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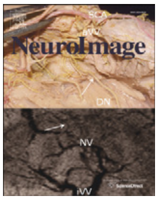

Time-on-task and sleep deprivation effects are evidenced in overlapping brain areas ☆

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ABSTRACT

Both sleep deprivation and extended task engagement (time-on-task) have been shown to degrade performance in tasks evaluating sustained attention. Here we used pulsed arterial spin labeling (pASL) to study participants engaged in a demanding selective attention task. The participants were imaged twice, once after a normal night of sleep and once after approximately 24 h of total sleep deprivation. We compared task-related changes in BOLD signal alongside ASL-based cerebral blood flow (CBF) changes. We also collected resting baseline CBF data prior to and following task performance. Both BOLD fMRI and ASL identified spatially congruent task activation in ventral visual cortex and fronto-parietal regions. Sleep deprivation and time-on-task caused a decline of both measures in ventral visual cortex. BOLD fMRI also revealed such declines in fronto-parietal cortex. Only early visual cortex showed a significant upward shift in resting baseline CBF following sleep deprivation, suggesting that the neural consequences of both SD and ToT are primarily evident in task-evoked signals. We conclude that BOLD fMRI is preferable to pASL in studies evaluating sleep deprivation given its better signal to noise characteristics and the relative paucity of state differences in baseline CBF.

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Introduction

The study of sustained attention and its decline with sleep deprivation (SD) and time-on-task (ToT) was first motivated by specific transport and military demands. The findings from this research have since gained broader appeal as more persons become part of the 24/7 global supply chains on which modern life depends. Sustained attention, one of the most severely and consistently affected cognitive domains following SD (Lim and Dinges, 2010), declines during extended task engagement. Resource models attribute this decline to the exhaustion of cognitive (Shaw et al., 2009; Warm et al., 2008) or neural (Doran et al., 2001) resources. Consistent with the notion that information processing capacity is reduced during SD (Kong et al., 2011, 2012), ToT effects have been shown to be more pronounced in sleep-deprived individuals (Van Dongen et al., 2011; Warm et al., 2008; Wilkinson, 1964). Such behavioral interactions suggest that SD and ToT may affect the same processing stages (additive factors logic; see Schweickert, 1985; Sternberg, 1969), and perhaps common neural pathways as well.

Functional imaging employing BOLD (Blood Oxygen Level Dependent) fMRI has provided insights into the neural underpinnings of the neurobehavioral deficits encountered during SD. Studies of preparatory attention (Chee et al., 2011), working memory (Bell-McGinty et al., 2004; Chee and Chuah, 2007; Habeck et al., 2004; Mu et al., 2005), and selective attention (Chee et al., 2010; Kong et al., 2012; Lim et al., 2010a; Tomasi et al., 2009) offer converging evidence for SD-related declines in task-evoked fronto-parietal activation. These decreases in BOLD signal are thought to result from reduced engagement of brain regions involved in the top-down control of attention (Corbetta and Shulman, 2002; Kastner et al., 1999), accompanied by reduced signal in their putative targets such as visual extrastriate cortex.

Resource theories of the ToT effect (Warm et al., 2008) predict decreases in neural activation and regional blood flow as one is engaged in a task over time. Accordingly, Transcranial Doppler Imaging has been used to demonstrate hemispheric reductions in cerebral blood flow velocity following sustained task performance (Shaw et al., 2009). However, the technique does not localize the brain regions responsible for the effect. Resource theories additionally predict that the brain regions showing ToT effects are the same ones engaged during task performance. Indeed, functional imaging studies using different modalities (arterial spin labeling (ASL), PET, NIRS, and BOLD fMRI) have demonstrated regionally specific ToT effects (Coull et al., 1998; Grant et al., 2009; Langner and Eickhoff, 2012; Lim et al., 2010b; Paus et al., 1997). To date, though, only one has investigated sleep-deprived persons. Furthermore, as these studies used different tasks, different combinations of altered parietal, frontal, and thalamic signal or blood flow have been reported (Coull et al., 1998; Grant et al., 2009; Langner and Eickhoff, 2012; Lim et al., 2010b; Paus et al., 1997). It is thus unclear whether SD and ToT effects occur in similar brain regions.

BOLD fMRI has been the dominant technique used in cognitive neuroscience because of its versatility and superior temporal and

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spatial SNR characteristics (Parrish et al., 2000). However, it has been proposed that investigations of vigilance and time-on-task effects might benefit from the greater temporal stability of arterial spin labeling (ASL) (Brown et al., 2007; Demeter et al., 2011; Lim et al., 2010b; Rao, 2012), which makes it well suited for studying gradual shifts in neural activity during continuous tasks (Aguirre et al., 2002; Wang et al., 2005). Unlike BOLD fMRI, which is a relative measure, ASL also provides a means to quantify cerebral blood flow (CBF) in physiological units (Buxton et al., 1998; Rao, 2012; Wong et al., 1997). This allows for the comparison of resting baseline CBF across sessions and states.

ASL and PET studies have identified regional CBF differences, both task-evoked and baseline, between SD and the well rested state (Braun et al., 1997; Poudel et al., 2012; Thomas et al., 2000; Wu et al., 1991, 2006). These state effects often represent CBF reductions during SD, but some regional increases have also been reported (Braun et al., 1997; Wu et al., 2006). One might expect similar BOLD findings, as BOLD and CBF signals are tightly coupled under normal circumstances (Hoge et al., 1999). However, under some conditions, such as those encountered during aging, this coupling may be altered so as to yield smaller BOLD signal changes during task performance (Ances et al., 2009; Bangen et al., 2009). If similar changes in vascular behavior occur during sleep deprivation, they may influence the interpretation of fMRI findings in studies involving sleep deprivation.

