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Distinct neural correlates of time-on-task and transient errors during a visuomotor tracking task after sleep restriction

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ABSTRACT

Sleep loss leads to both time-on-task slowing of responsiveness and increased frequency of transient response errors. The consequences of such errors during real-world visuomotor tasks, such as driving, are serious and life threatening. To investigate the neuronal underpinning of time-on-task and transient errors during a visuomotor tracking task following sleep restriction, we performed fMRI on 20 healthy individuals when well-rested and when sleep-restricted while they performed a 2-D pursuit-tracking task. Sleep restriction to 4-h time-in-bed was associated with significant time-on-task decline in tracking performance and an increased number of transient tracking errors. Sleep restriction was associated with time-on-task decreases in BOLD activity in task-related areas, including the lateral occipital cortex, intraparietal cortex, and primary motor cortex. In contrast, thalamic, anterior cingulate, and medial frontal cortex areas showed overall increases irrespective of time-on-task after sleep-restriction. Furthermore, transient errors after sleep-restriction were associated with distinct transient BOLD activations in areas not involved in tracking task per se, in the right superior parietal cortex, bilateral temporal cortex, and thalamus. These results highlight the distinct cerebral underpinnings of sustained and transient modulations in alertness during increased homeostatic drive to sleep. Ability to detect neuronal changes associated with both sustained and transient changes in performance in a single task allowed us to disentangle neuronal mechanisms underlying two important aspects of sustained task performance following sleep loss.

Introduction

Loss of sleep leads to impaired alertness during sustained-attention tasks, which is manifested as transient errors (Chee et al., 2008; Dinges and Kribbs, 1991; Doran et al., 2001) and increased time-on-task related reduction in performance (Oken et al., 2006). These effects can be observed even when sleep is only reduced to 4–6 h in bed, particularly during monotonous conditions (Åkerstedt et al., 2005; Devoto et al., 1999; Stutts et al., 2003). Performance errors compromise individual and public safety, particularly in occupations which require continuous monitoring or visuomotor control, such as truck drivers, locomotive drivers, pilots, air-traffic controllers, and process-control workers (Sagberg, 1999).

A continuous visuomotor task, such as pursuit tracking, can be used to capture moment-to-moment changes in alertness (Huang et al., 2008; Peiris et al., 2006; Poudel et al., in press). A pursuit-tracking task is also a good surrogate of an everyday monitoring/visuomotor task, such as driving, which is difficult to deliver in an imaging environment, and has been used to detect effects of behavioural microsleeps and eye-closures during continuous tasks (Poudel et al., 2010, in press). In a continuous task, both transient and sustained changes in performance can be recorded in near real-time, allowing for detection of errors with a high temporal accuracy (Davidson et al., 2007; Huang et al., 2008; Peiris et al., 2011). Furthermore, such visuomotor tasks engage brain networks involved in attention, motor control, and eye–hand coordination (Grafton et al., 2008; Grefkes et al., 2004), allowing us to probe multiple pathways using a single task. The most dominant visuomotor pathway is the dorsal stream that connects the striate and extrastriate cortices to the posterior parietal area and has anterior projections into the frontal motor system (Nishitani et al., 1999). This pathway is involved in transformation of visual information into motor behaviour and is continuously engaged throughout visuomotor performance (Fogassi and Luppino, 2005). The attentional network has its origin in the prefrontal cortex and is involved in allocating attentional resource and biasing of attention towards a target via its top-down connections to the parietal and visual cortices (Desimone and Duncan, 1995; Kastner et al., 1998). The fronto-parietal attentional system tends to be more active during the early stages of a complex visuomotor task and shows a progressive decrease in activity with time-on-task (Floyer-Lea and Matthews, 2004).

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Sleep restriction increases time-on-task and transient errors or lapses during visuomotor tasks (Lim and Dinges, 2010). Given the multiple networks engaged during visuomotor tasks, it is reasonable to suggest that some of these networks are modulated by sleep-restriction. There have been no neuroimaging studies of visuomotor tracking following sleep loss, but studies measuring BOLD fMRI during discrete vigilance tasks, which require button presses following a stimulus, have reported localized modulation in frontal and parietal cortical attention regions and thalamic regions when attention and alertness are compromised following sleep loss (Chee et al., 2008; Chee and Tan, 2010; Drummond et al., 2005a; Tomasi et al., 2008). In particular, thalamic and visual processing capacity declines following sleep loss leading to attentional lapses during a selective attention task (Chee et al., 2008; Chee and Tan, 2010). Sleep loss also reduces the capacity to downregulate medial frontal and posterior cingulate activity leading to prolonged reaction times in a vigilance task (Drummond et al., 2005b). The cortico-thalamic alertness network also shows compensatory response to sleep loss not only during complex tasks (Drummond et al., 2001; Tomasi et al., 2008) but also during an awake but resting state (Poudel et al., 2012).

To identify neural correlates of both sustained and transient changes in alertness after sleep restriction, we scanned participants performing a blocked design fixation vs 2-D pursuit-tracking task during rested and sleep-restricted sessions. Specifically, we investigated effects of a single night of acute sleep-restriction on performance during a pursuit tracking task and on BOLD activity. We hypothesized that sleep-restriction would (1) increase both sustained and transient errors in performance, (2) alter the BOLD response in visuomotor and arousal networks with time-on-task, and (3) elicit a distinct pattern of BOLD responses during transient errors.

