group (Table 2B). Therefore, the differences in emotion rating in the sleep deprived participants at an overall group level appear to be one expressed most consistently and significantly in female participants, supporting the hypothesis of gender specific sensitivity to sleep disruption within the domain of affective brain function.[21,22]

DISCUSSION

Using an affective face recognition task, here we demonstrate that a single night of sleep deprivation significantly disrupts the ability of the human brain to accurately identify salient emotional expressions in others, particularly in the moderate intensity range of emotion. In addition, these deficits were specific to some but not all affective categories, being most dramatic for emotions eliciting high autonomic arousal—Angry and Happy—corresponding to greatest threat relevant and reward relevant value, respectively. Furthermore, when separated by gender, the influence of sleep deprivation on emotion recognition was observed most reliably and significantly in female participants.

Table 2A—Response scores of total sleep deprivation group by gender

Gender	Emotion	Test1	Test2	Test1 vs. Test2
Females	Angry	2.41 ± 0.06	2.64 ± 0.07	P = 0.01
	Happy	2.37 ± 0.07	2.56 ± 0.09	P = 0.03
	Sad	2.41 ± 0.09	2.46 ± 0.05	P = 0.63
Males	Angry	2.4 ± 0.15	2.63 ± 0.10	P = 0.14
	Happy	2.23 ± 0.12	2.50 ± 0.12	P = 0.09
	Sad	2.30 ± 0.18	2.29 ± 0.12	P = 0.93

Average response scores (mean ± SEM) in the total sleep deprivation group, separated by gender. Subjects were sleep deprived during Test1 and sleep recovered during Test2. The last column gives P-values for *t*-tests comparing scores from Test1 versus Test2.

Table 2B—Response scores in sleep control group by gender

Gender	Emotion	Test1	Test2	Test1 vs. Test2
Females	Angry	2.63 ± 0.08	2.64 ± 0.07	P = 0.92
	Happy	2.21 ± 0.11	2.42 ± 0.09	P = 0.13
	Sad	2.44 ± 0.08	2.31 ± 0.11	P = 0.34
Males	Angry	2.44 ± 0.15	2.56 ± 0.13	P = 0.45
	Happy	2.41 ± 0.12	2.36 ± 0.15	P = 0.59
	Sad	2.40 ± 0.14	2.50 ± 0.07	P = 0.32

Average response scores (mean ± SEM) in the sleep control group, separated by gender. Subjects were sleep rested during both Test1 and Test2. The last column gives P-values for *t*-tests comparing scores from Test1 versus Test2.

Impact of Sleep Deprivation

It has been argued that facial expressions are the most biologically and socially significant visual stimuli in the human environment. Facial expressions have the ability to code numerous salient and motivational cues ranging from basic primary emotions to more complex informational signals, such as trustworthiness and even the intent of others.[8,16] The critical contribution made by facial recognition to optimal human behavior is exemplified by conditions of abnormal affective processing. For example, neurological patients who suffer from an inability to recognize certain emotions due to lesions in key extended limbic or prefrontal regions display marked social dysfunction, being unable to detect and subsequently be guided by relevant affective cues.[23] Developmental disorders such as autism provide additional evidence for impaired social interaction due to abnormal face processing, particularly expressions carrying emotional significance.[24]

Here we add to this collection of circumstances in which emotional face recognition is significantly disrupted: the condition of sleep deprivation. However, unlike the disorders described above, which express affective dysregulation due to structural brain abnormalities, the impact of acute sleep deprivation is, presumably, largely functional in nature, indicating there are additional circumstances, beyond substantive pathology, which can result in affective recognition deficits. Considering that 1) impairments imposed by sleep deprivation were observed for some but not all emotions, 2) these deficits only became evident as the emotion gradient increased to moderate intensity levels, where facial affect is more ambiguous, and 3) these changes dissipated towards the extremities of the emotion gradient, it would suggest that basic aspects of facial perception (early stage processing) are likely intact under conditions of sleep deprivation, at least in the current task. Rather, the progressive impairment within the mid-emotion spectrum range would suggest processing deficits down-stream of initial perceptual coding regions, being more associated with subsequent emotional evaluation and judgment.

