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Dual-tasking alleviated sleep deprivation disruption in visuomotor tracking: An fMRI study

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ABSTRACT

Effects of dual-responding on tracking performance after 49-h of sleep deprivation (SD) were evaluated behaviorally and with functional magnetic resonance imaging (fMRI). Continuous visuomotor tracking was performed simultaneously with an intermittent color-matching visual detection task in which a pair of color-matched stimuli constituted a target and non-matches were non-targets. Tracking error means were binned time-locked to stimulus onset of the detection task in order to observe changes associated with dual-responding by comparing the error during targets and non-targets. Similar comparison was made with fMRI data. Our result showed that despite a significant increase in the overall tracking error post SD, from 20 pixels pre SD to 45 pixels post SD, error decreased to a minimum of about 25 pixels 0–6 s after dual-response. Despite an overall reduced activation post SD, greater activation difference between targets and non-targets was found post SD in task-related regions, such as the left cerebellum, the left somatosensory cortex, the left extrastriate cortex, bilateral precuneus, the left middle frontal gyrus, and the left motor cortex. Our results suggest that dual-response helps to alleviate performance impairment usually associated with SD. The duration of the alleviation effect was on the order of seconds after dual-responding.

1. Introduction

As our society becomes more sleep deprived and more dependent on technology (National Sleep Foundation, 2011 *Sleep in America Poll*), people are frequently multitasking while suffering from sleep deprivation. While sleep deprivation tends to lower our performance on tasks (Bell-McGinty et al., 2004; Donnell, 1969; Durmer & Dinges, 2005; Habeck et al., 2004; Horne, Anderson, & Wilkinson, 1983; Pashler, 1994; Pilcher & Huffcutt, 1996), a number of multi-task studies showed that performance was maintained after sleep deprivation (Pace-Schott et al., 2009; Pilcher, Band, Odle-Dusseau, & Muth, 2007; Strangman, Thompson, Strauss, Marshburn, & Sutton, 2005). In a comprehensive 28-h sleep deprivation study, Pilcher et al. (2007) examined performance changes in tasks with a wide range of demand, from simple vigilance task such as the Psychomotor Vigilance Test (PVT) to the cognitively challenging Wombat, in which tracking task alternated with several bonus tasks. Performance on vigilance tests suffered after sleep deprivation but Wombat performance actually increased over the course of sleep deprivation sessions due to the learning effect. Strangman et al. (2005) reported that, in addition to maintained performance on a dual-joystick controlled navigation task, regions with increased as well as regions with decreased brain activation were found after sleep deprivation even though, with the exception of studies such as Drummond et al. (2000), traditional sleep deprivation studies generally showed only decreased brain activation with performance deficits (Chuah, Venkatraman, Dinges, & Chee, 2006; Drummond et al., 1999; Thomas et al., 2000).

The mechanism underlying multi-tasking has been studied extensively using dual-tasking paradigms (Brown, 1997; Jolicoeur, 1999; Pashler, 1994) in which performance interference has been reported in one or both tasks due to the limited resources that are shared by the tasks (Brown, 1997; Jolicoeur, 1999; Pashler, 1994). If both dual-tasking and sleep deprivation have negative effects on performance, combining the two factors should have even more detrimental effects. Thus it seems contradictory that under sleep deprivation stress, dual-tasking actually protected performance from SD effects in comparison to performance on single-tasks. However, not all multi-task tracking showed maintained performance after SD. Caldwell and Ramspott (1998) found a time-on-task post SD effect: performance worsened as the time spent on the task increased. The task used by the study was called the multi-attribute task battery (MATB), which consisted of a

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primary tracking task and three other detection tasks, one audio and two visual.

In a previous study, we examined a task similar to MATB but with only one detection task instead of three (Gazes et al., 2010). Behaviorally and with fMRI, we examined the effect of sleep deprivation on the MATB-like task to gain a better understanding of why a MATB-like task shows SD impairment but tasks used by Pilcher et al. and Strangman et al. do not. Tracking error means were binned so that they were time-locked to the stimulus onsets of the detection task to observe temporal changes in tracking relative to the secondary task. Understanding the discrepancy among multitask sleep deprivation studies by examining the interaction between SD and dual-tasking may pinpoint important cognitive mechanisms that can help to resist the debilitating sleep deprivation effects. Specifically, based on our finding from Gazes et al. (2010), the most interference occurs in dual-responding for our task, if dual-tasking interacts with SD to form a protective effect on performance under SD, then the protective effect should be most pronounced during dual-responses.