Materials and methods

Participants

Twenty right-handed volunteers (10 males and 10 females, aged 20 to 37 years, mean age 24.9 years) with no history of neurological, psychiatric, or sleep disorder participated in the study. For inclusion in the study, participants had to report a usual time to bed between 10 and 12 pm and a usual time in bed of between 7.0 and 8.5 h. Ethical approval for the study was obtained from the New Zealand Upper South B Regional Ethics Committee.

Study procedure

All participants visited the laboratory three times. On the first visit, they were briefed on the experimental protocol and provided with an Actiwatch (Respironics Inc., PA, USA) and a detailed sleep diary to record their sleep habits for 6 days and 5 nights prior to each of the two experimental sessions. They also recorded time of intake of caffeine, alcohol, and food in the diary. The second and third visits involved rested and sleep-restricted sessions, the order of which was counterbalanced across the participants. The sessions were 1 week apart to minimize residual effects of sleep restriction in participants who were sleep-restricted during the first session.

The participants were asked to sleep normal hours during the week prior to the rested session. They were asked to do likewise for the sleep-restricted session except for the immediately preceding night in which their time-in-bed was restricted to 4 h (3:00–7:00 am). Participants were requested not to engage in any safety-sensitive tasks (such as driving) following the sleep restriction. They were also asked not to consume any stimulants or depressants, such as alcohol, caffeine, and nicotine, on the day of either experimental session.

On the day of each scan, participants arrived at the laboratory an hour before the scanning session. Sleep habits recorded by the actiwatch and in the sleep diary were inspected prior to each of the scanning sessions to confirm compliance with the sleep schedule required for inclusion in the study. The sleep diary was used to confirm that participants did not consume any prohibited substances (caffeine and alcohol) on the day of scanning. Participants were provided with a lunch of hot noodles. They were also able to rate their current subjective sleepiness using the Karolinska Sleepiness Scale (KSS) (Akerstedt and Gillberg, 1990) and Stanford Sleepiness Scale (SSS) (Hoddes et al., 1972) before entering the scanner room. Their self-rated propensity to fall asleep during the day was estimated using the Epworth Sleepiness Scale (ESS) (Johns, 1991). The participants entered the scanner between 1:00 pm and 2:30 pm.

Experimental task

Each participant undertook a 12-min pursuit-tracking task in a blocked design (Fig. 1). During each of the 12 30-s tracking epochs, they had to manoeuvre an MRI-compatible finger-based joystick (Current Designs, Philadelphia, PA, USA) to pursue a 2-D random target moving continuously on a computer screen (Fig. 1.). The target (yellow disc) and the joystick response (red disc), generated by a custom-designed software, were presented via MRI-compatible goggles (Avotec, Stuart, FL, USA) with a resolution of 1024 × 768 pixels and a field of view of 30° × 23°. The target waveform was pseudorandom in nature with period of 30 s so that the complexity of the target was the same for all 30-s epochs of tracking but varied within each block. During the 12 30-s fixation epochs, the participants fixated on a fixed target and response disc in the centre of the screen with a grey background. Participants were familiarized with the tracking task for 2 min both inside and outside the scanner. They were instructed to control the

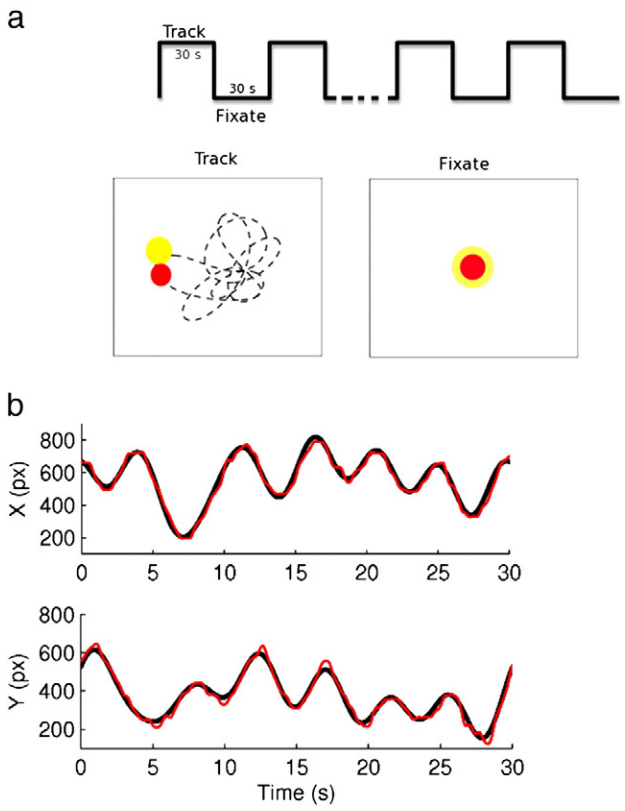

Fig. 1. The pursuit-tracking task. (a) During the 12 tracking blocks, participants used a finger-based joystick to track the displayed yellow target disc moving in a quasi-random trajectory (dotted line) with a red cursor disc. During the 12 fixation blocks, participants looked at the centre of the screen. (b) Accurate tracking led to the movement of the response disc along the same trajectory as the target disc as displayed in the target (smooth black line) and response (jerky red line) position for one cycle (30-s) of tracking. The units are in pixels (px).