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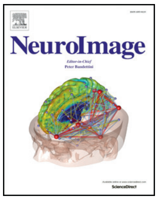

Modulating rest-break length induces differential recruitment of automatic and controlled attentional processes upon task reengagement

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A R T I C L E I N F O

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A B S T R A C T

Rest breaks are commonly administered as a countermeasure to reduce on-the-job fatigue, both physical and mental. However, this practice makes the assumption that recovery from fatigue, as measured by the reversal of performance declines, is the sole effect of taking a break on behavior. Here, through administering rest breaks of differing lengths in between blocks of a mentally demanding symbol decoding task, we show that this assumption may not be strictly true. First, we replicate previous work by showing that taking a longer break leads to two correlated effects: greater immediate rebound in performance, and greater subsequent time-on-task decline. Using fMRI, we reveal that time-on-task in this paradigm is associated with increasing recruitment of fronto-parietal areas associated with top-down control, and decreasing deactivation in the default-mode network. Finally, by analyzing individual differences, we reveal a potential neural basis for our behavioral observation: greater recovery following long breaks is associated with greater activity in the putamen, an area associated with the automatic generation of motor responses, followed by greater activity in left middle frontal gyrus by the end of those task periods. Taken together, this suggests a shift in the implicit engagement of automatic and controlled attentional processing following longer breaks. This shift may be undesirable or detrimental in real-world situations where maintaining a stable level of attention over time is necessary.

Introduction

Fatigue in the workplace is a serious but preventable cause of lapses, errors, and accidents (Landrigan et al., 2004; Williamson et al., 2011). Consequently, detecting and reversing its detrimental effects have been the subject of much ongoing investigation. One important focus of this research has been the impact of rest breaks and task interruptions on fatigue, work performance, and accident risk, with many studies finding a positive effect of rest on all of these variables (Tucker, 2003). The commonsense model, therefore, is that work and rest are two sides of the same coin, and that the processes associated with recovery are trivially a reversal of those associated with decline.

This assumption is implicit in the neuroergonomics literature (Parasuraman and Rizzo, 2008), in which the effects of mental fatigue but not recovery on human brain function have been well documented. One of the most robust findings in this field is that mental fatigue is associated with dysfunction in top-down executive control, and decreases in activity in associated areas (Paus et al., 1997; Coull et al., 1998; Boksem et al., 2005; Lim et al., 2010; Breckel et al., 2013; Langner and Eickhoff, 2013; Sun et al., 2014a). Specifically, these studies have shown that the integrity of the frontoparietal network is compromised with increasing time-on-task (TOT), leading to the failure of sub-processes such as goal maintenance, and target-driven reorientation of attention. The amplitude of event-related potential (ERP) components associated with error monitoring and inhibition is also significantly reduced as a person enters a state of fatigue (Boksem et al., 2005; Lorist et al., 2005). Using individual differences analysis, it has been shown that failure to maintain good performance occurs *in spite of* compensatory top-down effort, and not for want of it (Bonnefond et al., 2010; Demeter et al., 2011). In short, a fairly comprehensive picture of the brain under conditions of fatigue has emerged from these investigations.

In contrast, the cognitive neuroscience of mid-tasks breaks has been almost completely ignored. This is in part due to intuitions drawn from resource theory (Warm et al., 2008) that rest breaks simply reverse the neural effects observed over periods of fatigue by releasing demands on cognitive and neural resources, putatively allowing them to be replenished (Helton and Russell, 2012). However, recent work on this subject suggests that a more nuanced view might be warranted. For example, Lim et al. (2013) reported that there are substantial individual differences in the degree of recovery received during a rest period, with spectral power in the upper alpha (10–12 Hz) band of electroencephalographic activity predicting improvements in reaction time following a break. Helton and Russell (2015) reported that the specific activity performed during a break is an important moderator of how much recovery it affords. Finally, Lim and Kwok (in press) recently demonstrated that the immediate recovery observed after a break is

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inversely correlated with the time-on-task slope in the subsequent work block. This last behavioral finding prompted us to set up the current replication study, as well as interrogate the neural correlates of this novel effect.

To this end, we used fMRI to study brain activation in a test of cognitive throughput interspersed with breaks of different lengths. This test was self-paced; that is, participants determined the rate at which they worked, as opposed to the task having a pre-determined event rate. We hypothesized that we would replicate our previous behavioral findings: that the immediate recovery received from a break correlates with the slope of time-on-task in the succeeding task block. Furthermore, we predicted that higher levels of prefrontal activation would accompany greater TOT declines in the blocks following longer breaks, indicating the increased engagement of executive attention.

Methods

Participants

Participants were recruited from the National University of Singapore through online advertising and word-of-mouth. All participants were screened for right-handedness (Oldfield, 1971) and normal or corrected-to-normal vision, and to ensure they had no history of long-term physical or psychological disorders. Eligible individuals were invited for a behavioral screening session ($N = 31$), and those who achieved performance criterion during this session were invited for the fMRI session approximately one week later ($N = 30$). Of these, 1 participant dropped out prior to the fMRI session, and 2 were eventually excluded for excessive head motion in the scanner, yielding a final sample size of 27 (12 male; mean (SD) age = 22.7 (1.74)).

