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Tracking behavioral and neural fluctuations during sustained attention: A robust replication and extension

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ABSTRACT

Novel paradigms have allowed for more precise measurements of sustained attention ability and fluctuations in sustained attention over time, as well as the neural basis of fluctuations and lapses in performance. However, in recent years, concerns have arisen over the replicability of neuroimaging studies and psychology more broadly, particularly given the typically small sample sizes. One recently developed paradigm, the gradual-onset continuous performance task (gradCPT) has been validated behaviorally in large samples of participants. Yet neuroimaging studies investigating the neural basis of performance on this task have only been collected in small samples. The present study completed both a robust replication of the original neuroimaging findings and extended previous results from the gradCPT task using a large sample of 140 Veteran participants. Results replicate findings that fluctuations in attentional stability are tracked over time by BOLD activity in task positive (e.g., dorsal and ventral attention networks) and task negative (e.g., default network) regions. Extending prior results, we relate this coupling between attentional stability and on-going brain activity to overall sustained attention ability and demonstrate that this coupling strength, along with across-network coupling, could be used to predict individual differences in performance. Additionally, the results extend previous findings by demonstrating that temporal dynamics across the default and dorsal attention networks are associated with lapse-likelihood on subsequent trials. This study demonstrates the reliability of the gradCPT, and underscores the utility of this paradigm in understanding attentional fluctuations, as well as individual variation and deficits in sustained attention.

Introduction

Over the course of a day, individuals consistently employ and sustain attention to a multitude of tasks. Whether driving to work or reading a paper, the ability to maintain focused voluntary attention on a single task is a critical cognitive function that allows individuals to effectively interact with their environments and complete goals. Given that the ability to sustain attention can profoundly impact many other cognitive and sensory functions (Barkley, 1997; Fortenbaugh, Robertson and Esterman, 2017c; Sarter et al., 2001; H. Silver and Feldman, 2005), characterizing sustained attention abilities has been an active area of research for decades, with some studies focused on understanding fluctuations of or decrements in sustained attention ability across time in healthy observers (Berardi et al., 2001; Carriere et al., 2010; Esterman, Rosenberg and Noonan, 2014b; Fortenbaugh et al., 2015; Levy, 1980; Mackworth, 1948; Robertson et al., 1997; Rosenberg et al., 2016; Sarter et al., 2001; Staub et al., 2014; Staub et al., 2013), and others focused on characterizing deficits in sustained attention ability associated with psychiatric and neurological disorders (Altpeter et al., 2000; Barkley, 1997; Clark et al., 2002; Forster et al., 2015; Park et al., 2012; Rosenberg et al., 2016; Van Vleet and DeGutis, 2013).

In recent years, researchers have made substantial progress in characterizing the neural networks involved in sustained attention (Clayton et al., 2015; Esterman et al., 2013; Esterman, Rosenberg, et al., 2014b;

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Fortenbaugh, DeGutis and Esterman, 2017b; Langner and Eickoff, 2013; Lawrence et al., 2003; Rosenberg et al., 2016; Sarter et al., 2001). Enabling this progress has been the development of novel tasks and analytic methods that allow for more precise measurements of sustained attention ability and induce more failures in sustained attention over shorter testing periods, increasing sensitivity to individual differences, as well as behavioral relationships with brain activity/connectivity. One commonly used paradigm in this literature is the not-X continuous performance task, requiring participants to frequently respond to non-target stimuli and infrequently withhold responses to rare target stimuli. This task allows measurements of sustained attention and vigilance decrements to be obtained over much shorter periods of time than other tasks, which involve responses only to infrequent target events, while at the same time sampling behavior at a high rate. These include the commonly used Sustained Attention to Response Task (SART) (Robertson et al., 1997), and the Gradual Onset Continuous Performance Task (gradCPT) (Esterman et al., 2013), as well as many other innovative variations (Helton and Russell, 2011; Kucyi et al., 2017; Shalev et al., 2011; Temple et al., 2000). One unique feature that was introduced in the gradCPT is the use of gradual transitions from one trial image to the next, eliminating the abrupt offsets and onsets of stimuli between trials that can serve to orient involuntary attention toward the display (Fortenbaugh et al., 2015; Rosenberg et al., 2013). The removal of these abrupt offsets/onsets makes the task more dependent on endogenous attentional control both behaviorally and with regard to fluctuations in the fMRI signal.