Independent of objective changes in emotion reactivity, several reports to date have described the progressive dysregulation of subjective mood state following accumulated sleep loss,[9] amplifying negative mood states to disruptive daytime experiences, while reducing positive mood benefits associated with goal-enhancing activities.[6] Interestingly, mood and emotion have been conceptualized as representing related yet dissociable processes; the former reflecting an evaluation of internal state, that is more long lasting, the latter concerned with reactivity to evoking stimuli (external or internal), which are often short lived.[25] While no measure of subjective mood was assessed in the current study, understanding how sleep-associated changes in mood may contribute to alterations of emotion, such as face recognition, represents a fertile area for future investigations.

Direction of effect

Based on a recent report indicating that the human amygdala becomes hyper-reactive to increasingly negative stimuli under conditions of sleep deprivation,[14] it is perhaps surprising to find a blunting in emotional face recognition stimuli (including the emotion Angry) in similarly sleep deprived individuals. However, a number of findings are worth considering in this context.

First, amygdala activity has been more consistently associated with the emotion Fear (a category not tested in this study) than Anger; hence an amplified reaction to Angry or Sad faces when sleep deprived is not necessarily predicted. Instead, the emotion Anger has been more consistently associated with activation in regions of the basal ganglia, orbitofrontal cortex (OFC), and anterior cingulate cortex (ACC).[26] Moreover, neuropsychological studies indicate impaired recognition of Anger following lesions in the ventral basal ganglia.[27] Similarly, activation in ACC has been observed during the induction and evaluation of the emotion Happy, together with regions of the ventral prefrontal cortex,[28] yet these regions were not recruited significantly for the emotion Sad.

Second, the involvement of the ACC regions in processing Angry and Happy faces (in addition to Fear), but not Sad or neutral faces, may relate to the roles these areas play in the regulation of arousal: Anger and, to a lesser degree, Happiness are considered to involve a higher autonomic state of activation than Sadness.[29] Thus, ACC (and perhaps OFC) activation during the recognition of highly arousing emotional face stimuli may reflect the subject's own arousal elicited either in response to or in a mirroring of the emotion. If disrupted, the capability of this medial prefrontal system to accurately code and consequently rate stimuli that elicit stronger autonomic arousal would become impaired.

Consistent with this hypothesis, previous PET studies have demonstrated that regions of the medial prefrontal cortex, including the ACC, are amongst those most significantly impaired in their activity following sleep deprivation.[30,31] Furthermore, together with alterations in amygdala activity in response to

negative stimuli, significant reductions in associated medial prefrontal functional connectivity have been reported under conditions of sleep deprivation.[14] This susceptibility of the prefrontal lobe to sleep deprivation—including ACC regions involved in the evaluation and modulation of affective states—may offer an explanatory neural basis for the inability of subjects in the current study to accurately judge emotional expressions involving autonomic arousal. Indeed, due to these neural impairments, it is interesting to speculate that the ability of the sleep deprived brain to either represent or cogently mirror emotions of others would be diminished, which, as a consequence, would negate the appreciation and accurate rating of facial expressions.

The results of the delayed test (Test3; 3 weeks) also support the possibility that performance following one night of recovery sleep may still carry residual impairment from the sleep deprivation night. While remaining preliminary, such findings may indicate that the restitution of emotional brain function following acute total sleep deprivation requires more than one recovery night for restoration back to baseline abilities, similar to certain measures of cognition.[2]

Gender Differences

There is now a substantial literature indicating that females are at greater risk for developing major depression than males, post-puberty, and that this increased probability may be associated with co-occurring differences in sleep architecture.[21,22] Here we demonstrate that, in participants without preexisting mood disorders, sleep deprivation similarly imposes a more significant and reliable impairment in identifying emotion intensity in female compared to male participants. Such findings may indicate that healthy young females have a greater degree of sensitivity to the effects of sleep loss in the context of affective dysregulation, consistent with reported trends in clinical mood disorders.[21,22]

The underlying neurobiological basis for these gender effects continues to be examined, with the influence of different sex steroids and their consequential effects on down-stream neurotransmitter concentrations being particularly relevant.[21] Furthermore, based on gender differences in neurochemistry, it has been argued that women show a greater homeostatic sleep sensitivity and drive than men, such that small reductions in sleep amount, or even a delay-shift in the onset of sleep, triggers a stronger sleep rebound in females than males, especially for slow-wave sleep.[21] This same sensitivity may explain the more consistent effect imposed by sleep loss in our females subjects. Indeed, our findings indicate that this sensitivity can similarly be observed in measures of emotional reactivity in addition to physiological sleep changes, such as homeostatic drive.

