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Compensatory recruitment after sleep deprivation and the relationship with performance

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Abstract

This study examined the effects of total sleep deprivation (TSD) on cerebral responses to a verbal learning task with two levels of word difficulty. A total of 32 subjects were studied with functional magnetic resonance imaging (FMRI) after normal sleep and following 36 h of TSD. Cerebral responses to EASY words were identical on both nights, but several brain regions showed increased activation to HARD words following TSD compared with following a normal night of sleep (NORM). These regions included bilateral inferior frontal gyrus, bilateral dorsolateral prefrontal cortex, and bilateral inferior parietal lobe. Better free recall performance on the HARD words after TSD was related to increased cerebral responses within the left inferior and superior parietal lobes and left inferior frontal gyrus. Recall was negatively related to activation within the right inferior frontal gyrus. Overall, the findings support the predictions of the compensatory recruitment hypothesis that task demands influence both the likelihood and location of increased cerebral activation during task performance following TSD, and refine that hypothesis by identifying a specific task demand that plays a role. The performance relationships suggest increased activation may be both beneficial (compensatory) and interfere with task performance, depending on the brain regions involved.

Keywords: Cognitive performance; Functional magnetic resonance imaging; Verbal learning; Parietal lobes; Prefrontal cortex

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1. Introduction

Recent studies have reported that total sleep deprivation (TSD) results in altered brain responses to cognitive challenges. For example, piston emission tomography studies have found decreased glucose metabolism during sustained attention tasks (Wu et al., 1991; Thomas et al., 2000). Functional magnetic resonance imaging (FMRI) studies have found both increased and decreased cerebral responses to cognitive tasks following TSD. Increased responses have been reported during verbal learning (Drummond et al., 2000), short-term attention (Portas et al., 1998), divided attention (Drummond et al., 2001), and grammatical reasoning tasks after TSD (Drummond et al., 2004). Decreased cerebral responses, on the other hand, have been reported in arithmetic (Drummond et al., 1999) and verbal (Mu et al., 2005a,b) working memory tasks, while both increases and decreases have been reported during verbal (Chee and Choo, 2004; Habeck et al., 2004) and non-verbal (Bell-McGinty et al., 2004) item recognition tasks.

It is clear, then, that the brain's response to TSD is not homogenous across all tasks. We have argued that the increased activations seen after TSD represent compensatory recruitment of resources beyond those utilized after a normal night of sleep (NORM) (Drummond et al., 2000, 2001; Drummond and Brown, 2001). On the other hand, decreases may reflect cognitive dysfunction associated with performance deficits after TSD. We have also postulated that cognitive task-related factors may predict whether, and where, the brain will show increased or decreased responses to cognitive challenges following TSD (Drummond and Brown, 2001).

One possible task demand that may influence cerebral responses during TSD is task difficulty. Two recent reports suggest greater task difficulty is more likely to elicit increased cerebral responses after TSD than is seen with easier tasks. We studied subjects who had undergone 35 h of TSD and who then performed a grammatical transformation task that contained sentences of multiple complexity, and therefore difficulty, levels. We reported the brain recruited more resources in response to increasing difficulty during TSD relative to the response seen after NORM (Drummond et al., 2004). Similarly, Chee and Choo reported that, after 24 h TSD, a verbal item recognition task requiring both maintenance and manipulation of information showed greater increases in activation relative to a similar task that required only maintenance (Chee and Choo, 2004). One limitation shared by these two studies is that the more difficult version of each test explicitly added task demands compared with the easier versions. In Drummond et al., increasing grammatical complexity required greater working memory capacity as well as increased manipulation of information. In Chee and Choo, the more difficult condition added manipulation of information to the maintenance demands of the easier condition. Therefore, it is possible that the increased cerebral recruitment following TSD related to these additional task demands rather than to difficulty, per se. Here, we manipulated the difficulty of a task without explicitly adding additional cognitive processes, thereby allowing a more direct test of whether compensatory recruitment is influenced by increasing task difficulty.

Another issue to consider is whether changes in cerebral responses with TSD are beneficial. Increased brain responses after TSD could be interpreted either as compensatory recruitment benefiting performance or as interfering with cognitive performance. One way to address this issue is to examine the relationship between individual differences in cognitive performance and cerebral responses after TSD.

Here, we examined the interaction of task difficulty and state (TSD vs. NORM) in a relatively large group of subjects ($n=32$) by manipulating task difficulty without adding additional cognitive processes. Our hypothesis was that increased difficulty would augment compensatory recruitment after TSD. Another hypothesis was that performance would be positively correlated with the FMRI blood oxygen level dependent (BOLD) response in regions showing an effect of TSD.

2. Methods

2.1. Subjects

A total of 35 subjects drawn from two separate but concurrent studies (17 from one study and 18 from the other) were enrolled. One was excluded because of excessive movement during scanning on the TSD night, one was excluded because of FMRI artifact