

Decision-Making Under Conditions of Sleep Deprivation: Cognitive and Neural Consequences

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Previous research has presented a mixed picture of the cognitive and neural consequences of sleep deprivation on decision-making. Functional magnetic resonance imaging (fMRI) was used to examine the neural changes associated with simple and integrated decision-making under conditions of sleep deprivation. When rested, regions of the anterior prefrontal cortex (aPFC) were recruited to a greater degree for integrated decision-making (ID). After 24 hours of sleeplessness, there was minimal effect on simple decision-making but a clear vulnerability of ID to sleeplessness that was accompanied by a breakdown in task-specific neural activity in prefrontal cortex that, when rested, correlated with behavioral performance.

Understanding the cognitive consequences of sleep deprivation has become increasingly important in a society that relies heavily on people performing critical services who are often chronically sleep deprived. As part of their responsibilities, many of these individuals are often confronted with situations where they need to make fast and complex decisions. An emerging literature has begun to explore the consequences of sleep deprivation on cognition in general and decision-making more specifically (Harrison & Horne, 2000). In addition, a number of these studies utilize functional brain imaging techniques to examine the corresponding neural consequences of sleep deprivation (Van Dongen, 2005).

Decision-making, which generally falls under the domain of executive functions, engages a number of cognitive operations that have been examined under conditions of sleep deprivation, including working memory (Williamson,

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Feyer, Mattick, Friswell, & Finlay-Brown, 2000), rule learning and implementation (Herscovitch, Stuss, & Broughton, 1980), inhibition of automatic responses (Sagaspe et al., 2006), and probabilistic assessment (Harrison & Horne, 1998; McKenna, Dickinson, Orff, & Drummond, 2006; Neri, Shappell, & DeJohn, 1992). One review of the literature concluded that there were a number of decision-making domains that appeared unaffected by sleep deprivation but that those domains that were affected tended to involve complex integrating tasks that require flexibility, innovation, or plan revision (Harrison & Horne, 2000).

Much of the executive control and decision-making literature has focused on the role of prefrontal cortex (PFC) in these functions. Studies can be organized into a hierarchy of cognitive operations with specific PFC regions engaged during those operations. For simple categorical selection, the data suggest that dorsolateral PFC (Brodmann area [BA] 9/46) is involved (Dobbins, Foley, Schacter, & Wagner, 2002). In addition to the dorsolateral regions, ventrolateral PFC responses (BA 47) and mid-ventrolateral (BA 45) appear to be brought online when the simple stimulus categorization requires selection among closely competing alternatives (Thompson-Schill, Aguirre, D'Esposito, & Farah, 1999; Wagner, Paré-Blagoiev, Clark, & Poldrack, 2001). Finally, as decision-making involves increasing complexity, and the integration of multiple subroutines is required, more anterior portions of PFC appear to be brought online (BA 10; Koechlin & Hyafil, 2007).

The current study proposes to take advantage of this decision-making hierarchy to examine the neural and cognitive changes associated with sleep deprivation. Tasks were designed with novel stimuli to tap increasing levels of complexity by engaging participants in simple perceptual matching and integrative decision-making. Integrative decision-making requires combining two or more lower level decisions into a final decision outcome.¹ Novel stimuli were used in this work to eliminate frontal cortical activations typically associated with semantic retrieval (Wagner et al., 2001). A neuroimaging study examining the neural consequences of sleep deprivation during decision-making will provide critical information about the brain's ability to adapt to mental fatigue as well as revealing important biomarkers of significant cognitive impairment.

METHOD

Overview

Subjects performed the decision-making tasks while undergoing fMRI scanning in the morning after a good nights sleep (Day 1) and then again at the same time on Day 2 after remaining awake for 24 hours (Day 2).

Participants

Fifteen participants (4 female), including 13 undergraduate cadets from the United States Military Academy at West Point and 2 University of Texas graduate students, participated in the experiment. Two of these participants were excluded from the final analysis due to excessive sleepiness on Day 2 that resulted in greater than 20% missed trials.

