Sleep Deprivation Elevates Expectation of Gains and Attenuates Response to Losses Following Risky Decisions

Vinod Venkatraman, MEng1,2; YM Lisa Chuah, PhD1; Scott A. Huettel, PhD2,3; Michael WL Chee, MBBS, MRCP(UK)1,2

1Cognitive Neuroscience Laboratory, Duke-NUS Graduate Medical School, Singapore; 2Brain Imaging and Analysis Center and 3Center for Cognitive Neuroscience, Duke University, Durham, NC

Study Objectives: Using a gambling task, we investigated how 24 hours of sleep deprivation modulates the neural response to the making of risky decisions with potentially loss-bearing outcomes.

Design: Two experiments involving sleep-deprived subjects were performed. In the first, neural responses to decision making and reward outcome were evaluated. A second control experiment evaluated responses to reward outcome only.

Participants: Healthy right-handed adults participated in these experiments (26 [mean age 21.3 years] in Experiment 1 and 13 [mean age 21.7 years] in Experiment 2.)

Measurements and Results: Following sleep deprivation, choices involving higher relative risk elicited greater activation in the right nucleus accumbens, signifying an elevated expectation of the higher reward once the riskier choice was made. Concurrently, activation for losses in the insular and orbitofrontal cortices was reduced, denoting a diminished response to losses. This latter finding of reduced insular activation to losses was also true when volunteers were merely shown the results of the computer’s decision, that is, without having to make their own choice.

Conclusions: These results suggest that sleep deprivation poses a dual threat to competent decision making by modulating activation in nucleus accumbens and insula, brain regions associated with risky decision making and emotional processing.

Keywords: Functional neuroimaging, risk taking, decision making, nucleus accumbens, orbitofrontal cortex

Citation: Venkatraman V; Chuah YML; Huettel SA et al. Sleep deprivation elevates expectation of gains and attenuates response to losses following risky decisions. SLEEP 2007;30(5):603-609

SLEEP DEPRIVATION HAS GROWN INCREASINGLY COMMON IN DEVELOPED COUNTRIES.1 LACK OF ADEQUATE SLEEP IMPAIRS VIGILANCE, FLEXIBLE THINKING, working memory, and executive functioning.2-5 These cognitive changes may combine to impair the ability to make favorable decisions under conditions of risk.

Understanding why we make poorer decisions when sleep deprived is important, not only because of the increasing numbers of persons affected, but also because of unprecedented opportunities to incur damaging losses by means such as online gambling.6 Indeed, sleep-deprived participants have been shown to choose higher-risk decks and exhibit reduced concern for negative consequences when performing a variant of the Iowa Gambling Task.3,7 Well-rested participants learn to avoid high-risk decks and to choose from the advantageous decks, but sleep-deprived participants tend to continue to choose from the risky decks as the game progresses.3,7

Two aspects of decision making are particularly likely to be affected by sleep deprivation: the ability to ascertain risk as well as the ability to learn emotionally from the consequences of decisions.8 The former involves harnessing prior knowledge of potential rewards and their valuation to make decisions and involves activation of the dorsolateral prefrontal cortex and the striatum.9 The effects of sleep deprivation on dorsolateral prefrontal cortex activation in non-gambling tasks have been well characterized. They vary with task10,11 as well as across individuals,12,13 with relatively preserved task performance being associated with either higher activation15,16 or only modest activation decline.14 In contrast, the effect of sleep deprivation on the engagement of striatal regions remains unexplored. Work to date on healthy, non-sleep-deprived adults suggests that the ventral striatum participates in both the anticipation and the receipt of reward,17,18 whereas the dorsal striatum has been associated with the processing of experienced reward magnitude and valence.19

Recent findings suggest that emotion also plays an important role in decision making.20 As an example, choices made in a gambling task after 49 hours of sleep deprivation are similar to those of patients with lesions in the ventromedial prefrontal cortex,7 a brain region (in conjunction with the neighboring orbitofrontal cortex) that is associated with emotional experiences of gains and losses.9 Work involving a non-gambling task has also shown reduced glucose metabolism in the orbitofrontal region following sleep deprivation,21 but the link between risky behavior following loss of sleep and orbitofrontal engagement has not been explicitly demonstrated.