2. Experimental procedure

2.1. Participants

Twenty-four healthy participants completed the sleep deprivation protocol. Nineteen participants (11 males, 8 females), between the ages of 20 and 34 years (age = 23 ± 3.6 years), were included in the analyses. Four participants were excluded due to equipment problems and one participant was excluded based on a pre SD root-mean-square tracking error of greater than three standard deviations above the mean. All participants were right-handed and carefully screened to ensure that they had no history of medical, psychiatric, neurological or sleep disorder. Habitual coffee drinkers (1 cup or more coffee per day) were excluded from the study. Participants maintained a sleep log for 2 weeks prior to study; the average amount of sleep per participant per day was 8.5 h. Mean within-subjects variability across the 14 days prior to the experiment gave a mean standard deviation of 1.3 h. Sleep data was missing for two participants. Participants were instructed to stop drinking caffeine 24 h prior to study participation and for the duration of the study. All participants passed substance abuse screening tests. Participants were supervised at all times, and polysomnographic monitoring confirmed that they remained awake during the sleep deprivation period. Informed consent, as approved by the Internal Review Board of the College of Physicians and Surgeons of Columbia University, was obtained prior to study participation and after the nature and risks of the study were explained. Participants were paid for their participation in the study.

2.2. Study protocol

Participants were admitted into the hospital on a Monday and received a full night of rest (>8 h). Research personnel arrived at participant's room at 9 AM. The initial test scan occurred at 10 AM (pre SD) Tuesday morning, and the follow-up scan occurred at the same time 48 h later (post SD) to eliminate confounding circadian effects, yielding approximately 49 h of prolonged wakefulness. The tracking study was performed as part of a larger experiment in which repetitive transcranial magnetic stimulation (rTMS) was administered twice on both Tuesday and Wednesday. Regions that received rTMS were based on a set of cortical regions identified by Habeck et al. (2004) to be associated with performance in a second task studied in the experiment, and thus the manipulation was not targeted at the tracking task. None of the effects of interest both behaviorally and in neuroimaging discussed in this paper showed an interaction with TMS manipulation (SD × TMS: $F(1, 17) = 0.200$, $p = 0.660$; SD × Single/Dual Condition × TMS: $F(1, 17) = 1.99$, $p = 0.177$; SD × Single/Dual Condition × Target/Nontarget × TMS: $F(1, 17) = 1.41$, $p = 0.252$).

2.3. Task

All participants were tested in both the single- and the dual-task conditions. The single-task condition was added as a control condition in which participants performed only a visuomotor compensatory tracking task. In the dual-task condition, participants also performed a color matching visual detection task. For the continuous visuomotor tracking, a white plus sign constituted the reference position and was drawn fixed at the center of the screen (see Fig. 1). At trial onset the cursor was aligned with the crosshair. At each update, a continuously varying pseudorandom perturbation was added to the previous x and y coordinates of the cursor. This had the effect of moving the cursor away from the center as though an unpredictable force had been applied to the participant's hand. The task was then to maintain the cursor position aligned with the reference position (the plus sign) and to counteract the perturbation force using the right hand to control a joystick. The cursor position at each update was further determined by the net sum of all previous joystick movements such that a 2 unit movement in the positive x direction would continue to push the cursor to the right by 2 units until a joystick movement in the negative x direction of equal magnitude was made. Movements in the x- and y-axis were calculated independently. The cursor was restricted to within a radius of 100 pixels from the reference position, thus setting a maximum distance of 100 pixels in any direction. If the cursor reached the maximum distance of 100 pixels, it remained at the same location until the participant moved it away.

For both training and testing, each tracking trial lasted 126 s. Training for the task lasted 27.4 min on 6 trials each of single- and dual-task conditions. Testing in the MRI scanner consisted of 3 blocks in which 2 trials of each condition were presented (4 trials per block) and randomly ordered across participants. Each testing

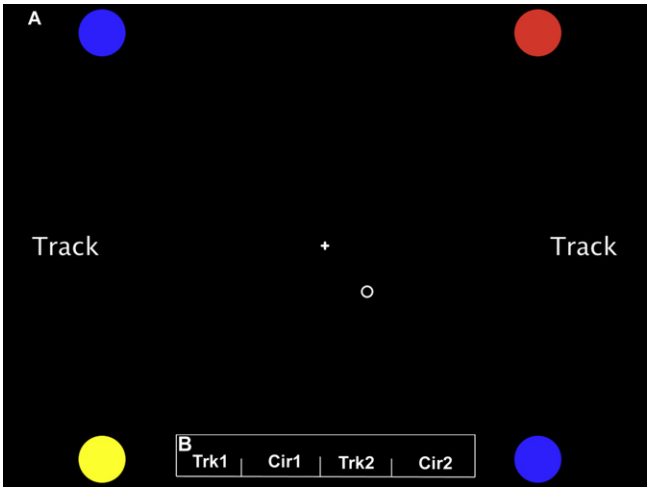

Fig. 1. (A) Screenshot of the task showing tracking stimulus at the center and visual detection stimulus at the four corners. The small circle to the lower right of the plus sign is the tracking cursor controlled by participants. Colored circles for the visual detection task can be any of four colors: red, green, blue, and yellow. The two matching blue circles constitute a target and the non-matching red and yellow circles are non-targets. The word "Track" on either side of screen signals a single-task condition while "Circles" (not shown) signals a dual-task condition. (B) The structure of a block, consisting of two trials of each condition. Single-task is shown as Trk1 and Trk2, and dual-task as Cir1 and Cir2. The order of trials shown is an example. The trial order is randomized for each block.