Blocked Symbol Decoding Task (BSDT)

To measure the effects of variable rest pauses on a self-paced task, we used a modified symbol-decoding task similar to the Symbol-Digit Modality Test (Smith, 1982) (Fig. 1). Participants learned a mapping of four symbols ('⊥' '+' '×' 'Λ') to four letters ('f' 'g' 'h' 'j'), and were required to press the appropriate letter key (on a standard QWERTY keyboard) with their right hand when each symbol appeared. Each self-paced trial consisted of one symbol presented at a time in the centre of the screen, at approximately 1 degree of visual angle. This symbol was replaced by a blank screen for 100 ms following a response, before presentation of the next symbol. Consecutive stimuli were always different. Each block of the BSDT consisted of 150 trials, followed by a pseudorandom, predetermined rest break of either 12 s or 28 s. Stimuli were presented using Psychtoolbox (Brainard, 1997; Pelli, 1997), via MATLAB R2012A (http://www.mathworks.com).

Procedure

All testing took place in the Cognitive Neuroscience Laboratory of the Duke-NUS Graduate Medical School, and all testing sessions were held between 1:00 and 4:00 pm to control for possible circadian confounds. The first session was a behavioral screening session, which was administered to minimize practice effects during the fMRI scanning session, as well as to exclude very slow responders, due to the time limitations of the fMRI scan.

During this screening session, participants were first instructed on how to perform the BSDT, and underwent two practice runs. In the first practice run, participants were shown a legend mapping the symbols to the appropriate letters. They performed 600 trials in this first practice run to learn the mapping of the symbols to the letters. In the second practice run, participants performed 150 trials of the same task, with the legend removed. In both practice runs, participants received feedback if they made an incorrect response. Following these two practice runs, participants underwent two experimental runs consisting of 7 task blocks interleaved with 6 rest breaks. A 5-minute rest opportunity was provided between the two runs. We excluded participants who did not achieve at least 90% accuracy during the two experimental runs, and or had median reaction times of >1000 ms (>3 SD than median RT of the sample).

Participants who achieved criterion in the screening session were invited for fMRI scanning on a separate day approximately one week later. They were asked to refrain from alcohol and caffeine for 6 h prior to arrival for scanning. On arrival at the center, participants performed a two-block (300 trial) practice run before the fMRI scan as a reminder of the task procedure. They were then given a 30-minute rest opportunity before entering the scanner. fMRI scans were collected in the following order: resting-state fMRI (~8 min), BSDT, high-resolution MPRAGE, BSDT, and resting-state fMRI. Data from resting-state fMRI scans are not reported in this paper.

In the scanner, BSDT stimuli were projected onto a screen using an LCD projector, and participants viewed these through a mirror positioned at their eye level inside the head coil. Participants responded

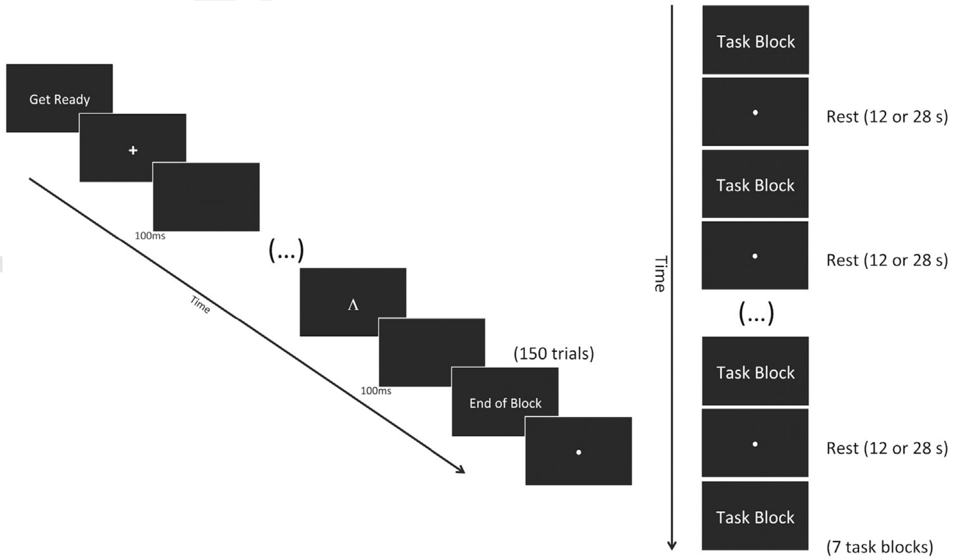

Fig. 1. Experimental paradigm. Participants performed the Blocked Symbol Decoding Task (BSDT). Left: each task block consisted of 150 decoding trials separated by an inter-stimulus interval of 100 ms. Right: Participants performed 7 blocks of the task in each run. Blocks were separated by break periods of either 12 s or 28 s, in a pseudo-random, predetermined order.

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