In the present experiment, we employed an fMRI sequence that allowed us to analyze both BOLD and ASL signals related to performing an extended attention-demanding task. Each participant completed the experiment when rested and again after a night of total sleep deprivation. This design allowed us to address three outstanding issues. First, we directly compared the neural correlates of sleep deprivation and time-on-task effects to determine if they spatially overlapped. Given our challenging task and the task breaks required for BOLD fMRI, we explored both short-term, within-run effects (Ong et al., in press; Temple et al., 2000) and long-term, between-run effects (Coull et al., 1998; Lim et al., 2010b; Paus et al., 1997). Second, we examined whether BOLD and CBF measures of task-related neural activity are congruent across the rested and sleep deprived states. A crucial issue to be addressed by the study is whether a reasonably long experiment using ASL and BOLD would result in agreement regarding how SD modulates task-related activation. Finally, we examined resting baseline shifts in CBF across state and time-on-task.

Materials and methods

Participants

Twenty members of the National University of Singapore (NUS) community (11 females, aged 22.2 +/− 2.7, mean +/− standard deviation) were studied after providing informed consent, in compliance with a protocol approved by the NUS Institutional Review Board. They were selected from respondents of a web-based questionnaire who (1) were right-handed, (2) had regular sleeping habits, (3) slept no less than 6.5 h/night, (4) were not on any long-term medications, (5) had no symptoms or history of psychiatric, neurological, or sleep disorders, (6) drank fewer than 3 caffeinated drinks per day, and (7) were not of an extreme chronotype as assessed by the Horne-Östberg Morningness-Eveningness questionnaire (Horne and Östberg, 1976), i.e. having a score between 35 and 65. All reported having normal or corrected-to-normal vision.

The participants' sleep habits were monitored throughout the duration of the study using motion-sensing wrist actigraphy (Actiwatch, Philips Respironics, USA). Only those whose actigraphy data indicated habitual good sleep (slept >6.5 h per night; slept no later than 1:00 am; woke no later than 9:00 am) for the week prior to each fMRI scanning session were included. All the participants indicated that they did not consume any medication, stimulants, caffeine, or alcohol and did not smoke for at least 24 h prior to and during each experimental session.

Study procedure

Each participant visited the laboratory for three sessions: 1) briefing, 2) rested wakefulness (RW), and 3) sleep deprivation (SD). During the briefing session, the participants were given an actigraph and issued sleep diaries. Participants were scanned during the second and third sessions, with the order of these sessions (RW and SD) counterbalanced across participants. To ensure that regular sleep times were maintained, the first scanning session followed the briefing session by at least one week. The two scan sessions were also separated by one week to minimize residual effects of SD on cognitive performance.

The participants completed a temporal discounting task (~1 hour duration) in the scanner before starting the sustained attention task. This first task presumably taxed different neural circuitry from the task of interest (Hung et al., 2013), and its effects were further reduced by giving the participants a ~15 minute break outside the scanner between tasks. The sustained attention task began at ~9:00 am (RW) or ~7:00 am (SD), times that reflect the start of a typical workday and vigilance's nadir after a night of SD, respectively (Doran et al., 2001; Graw et al., 2004). For the SD session, participants arrived by 7:00 pm and were under the constant supervision of a research assistant. Participants engaged in non-strenuous activities such as reading and watching movies, save an hourly assessment of vigilance with a 10-minute Psychomotor Vigilance Task (PVT) (Dinges et al., 1997).

Behavioral paradigm

Stimuli were generated and presented using the Psychophysics Toolbox (Brainard, 1997; Pelli, 1997) for MATLAB (2009a, 7.8.0.347; Mathworks; Natick, MA, USA). Participants viewed the stimuli through VisualSystem goggles (NordicNeuroLab; Bergen, Norway). The system's eyetracker was used to ensure that participants were awake and viewing the stimuli throughout the experiment.

While being scanned, participants completed a highly attention-demanding search task (Fig. 1) (Marois et al., 2000), designed to elicit time-on-task declines even across the task breaks (both within-run and between-run) required for BOLD fMRI. Participants attended to a rapid serial visual presentation (RSVP) stream of white letters (200 ms per item, 0.5° of visual angle; the distractor set included all non-target letters save vowels, Q, X, and Y) on a gray background, searching for the target letters J or K (inter-target interval = 2–10 s, uniform distribution). Participants identified each target as quickly as possible by pressing the response box with their right index (J) or middle (K) finger. Unlike in the PVT (Dinges et al., 1997; Lim et al., 2010b), where each target remains on screen until the subject's response, the target was presented for 200 ms and then masked by the trailing distractor regardless of reaction time. As such, this paradigm's critical behavioral measure was accuracy (Ong et al., in press; Warm et al., 2008), and visual stimulation was independent of subject performance. During each of four 6.5 minute fMRI runs, the RSVP task was presented in six task blocks (each 32 s) with fixation blocks preceding, following, and interleaved (each 24 s). Concurrent with the RSVP stream, a contrast-inversing checkerboard (10 Hz) was presented in the periphery. The luminance of the display was ~30% for half of the task blocks, but this contrast manipulation did not interact with any of our variables of interest and is not further discussed here.

Before entering the scanner, subjects practiced two blocks of the main task. Between each run, subjects rated their subjective sleepiness using the Karolinska Sleepiness Scale (KSS) (Åkerstedt and Gillberg, 1990). KSS data for one subject were not properly recorded and thus excluded.

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