In Experiment 1, we characterized the effect of sleep deprivation on putative substrates for risk-reward ascertainment (dorsolateral prefrontal cortex and striatum), as well as emotional learning (ventral and orbitofrontal cortex), using a gambling task (Figure 1a). Only a few gambling experiments involving functional magnetic resonance imaging have evaluated decision making, anticipation, and reward processing concurrently,22,23 and none of those have used a sleep deprivation manipulation.

We separated decision and reward phases of the task in Experiment 1, but a potential concern was that the relatively slow evolution of the BOLD response could cause activation associated with decision making to influence the peristimulus baseline in the reward phase. A further concern in Experiment 1 was a limited number of loss trials, particularly for the risk-averse individu-
als. To alleviate these concerns, we ran a second experiment that involved the presentation of passive gambles in which decision making was rendered unnecessary by having the computer make predetermined choices (consisting of equal number of losses and gains; Figure 1b).

METHODS

Participants

Twenty-six right-handed, healthy adults (12 women, mean age = 21.3, SD = 1.6 years) participated in Experiment 1 and a further 13 adults (3 women, mean age = 21.7, SD = 1.5 years) participated in Experiment 2. Wrist actigraphy was used to monitor the sleeping habits of the participants over the duration of the study (approximately 2 weeks). The actigraphy data of all the participants indicated habitually good sleep (ie, they usually went to sleep no later than 1:00 AM and woke no later than 9:00 AM). Participants refrained from smoking and did not ingest medications, stimulants, caffeine, or alcohol for at least 24 hours prior to scanning. The study was approved by the Singapore General Hospital Institutional Review Board, and informed consent was obtained from all participants.

Study Procedure

Participants visited the laboratory 3 times. They first attended a briefing session during which they were informed of the study protocol and requirements and were practiced on the study task. At the end of this session, every participant was given an actigraph to wear throughout the study. The first scanning session took place approximately a week later. The order of the 2 sessions (rested wakefulness and sleep deprivation) was counterbalanced across all the participants and separated by 1 week. This was to minimize the possibility of residual effects of sleep deprivation on cognition for those participants whose sleep-deprivation session had preceded their rested-wakefulness session.24 The rested-wakefulness session took place at 8:00 AM. For the sleep-deprivation session, participants were monitored in the lab from 6:30 PM onward, and scanning took place the next day at 7:00 AM. During the sleep-deprivation session, participants were allowed to engage in non-strenuous activities such as reading and watching videos.

Experiment 1: Procedure

Three gamble types (Certain, Low-Risk and High-Risk) were arranged in 2 possible pairings: Certain/Low-Risk and Low-Risk/High-Risk. All gambles were depicted on a pie chart in 2 neutral colors (brown and light green), highlighting the contrast between the 2 options in a risky gamble. A Certain gamble was associated with a 100% chance of winning the indicated sum. Risky gambles consisted of a choice between 2 rewards associated with paired probabilities of 25% and 75% or 50% and 50%. Volunteers always stood to gain in a Low-Risk gamble, whereas a High-Risk gamble involved the pairing of a loss with a significantly higher reward.
The reward magnitude in a risky gamble was determined by taking into account the associated probabilities. The expected values were only approximately matched between the 2 pairs of gambles presented in individual trials, but they were balanced across all trials in the experiment. The reward values varied between $4 and $30 for Certain gambles (mean expected value = $15), between $2 and $40 for Low-Risk gambles (mean expected value = $16 in Certain/Low-Risk pairs and $15 in Low-Risk/High-Risk pairs), and between $30 and $70 for High-Risk gambles (mean expected value = $14). No trial was repeated within a session, but the same gamble pairs were used in both sessions.