Equipment

The paradigms were run under Matlab using Psychophysics toolbox (Brainard, 1997; Pelli, 1997) on a PC-compatible laptop computer that presented the visual image using a LCD projection system located behind the MRI and projecting to a back-projection screen mounted in the bore approximately 16 inches from the participant's eyes. Participants viewed the images through a mirror mounted on the MR head coil and responded to the task using fiber optic-controlled buttons placed in the right hand.

Materials

Each participant performed four tasks, one visuo-motor control (VMC) task and three decision-making tasks. The VMC task consisted of a prompt "Indicate X" in the center of the screen with "X" and "O" signs displayed underneath. Participants needed to press a button indicating on which side of the screen the "X" sign was presented. Stimuli for the three decision tasks were novel abstract shapes adapted from Slotnick and Schacter (2004). Each task required participants to match perceptually similar shapes (derived from the same underlying prototype). In the two-alternative forced-choice (2AFC) task, participants saw an exemplar shape on the top of the screen simultaneously with two test shapes on the bottom of the screen and the prompt "Which one?" The participants' task was to indicate which of the two test shapes matched the exemplar shape. They were told that these shapes represented hand-written scripts in a foreign language and would only closely match. The three-alternative forced-choice (3AFC) task was similar, except that participant had to choose from three test items rather than two. In each case there was always exactly one matching shape. In the integrative decision (ID) task, the display again consisted of one exemplar shape and two test shapes with the prompt "Exactly one?" The participants' task was to indicate whether exactly one, and only one, of the test items matched the exemplar item. Both could match ("no" response required), one could match ("yes" response required) or neither of them could match ("no" response required). An example of the stimuli and screen for the ID task can be seen in Figure 1. Each trial lasted 4 s and consisted of a prompt (e.g., "Which one?") for 200 ms, followed by the exemplar and test shapes

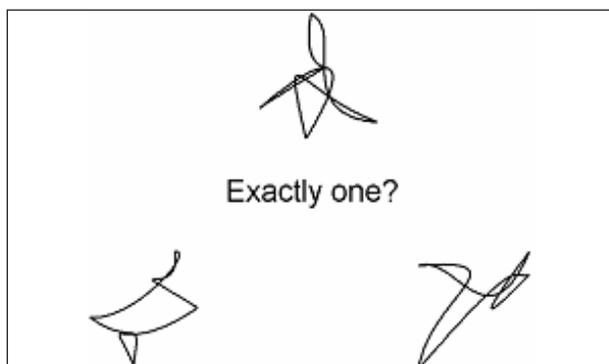


FIGURE 1 Example stimuli and integrative decision-making screen.

display. The full display was on until the participant responded or until the response deadline (3600 ms) passed; then the display was replaced with a fixation cross until the beginning of the next trial.

Procedure: Decision-Making Task

Participants first received instructions and completed a training session outside of the scanner. After training, each participant completed four runs during which functional MRI scans were acquired. Conditions were alternated in a block design. Two runs consisted of alternating 2AFC and ID tasks separated by the control task and two runs consisted of alternating 3AFC task and ID task separated by the control task. During each run, participants completed five cycles consisting of 16 s (four trials) of the control task, 24 s (six trials) of an AFC, 16 s of the control task and 24 s of the ID task (6 min 40 s total). Order of the runs and order of the tasks within a run were counterbalanced both between and within subject. Each participant completed two sessions on two consecutive days. The procedure and task orders were identical within subjects on Day 1 and Day 2.

Procedure: fMRI

MRI scanning was performed on a General Electric 3T Excite system utilizing an eight-channel phased array head coil. Thirty-one 3.5-mm slices were acquired oriented 20 degrees off the axial plane utilizing a GRAPPA EPI sequence optimized to reduce EPI distortion. In-plane resolution was 3.75×3.75 mm and two-shot scans were collected with a TE of 30 ms and a TR of 2 s. On Day 1, following informed consent, participants entered the MR scanner and a high-resolution T1 image was collected after which they engaged in four runs of two different tasks separated by another T1 scan. Whether the decision-making task was first or second was counterbalanced across subjects. Each run of the decision-making task lasted

6.4 min for a total of approximately 30 min. After both tasks, a DTI scan was acquired. On Day 2, no structural or DTI scans were obtained.