Ecological Relevance

The current findings offer implications at both societal as well as professional levels. Social interactions are critically guided by, and indeed are predicated on the basis of, accurately recognizing emotional facial expressions. Only through such accurate recognition can cogent social judgments and subsequent actions be made. Furthermore, considering that sleep time continues to show a decrease across many age ranges, the relevance of the current findings become increasingly pertinent (National Sleep Foundation poll 2007: http://www.sleepfoundation.org/). Nowhere are these accurate emotional face judgments (which require reciprocal affective and empathetic evaluations and behaviors) more critical than in many professions that are associated with sleep curtailment, including emergency and resident medical staff, military personnel, and even new parents. Based on the emerging results indicating an intimate link between sufficient prior sleep and appropriate next day affective regulation,[5] a greater appreciation of the importance of sleep in beneficially modulating emotional reactivity and stability at a social, professional and mental health level appears increasingly necessary.

Study Limitations

Our findings should be appreciated within the context of a number of important limitations. First, no assessment of participant's chronotype was performed in this cohort of young adults. Delayed sleep phases are becoming increasingly common in adolescence and early adulthood, and this may be especially so in young males.[32-34] Such changes may have contributed to the observed gender differences reported here, reflected in greater variance of impairment observed under conditions of sleep deprivation in male participants. Considering chronotype is also known to modulate cognitive performance,[35] rather than testing all participants at a fixed clock time, as performed in the current study (16:00), an alternative and interesting future methodological approach will be to evaluate subjects based on their respective chronotype schedule.

A second study limitation concerns the lack of measured task motivation and/or interest.[36,37] Decreased motivation, independent of general sleepiness, may represent an additional influencing factor in the current study, such that if the task were made more engaging, the observed performance decrements in the deprivation group would be obviated. Although we cannot exclude this possibility, we do note, however, two features of our results that suggest a lack of motivation or interest are less parsimonious explanations; 1) the emotional blunting in the total sleep deprivation group was principally observed only in one portion of the emotion spectrum (middle sections, where faces were more ambiguous). A general lack of motivation or interest would predict blunting to be observed more ubiquitously across emotion stimulus gradient. Furthermore, the stimuli were presented in a random order within and across subjects, controlling for a possible time-on-task effects. Also, 2) the emotional blunting was only apparent for the emotion categories of Anger and Happy, and not for Sad. A motivation or interest explanation would perhaps predict ubiquitous impairments across all categories. Therefore, the specificity and selectivity of impairment, both within and across emotion categories, supports a more discreet affective dysregulation, rather than a general motivation contribution.

A third study limitation is the lack of objective measures verifying compliance with sleep duration and sleep-wake times (e.g., actigraphy, polysomnography), as well as sleep deprivation. The addition of physiological verification of sleep-wake parameters in future studies will help improve homogeneity of study compliance, potentially reducing variability in task performance across subjects, particularly in the sleep-deprived condition.

A final cautionary consideration is the potential contribution of learning effects. Although the current task was not designed

to assess memory, the process of facial recognition and rating has the potential to be affected by prior task exposure. We did not observe learning effects in the control group, evidenced by the lack of significant differences between Test1 and Test2 performance. This would suggest a degree of repeatability that is independent of learning effects, although it does not discount the possibility. However, at Test3 in the sleep deprivation group, relative to Test1 performance (both sleep-rested measures), we did observe a significant difference in one of the three emotion categories—Sad. This may suggest that with multiple task exposures (e.g., > 2), there are potential learning related contributions to changes in performance for some emotions. Future repeated measures experiments would substantially benefit from the use of a counter-balanced crossover design, which would control for such learning related effects, unlike the current study protocol.

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DISCLOSURE STATEMENT

This was not an industry supported study. Dr. Walker has consulted for Actelion and has participated in a speaking engagement for Sanofi-Aventis. The other authors have indicated no financial conflicts of interest.

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