Each session consisted of 6 runs. Each run started with a 15-second fixation interval, the first 10 seconds of which was discarded to allow for attainment of a steady state of scanner magnetization. Each run consisted of 10 trials of each of the 3 experimental conditions and lasted a total of 305 seconds. At the beginning of each trial, 2 gambles were presented, and subjects had to choose 1 of them by pressing the appropriate button on the response box within a 5-second interval (Figure 1). A ball then appeared on each of the gambles and spun along the circumference of the circles for 1.5 to 6.5 seconds. The payout on each of the gambles was determined according to where the ball stopped. A text message then appeared, stating the amount won, as well as what would have been won had the alternative decision been taken. This message appeared for 1 second and was replaced by a variable (1.5, 4, or 6.5 seconds) inter-trial fixation interval. All 20 trial types were randomized within each run for each session and for each subject. After 20 trials (or 290 seconds from onset of the run), a fixation cross appeared and remained till the end of the run.

In the event that the subject failed to respond within 5 seconds, the trial was classified as a lapse. In such an event, the balls proceeded to spin, and messages indicating potential earnings for each gamble appeared. Across the entire cohort, there were a total of 20 such trials during the rested-wakefulness session and 28 such trials following sleep deprivation. These lapse trials were modeled as separate nuisance predictors but were not analyzed.

**Experiment 2: Procedure**

In our analysis of imaging data from the first experiment, we found that interesting differences in the neural responses to different gamble outcomes manifested as negative deflections relative to baseline. To evaluate the possibility that this was a result of inadequate temporal separation of the BOLD response to the decision-making and reward-outcome phases of the trials, we modified the original experiment to capture the effects of reward processing while omitting decision making.

Each trial involved the presentation of a single Certain or a High-Risk gamble (Figure 1b). Subjects were instructed to respond to every gamble by pressing a single button as soon as the gamble appeared, thus maintaining a motor-response requirement but eliminating the decision phase. Following a response, a ball appeared and spun around the gamble for the remaining part of the current TR. The predetermined outcome of each trial, selected at random, was presented as a 1-second text message. Inter-trial intervals (fixation) varied between 1.5 to 6.5 seconds. Twenty trials of the Certain gamble and 40 trials of the High-Risk gamble, half of which resulted in losses and the other half in gains, were presented. These trials, with the same range of reward values as used for Experiment 1, were presented over 2 runs in each state.
RESULTS

Experiment 1: Behavioral Results

A 4 (decision: Certain/Low-Risk, Certain/Low-Risk, Low-Risk/High-Risk, Low-Risk/High-Risk) by 2 (state: rested wakefulness, sleep deprivation) repeated-measures ANOVA on reaction times revealed significant main effects of decision ($F_{1,25} = 20.1, P < 0.001$) and state ($F_{1,25} = 7.69, P = 0.01$) but no interaction ($F_{1,25} = 1.77, NS$). Participants took longer to make decisions following sleep deprivation (Table 1). Subjects also took less time to choose the Low-Risk option in both gamble pairs, indicating that this was the default option for most decisions.

We defined risk preference for each session as the number of times that the participant selected the riskier options: Certain/Low-Risk, Low-Risk/High-Risk. There was no significant difference in risk preference between the 2 states. Subjects earned an average bonus of $35.50 (SD = $6.71) for the rested-wakefulness session and $35.70 (SD = $10.08) for the sleep-deprivation session.

Experiment 1: Neural Correlates of Decision Making

Consistent with other studies, decision making in both states activated a common network of regions. This included bilateral activation of dorsolateral prefrontal cortex, anterior insula, precentral gyrus, thalamus, anterior cingulate cortex, intraparietal sulcus, and inferior parietal lobule. A 4 (decision) by 2 (state) repeated-measures voxel-by-voxel ANOVA revealed significant effects of risk in the bilateral nucleus accumbens, anterior insula and right caudate (greater activation for risky compared to conservative decisions, Figure 2a) and significant effects of state in the right nucleus accumbens and dorsal anterior cingulate (greater activation following sleep deprivation). Posthoc tests of nucleus accumbens activation showed that there was significantly greater activation following sleep deprivation only for riskier decisions (Figures 2b and 3; Table 2).