RESULTS

Behavioral

The change in decision-making performance associated with 24 hours of sleep deprivation was examined by calculating each participant's mean accuracy across the three conditions of interest (2AFC, 3AFC, and ID) for both Day 1 and Day 2. From these accuracy scores, knowledge scores were calculated to factor out the proportion of accuracy attributable to chance responding [knowledge score = (accuracy - chance)/(1 - chance)]. These values were then used to compute a proportion change score by subtracting the knowledge score from Day 2 from Day 1 and dividing by Day 1 performance. A single subject was dropped from the accuracy analysis for the ID and 3AFC task due to below chance performance on Day 1.

Results of the accuracy calculations indicated that a participant's ability to make integrative decisions declined significantly from Day 1 to Day 2, $t(11) = 2.50, p < .05$, while the simple 2AFC perceptual matching did not, $t(12) < 1$. In addition to the impairment in ID, the 3AFC task also was significantly impaired, $t(12) = 2.66, p < .05$; however, the impairment in ID was marginally greater than that in 3AFC, $t(11) = 1.97, p < .075$. These results can be seen in Figure 2.

fMRI

Preprocessing and data analysis were conducted using FEAT (FMRI Expert Analysis Tool) Version 5.63, part of FSL (<http://www.fmrib.ox.ac.uk/fsl>) software (Smith et al., 2004). Preprocessing included motion correction, high-pass temporal filtering (80 s), and spatial smoothing (5 mm FWHM). Data from each run of each participant were analyzed separately in a first level of analysis. Conditions were modeled convolving the time course of each condition with the canonical hemodynamic response function. Maps were generated for contrasts of interest and a second level of analysis was performed for each subject that combined the four runs. This analysis was performed separately for Day 1 and Day 2 and then contrasted within subject using a fixed-effect analysis. Finally, a group analysis for each of the subject-level contrasts was performed treating subjects as random effects.

For purposes of the current examination we contrasted all decision-making (2AFC, 3AFC, and ID) versus the VMC task with a cluster corrected threshold of $p < .05$. These maps were then queried to examine the specificity of activations for AFC tasks and ID tasks in regions of PFC. On Day 1, right PFC revealed a greater response during decision-making than left. Collapsing across both 2AFC and 3AFC, a region of right middle frontal gyrus (BA 6/44; MNI coordinates 52, 30,

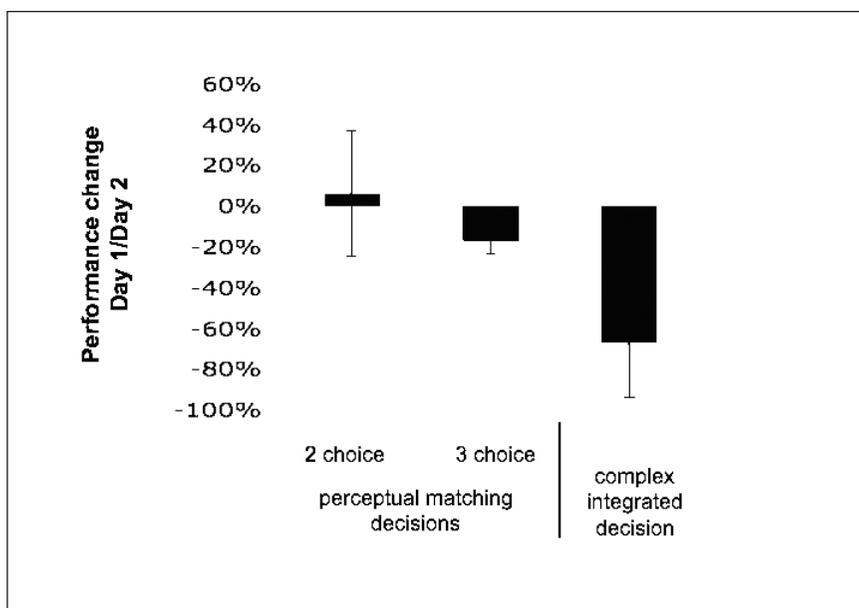


FIGURE 2 Change in decision-making accuracy due to sleep deprivation. Performance change is calculated as the proportional difference between the accuracy on Day 1 and after 24 hours of sleep deprivation on Day 2.

