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Research article

24-h sleep deprivation impairs early attentional modulation of neural processing: An event-related brain potential study

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ABSTRACT

Prior research indicates sleep deprivation negatively impacts selective attention, although less is known about the neural bases of these effects. The present study used event-related brain potentials (ERPs) to examine whether the effects of total sleep deprivation could be traced to the earliest stages of sensory processing influenced by selective attention. Participants were randomly assigned either to a regular sleep or 24-h total sleep deprivation condition. Following either sleep deprivation or regular sleep, participants completed a dichotic listening selective attention task while ERPs were acquired. Well-rested participants showed typical attentional modulation of the N1 between 150 and 250 msec, with larger amplitude responses to attended relative to unattended auditory probes. In contrast, these effects were significantly reduced in sleep-deprived participants, who did not show significant effects of selective attention on early neural processing. Similar group differences were observed in the later processing negativity, from 300 to 450 msec. Taken together, these results indicate that 24-h total sleep deprivation can significantly reduce, or eliminate, early effects of selective attention on neural processing.

1. Introduction

Sleep deprivation is a pervasive problem linked to cognitive deficits, increased levels of irritability, and adverse health outcomes [for reviews, see 2,9,24]. For those working or driving while sleep deprived, error-related accidents also become more likely, at great cost both to individuals and society [9,12]. Despite these detrimental consequences, over 20% of adults are estimated to get insufficient sleep on a regular basis [12], and sleep deprivation is especially common among college student populations [26,31].

Experimental studies of sleep deprivation typically examine the effects of total sleep deprivation, defined as 24-h or more without sleep, though repeated nights of partial sleep deprivation have similarly detrimental effects [33]. Across a number of experimental studies, sleep deprivation is causally related to a range of cognitive deficits, though aspects of attention appear particularly vulnerable [1,12,15,24]. Here, we focus specifically on selective attention, or the ability to preferentially process relevant information from the environment while excluding irrelevant distractors. In behavioral studies, sleep deprivation is associated with deficits on a range of tasks requiring selective attention, including filtering irrelevant visual stimuli from a memory array [10], finding embedded figures in complex images [1], and performance on Stroop-like tasks [24]. However, as behavior represents the sum of multiple stages of processing, behavioral studies have not yet been able to specify which stages of processing are affected by sleep deprivation, nor the neural systems most affected.

Using functional magnetic resonance imaging (fMRI), recent studies have begun to address the neural mechanisms underlying the effects of sleep deprivation on selective attention. These studies suggest that such deficits result in part from disruption of fronto-parietal top-down control networks, which following sleep deprivation exhibit reduced task-related neural activity and/or aberrant functional connectivity [3,25]. fMRI studies have also begun to characterize the effects of such disruptions on sensory processing. For example, the visual system parahippocampal place area (PPA), which in well-rested participants responds preferentially to house over face stimuli, fails to show attentional modulation following total sleep deprivation [25] unless the stimuli appear in predictably cued patterns [3]. However, the relatively poor temporal resolution of fMRI renders it difficult to interpret whether the differences in PPA activity reflect feed-forward versus feedback differences in attentional modulation and, more specifically, whether earlier stages of sensory processing are impaired by sleep deprivation.

Despite the temporal limitations of fMRI, Kong and colleagues [23] used fMRI to assess the effects of total sleep deprivation on two at least partially dissociable components of selective attention: distractor

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suppression (reduced processing of task-irrelevant stimuli) and signal enhancement (increased processing of task-relevant stimuli). The authors used chimeric house-face stimuli, which superimposed face and house stimuli into a single visual image. Participants attended either to the face or house stimuli in the chimeric images in separate blocks. Kong and colleagues found that sleep deprivation selectively impaired distractor suppression, with sleep-deprived participants failing to show the same levels of reduced PPA activity to chimeric house-face stimuli when faces were attended (i.e., houses as irrelevant distractor) relative to PPA activity in a baseline passive viewing condition. In contrast, no differences were observed between the sleep-deprived and well-rested participants in the enhancement of PPA activity to the chimeric stimuli when houses were attended relative to the passive viewing baseline. Together, these fMRI studies suggest that sleep deprivation impacts attentional modulation and may be specific to impairing distractor suppression, though it is unclear whether such effects occur during early stages of sensory processing.