Contrary to some prior studies, sleep deprivation did not

Table 1—Reaction times of decisions and the percentage of risky decisions made for each gamble type during normal sleep and following sleep deprivation

<table>
<thead>
<tr>
<th></th>
<th>Normal Sleep</th>
<th>Sleep Deprivation</th>
<th>t-value (Sig.)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Reaction Time, ms</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Certain/Low-Risk</td>
<td>1660 ± 362</td>
<td>1827 ± 390</td>
<td>2.54 (.018)</td>
</tr>
<tr>
<td>Certain/Low-Risk</td>
<td>1509 ± 382</td>
<td>1636 ± 454</td>
<td>2.98 (.006)</td>
</tr>
<tr>
<td>Low-Risk/High-Risk</td>
<td>1745 ± 441</td>
<td>1777 ± 452</td>
<td>0.89 (NS)</td>
</tr>
<tr>
<td>Low-Risk/High-Risk</td>
<td>1821 ± 518</td>
<td>1946 ± 568</td>
<td>2.13 (.043)</td>
</tr>
<tr>
<td>Percentage of Risky Choices, %</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Certain/Low-Risk</td>
<td>65.51 ± 13.1</td>
<td>68.91 ± 14.0</td>
<td>1.53 (NS)</td>
</tr>
<tr>
<td>Low-Risk/High-Risk</td>
<td>41.98 ± 14.8</td>
<td>40.51 ± 10.1</td>
<td>0.64 (NS)</td>
</tr>
</tbody>
</table>

Data are presented as mean ± SEM. The t values represent the effect of state on these measures, investigated using paired-samples tests.
have an effect on activation in the dorsolateral prefrontal cortex, an area important for maintaining task goals. There was also a notable paucity of performance lapses compared with our prior studies that tested working memory and inhibition, attesting to higher motivation levels associated with the reward-bearing nature of the gambling task.

**Experiment 1: Neural Correlates of Reward Processing**

A 2 (outcome: Loss, High-Gain) by 2 (state) repeated-measures voxel-by-voxel ANOVA showed that sleep deprivation significantly reduced activation in both right and left anterior insula, as well as ventrolateral prefrontal cortex, left orbitofrontal cortex, and right superior frontal gyrus. Independent of state, greater activation for losses relative to gains occurred in bilateral anterior insula, anterior cingulate cortex and intraparietal sulcus. Greater activation for gains compared to losses was observed in the ventral striatum, including the nucleus accumbens and anterior medial prefrontal cortex. A significant state-by-outcome interaction was also present in the left anterior insula, left orbitofrontal cortex, and right superior frontal gyrus (Figures 4 and 5, Table 3).

**Experiment 2: Reward Processing without Decision Making**

Parameter estimates from regions of interest in left anterior insula, right superior frontal gyrus, and left orbitofrontal regions, defined by the activation mask obtained from Experiment 1, were subjected to a 2 (Outcome: Loss, Gain) by 2 (State) repeated-measures ANOVA. A significant outcome by state interaction was obtained for the left anterior insula (Figure 5) but not for the right superior frontal gyrus and left orbitofrontal cortex. These findings corroborated our earlier observation pertaining to a reduced activation for losses following sleep deprivation in left anterior insula. The absence of significant effects in the left orbitofrontal cortex and right superior frontal gyrus could be attributed to a lack of need to adapt future decisions based on feedback from the current trial.