26) demonstrated equivalent levels of activation between AFC and ID tasks. By contrast, a more anterior region of PFC (BA 45/10; MNI 50, 40, 14) demonstrated some decision task specificity, showing greater activation for the ID task than for the AFC tasks. Though overall Day 2 resulted in greater activation in these regions than in Day 1, the same pattern of differences between conditions in the middle frontal gyrus (MFG) and aPFC remained (Figure 3).

To test the changes in the regional specificity of activation between Day 1 and Day 2 for the ID task, mean percentage signal change was extracted from five regions of interest, across left and right hemispheres active during the task—superior parietal lobe, superior frontal gyrus, middle frontal gyrus, orbital frontal, and inferior and medial polar frontal. Task-specific activity in these regions was calculated by subtracting mean activation for the VMC task from the ID task and entered into a repeated-measures ANOVA with region, hemisphere, and day as within-subject factors. The results of this ANOVA revealed a main effect of day such that task-specific activation for ID was less on Day 2 than on Day 1, $F(1, 12) = 10.11$, $p < .01$. There was also a main effect of hemisphere, $F(1, 12) = 11.46$, $p < .01$, and region, $F(4, 48) = 11.92$, $p < .001$. Moreover, the main effect of hemisphere was modified by a significant interaction with Day, $F(1, 12) = 5.09$, $p < .05$, indicating that the significantly greater activity in the right hemisphere (compared to the left)

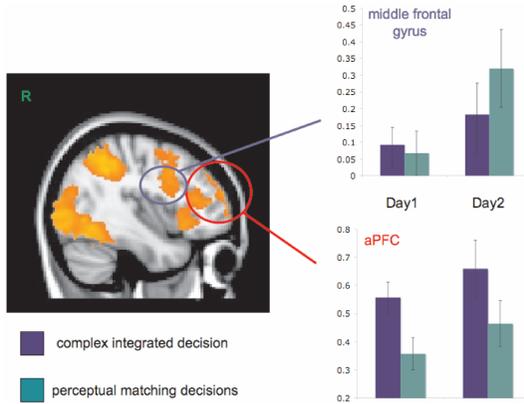


FIGURE 3 Task specificity of neural activity in regions of right prefrontal cortex. Between AFC and ID tasks, no difference was found on either Day 1 or Day 2 for the region of MFG, while the region of aPFC demonstrated task specificity for the ID task. The Y axis represents percentage signal change.

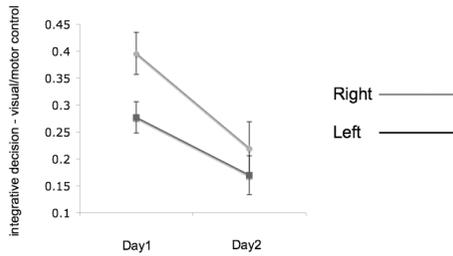


FIGURE 4 Task-specific activity associated with ID (ID-VMC) across five regions of interest in the left and right hemisphere. Changes from Day 1 to Day 2 revealed a significant decrease in activation. Additionally, there was a significant day by hemisphere interaction indicating the loss of task-specific lateralization.