Previous studies using the gradCPT have leveraged its sensitive and data-rich behavioral output to identify and examine a number of behavioral and neural indicators of both instantaneous attentional state and overall sustained attention ability. For example, results from the original gradCPT study (Esterman et al., 2013) showed that while the default, dorsal attention, and sensory regions demonstrated characteristic task-negative and task-positive BOLD responses to the onset of target (mountain) scenes, preparatory (pre-trial) activity in these regions was also associated with subsequent accuracy. Specifically, greater activity in stimulus-selective parahippocampal place area (PPA) and dorsal attention network (DAN) was associated with subsequent accuracy, while greater activity in the default mode network (DMN) was associated with subsequent errors. These results are consistent with other studies that indicate that ongoing DMN activity may reflect task-unrelated thoughts such as mind wandering (Andrews-Hanna et al., 2014; Broyd et al., 2009; Christoff et al., 2016; Greicius et al., 2003; Mason et al., 2007; Raichle et al., 2001), and that ongoing sensory/DAN activation may reflect ongoing attention to task-related stimuli (Corbetta and Shulman, 2002; Posner and Peterson, 1990; M. A. Silver and Kastner, 2009). In addition to examining activity surrounding rare target events, the original study by Esterman et al. (2013) computed a continuous dynamic metric of reaction time variability, which revealed that sustained performance can be characterized by at least two states: when participants are "in the zone" versus "out of the zone". Periods of being "in the zone" are defined based on low reaction time variability to frequent non-target stimuli (e.g., images of city scenes) while "out of the zone" is defined as periods of higher reaction time variability. Analyses of in-the-zone versus out-of-the-zone periods revealed that accuracy was higher (fewer errors of commission and omission) during in-the-zone periods. In contrast to preparatory activation associated with target accuracy, fluctuations between these attentional states were coupled with on-going brain activity in the default mode network (DMN) such that greater activation was associated with being in the zone. The dorsal attention network (DAN) exhibited the opposite relationship–greater activity when out of the zone. Subsequent studies corroborated and extended the findings about these relationships, indicating greater task-negative activation when in the zone and greater task-positive activation when out of the zone (in dorsal and ventral attention regions; Kucyi et al., 2016; Esterman et al., 2014a, 2016). Further, these patterns interacted with preparatory activity before targets (correct vs. incorrect) such that task-positive effects were stronger out of the zone and task-negative effects were stronger in the zone. This led to the hypothesis that optimal attentional states are not simply reflected by task-positive and task-negative activation alone. Specifically, attentional fluctuations can be described with multiple behavioral markers-accuracy, mind wandering, RT variability, and motivational state-each of which may have independent and even opposing contributions to brain activity across large-scale brain networks. This dichotomous relationship between the neural markers of accuracy and variability suggest that, for tasks that require constant engagement across extended periods of time, prolonged suppression of DMN and/or activation of DAN may not be sustainable and may undermine attentional stability over time. Thus, in relation to the observed variability coupling with brain activity, moderate increases in DMN activity during "in the zone" periods and decreases in task-positive attentional control regions such as the DAN may indicate a more distributed and/or efficient attentional state that can be maintained over periods of time. One unanswered question regarding this somewhat surprising variability-brain coupling is whether the degree to which DMN and DAN are coupled with fluctuations in variability is related to overall attention ability across participants. Specifically, do participants with better sustained performance show greater coupling, supporting the idea that this coupling helps maintain a balance or optimal activation across task-negative and task-positive networks.

Since the initial publication, the gradCPT and its variants have been used to further characterize sustained attention both in neurotypical (Esterman et al., 2015, 2016; Esterman et al., 2017; Esterman, Reagan, Liu, Turner and DeGutis, 2014a; Esterman, Rosenberg, et al., 2014b; Kucyi et al., 2016; Kucyi et al., 2017; Rosenberg et al., 2013) and clinical populations (Auerbach et al., 2014; Fortenbaugh, Corbo, et al., 2017a; Rosenberg et al., 2016). Further, this task has been used to explore variation in sustained attention associated with age, gender, sociocultural factors, and time of day (Fortenbaugh et al., 2015; Riley et al., 2017; Riley et al., 2016). Performance, as well as the neural correlates of fluctuations in accuracy (preparatory activity) and variability (in/out of the zone), have been shown to be modulated by motivation and reward (Esterman et al., 2016, 2017; Esterman, Reagan, et al., 2014a). In clinical samples, behavioral performance on the gradCPT has been associated with PTSD, depression, and early life trauma (Auerbach et al., 2014; DeGutis et al., 2015; Fortenbaugh, Corbo, et al., 2017a). Analyses of functional connectivity during the task, although outside the scope of this paper, are sensitive to individual differences in performance, early life trauma, and ADHD (Fortenbaugh, Corbo, et al., 2017a; Rosenberg et al., 2016).

There were two goals of the present study. First, we sought to replicate the core original findings from the Esterman et al. (2013) study. While multiple studies have utilized the gradCPT paradigm to ask novel questions, to date, the core findings regarding the relationship between ongoing activity in the DAN and DMN to ongoing attentional stability and pretrial activity in these regions to attentional lapses, has not been replicated. This is important as questions have arisen in recent years regarding the extent to which many findings in psychology and neuroscience replicate and generalize to larger samples that are not limited to self-selecting college students, have a greater range in baseline intelligence/cognitive functioning, and are more representative of the general population as a whole (Boekel et al., 2015; Button et al., 2013; Open Science Collaboration, 2015; Poldrack et al., 2017). Within the neurosciences, one of the primary issues that has been raised regarding findings from functional magnetic resonance imaging (fMRI) studies, is the low power that is associated in part with small sample sizes (Button et al., 2013). Given the diverse set of inferences being drawn from gradCPT, it is critical to determine whether the core behavioral and neural findings are both replicable and robust to changes in sampling population. The behavioral aspects of the gradCPT, including overall performance, the relationship between variables, as well as the reliability of each variable, have been validated in a large, heterogeneous sample of participants (>10,000). In terms of the fMRI findings, variability-BOLD correlations