**DISCUSSION**

The present findings illustrate how sleep deprivation modulates the neural substrate for decisions that involve tradeoffs between risky and safe options.
potentially higher gains associated with the risk of a loss. Historically, although several studies have shown sleep deprivation to be associated with increased risk-taking behavior, these have involved at least 36 hours of sleep deprivation. Here, we found that 24 hours of sleep deprivation modulated neural systems associated with decision making in the absence of (and plausibly prior to) behaviorally manifest changes in risk preference. Our findings suggest that imaging data might lead standard behavioral measures in detecting this cognitive phenomenon.

### Effects of Sleep Deprivation on Decision Making

Following sleep deprivation, greater activation of the dorsal anterior cingulate was observed in the decision-making phase irrespective of the type of decision made. The contributions of the cingulate to cognitive control include the detection of errors as well as monitoring for response conflict, and the present findings may reflect greater effort in resolving the conflict between maximization of expected value and minimization of regret when sleep deprived. 

Activation of the nucleus accumbens is typically associated with gain prediction and has been shown to correlate with the magnitude of anticipated gains. Recently, activation in this region was shown to precede risky choices in a financial decision-making task. In this study, we observed increased activation in this region for the riskier decisions in both states. Additionally, choosing gambles with higher risk relative to the alternative gamble elicited significantly greater activation in the right nucleus accumbens following sleep deprivation.

We hypothesize that this increased activation could represent an increased expectation of winning the higher payout associated with the riskier decision. Thus, whereas sleep-deprived volunteers faced with any decision show behavioral and imaging features of heightened response conflict, only making a relatively higher risk choice is accompanied by a greater expectation for being rewarded.

### Effects of Sleep Deprivation on Reward Processing

The flip side to the emotional high of being rewarded for a gamble is being able to learn from disadvantageous decisions. As this involves processing of emotions related to loss and regret, we evaluated the influence of sleep deprivation on emotional responses to decision outcome by comparing activation associated with losses and gains across the states.

In both experiments, selectively attenuated responses for loss in the insula may correspond to reduced disappointment in response to losses. The insular cortex, through its afferent and efferent connections to the medial and orbital prefrontal cortex, anterior cingulate, and amygdala, is thought to evaluate the emotional significance of a stimulus and generate an appropriate affective response. In contexts that do not involve counterfactual reasoning, as in Experiment 2, the insula appears to respond to both positive and negative outcomes. However, only the response to losses appears to be consistent across experiments, corroborating accounts that this region is important in signaling disappointment.

The lateral orbitofrontal cortex appears to be sensitive to the magnitude of punishment. Reduced activation in this region to losses under conditions of sleep deprivation in Experiment 1 suggests a state-dependent impairment of the learning of negative reward associations. Damage to the orbitofrontal cortex is thought to impair learning and the ability to reverse reward associations, perhaps by disrupting the ability to use emotional markers to guide decisions. Regret following poor decisions is 1 such emotional marker. In Experiment 1, losses elicited significant lateral orbitofrontal cortex activation when subjects were sleep deprived, possibly reflecting learning to avoid subsequent bad decisions. As regret (distinct from disappointment) and response learning are contingent on being able to influence outcome through choice, it is possible that the lack of effect in the orbitofrontal region in the second experiment could stem from the predetermined nature of outcomes.

### CONCLUSIONS

Sleep deprivation was associated with increased activation in the nucleus accumbens for risky decisions, indicating a possible shift toward risk-seeking behavior. Additionally, there was decreased activation in the anterior insula following losses when sleep deprived. Finally, the attenuation of activation in the orbitofrontal cortex suggests that, in addition to altering risk preferences, sleep deprivation may also diminish the ability to learn from the negative consequences of risky behavior.

### ACKNOWLEDGMENTS

This work was funded by DSO National Laboratories, Singapore (No. DS0CL05141) and the SingHealth Foundation. We...
would also like to acknowledge the contributions of Dr. Wei-Chieh Choo and Julian Lim in subject recruitment and scanning.

REFERENCES