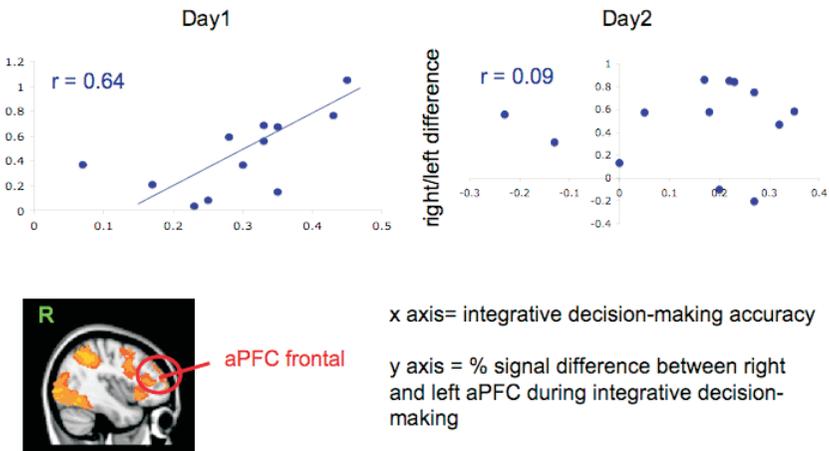


FIGURE 5 Correlation between right-left laterality index for ID in aPFC and task performance. A significant relationship was found for Day 1 but not for Day 2.

on Day 1 was not evident on Day 2 (refer to Figure 4). The interaction between day and hemisphere did not interact with region.

Finally, to examine the functional significance of the changes in cortical laterality from Day 1 to Day 2 on the ID task, a laterality index was calculated for the region of aPFC that revealed ID task specificity. The index was computed as the difference between mean activation in the right hemisphere minus left hemisphere. Therefore, the greater this index, the greater the right unilaterality in the activation. This score correlated significantly with task performance on Day 1 ($r = 0.64, p < .05$) but not on Day 2 ($r = 0.09, ns$, see Figure 5).

DISCUSSION

This study examined the cognitive and neural effects of 24 hours of total sleep deprivation (TSD) on simple and complex decision-making. While behavioral performance on the simple decision-making task, requiring a perceptual matching decision (2AFC), remained relatively unaffected by TSD, the complex decision-making task that required integration of multiple simple perceptual matching decisions (ID) was significantly impaired. Moreover, fMRI data revealed a distinct pattern of task-specific activations for ID that included a hemispheric laterality when participants were rested. By contrast, after 24 hours of sleep deprivation the patterns of task-specific brain activity were significantly altered.

Previous research examining the changes in neural activity associated with sleep deprivation has revealed a mixed picture. Several studies examining working memory, a critical component of decision-making, have shown decreased cortical activations (Mu et al., 2005) associated with sleep deprivation, while others have shown increased activations across a network of regions engaged in working memory (Chee & Choo, 2004) and those involved in divided attention (Drummond, Gillin, & Brown, 2001). As a result of observations of increased activation and relatively sustained working memory performance after 36 hours of TSD, Drummond et al. (2001) proposed an “adaptive cerebral response” model. They postulated that the brain frequently can adapt to sleep deprivation by bringing additional neural resources online. A very similar model has been proposed to explain neuroimaging findings in aging (Cabeza et al., 1996) and later formulations of the aging literature included the consistent finding of reduced hemispheric asymmetry in frontal lobe activity (Anderson & Craik, 2000).

The results of the current work do not support the adaptive cerebral response model. While overall there was an increase in neural activity, this increase was nonspecific and included the visual motor control task. When this more global change was controlled for there was actually a decrease in task specific activity associated with decision-making after 24 hours of TSD. In tandem with this decrease was a corresponding loss of hemispheric asymmetry—an asymmetry that was cor-

related with task performance when participants were rested. The current results argue that neural efforts to compensate for the effects of sleep deprivation are not always successful at maintaining functioning. Furthermore, the finding of increased cortical activity that was not helpful argues against interjecting more “energy” into the system as a possible way to remediate decrements in performance. These results have important implications for persons engaged in decision-making tasks under conditions of sleep deprivation.

NOTE

1. As a real-world example, one can consider an imbedded math problem such as $(6 \times 9) + (12/3)$. The problem requires the solving of each portion individually, holding those answers in mind and then performing the final operation by integrating the two previous solutions.

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