In contrast to fMRI, event-related brain potentials (ERPs) have exquisite temporal resolution, making the technique particularly valuable to studies of selective attention [18–20]. In a typical ERP selective attention paradigm, competing streams of visual or auditory stimuli are presented simultaneously, with participants attending selectively to one of the streams. Comparing ERPs to probe stimuli in the attended versus unattended stream provides a relatively pure index of the effects of selective attention on neural processing, while keeping the physical stimuli, task demands, and overall arousal levels constant. Using variations of this paradigm, the effects of selective attention have been documented during the first few hundred milliseconds of neural processing [18–20,34]. For auditory stimuli, these enhancements are most consistently observed on the N1, the first large negative deflection in the ERP waveform emerging approximately 100 msec after stimulus onset. As a relatively early sensory component, early N1 attention modulation is believed to reflect sensory gain control as a largely feed-forward modulation of neural activity [16]. As well, in studies of change-over-time or between-group comparisons, the ERP technique can separately assess differences in distractor suppression versus signal enhancement by comparing neural responses to probe stimuli embedded in either the unattended or attended stream [13,27,30]. Such studies have shown change-over-time or group differences specific to both distractor suppression [13,30] and signal enhancement [27], indicating the technique is sensitive to both types of group difference. Most importantly, the temporal resolution of the ERP technique allows claims of overall differences in the effects of selective attention on neural processing to be isolated in time and traced to early stages of sensory processing.

To date, only a few studies have used ERPs to examine the effects of sleep deprivation on aspects of attention, and none have used a manipulation of selective attention as described above. For example, both Zerouali and colleagues [35] and Cote and colleagues [7] evaluated the N1 elicited by auditory sounds among participants exposed to partial sleep deprivation. While neither study found significant overall effects of partial sleep deprivation on N1 amplitude, these studies did not use a manipulation of selective attention that maintained constant task demands and arousal level across conditions. Instead, the studies compared the N1 across different task conditions, or only in a single condition. Thus, it remains unclear, both from the available fMRI and ERP data, whether sleep deprivation affects early stages of sensory processing that, in well-rested individuals, are the first stages of processing modulated by selective attention.

The goal of the present study was to address these limitations by examining the effects of total sleep deprivation on early indices of selective attention using a well-established ERP measure of selective auditory attention. Adult volunteers completed an ERP dichotic listening selective attention task following random assignment either to regular sleep or 24-h of monitored sleep deprivation. It was predicted that sleep deprivation would result in reduced or absent effects of selective attention on the N1, indicating disruptions in early, feed-forward effects of selective attention on neural processing. We also examined the later processing negativity, believed to index further endogenous processing of attended stimuli, particularly when these stimuli are more difficult to discriminate [14,28]. It was further predicted, based on previous fMRI literature [23], that if deficits could be localized they would be specific to, or larger for, distractor suppression versus signal enhancement.

2. Material and methods

2.1. Participants

The final sample included 35 participants, aged 18–22, including 20 in the regular sleep condition (5 male, mean age 19.8 years) and 15 in the sleep deprivation condition (4 male, mean age 19.7 years), drawn from an original sample of 46 participants. Reasons for exclusion included equipment malfunction (one regular sleep participant) or poor ERP data quality following standard artifact rejection procedures detailed below (7 sleep deprived participants; 3 regular sleep participants). All participants were fluent in English with normal or corrected-to-normal vision. Participants received $20 for participation, regardless of condition. All participants provided informed consent. Procedures were approved by Willamette University's Institutional Review Board.

2.2. Procedure

One to three days prior to testing, participants came to the laboratory for a tour and study overview. During this orientation, participants completed demographic questionnaires and signed a consent form. The day before testing, participants were informed via email if randomly assigned to the sleep deprivation (n = 22) or regular sleep (n = 24) condition. Participants in both conditions were requested to abstain from napping, and also caffeine, alcohol, and psychoactive substances, for the 24-h prior to testing. Participants in the regular sleep condition were instructed to go bed at their usual time and report to the lab at 8 am for testing. Participants in the sleep deprivation condition were told to report to the lab at 10 pm for monitoring, with testing to commence at 8 am the following day. Following previous research [4,5,32], adherence to the sleep deprivation condition was monitored by trained research assistants who ensured participants remained awake throughout the sleep deprivation period. During the sleep deprivation period, participants could engage in non-strenuous activities of their choosing, such as reading, watching TV, or doing homework.

2.3. ERP assessment of selective auditory attention

Participants completed an ERP selective auditory attention task based on a modified version of a classic auditory attention paradigm [17]. Variations of this task have been used to assess auditory selective attention in young children and adults [11,28–30]. Briefly, pairs of 2.5-3.5 min children's stories (one male-narrated, one female-narrated) were recorded and pasted into separate channels of a stereo audio channel. Stories were presented from speakers ~21 inches on either side of the participant, who was instructed to attend to one of the two stories, while ignoring the story in the unattended channel.

In total, participants attended to eight stories (attended narrator counterbalanced within a participant). Attended side, right (R) or left (L), was pseudorandomized with order RLLRRLLR. After each story, participants were asked three basic comprehension questions about the attended story. Due to experimenter error, comprehension questions were not asked of three participants (one regular sleep; two sleep deprived participants).[1] Of participants with comprehension question

[1] All of the ERP results reported in the main text remained if analyses were restricted to participants with comprehension question data.