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Beyond mind wandering: Performance variability and neural activity during off-task thought and other attention lapses

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ABSTRACT

To study the characteristics of attention lapses, a metronome response task and experience sampling were employed while recording fMRI data. Thought prompts queried several attention states (on-task, task-related interference, off-task, inattention). Off-task thoughts were probed on whether they arose in a spontaneous or constrained (i.e., directed) manner. Increased fMRI activation was observed in the default mode network during off-task thought and in subregions of the anterior cingulate cortex and inferior frontal gyrus during inattention. Activation also increased in the left hippocampus during constrained thoughts. Functional connectivity increased between the left superior temporal sulcus and right temporoparietal junction for constrained compared to spontaneous thoughts. Overall, behavioral results indicated a monotonic increase in performance variability from on-task to inattention. However, subtle but consistent differences were observed between self-reported attention state and performance. Results are discussed from perspectives of mind wandering frameworks, the function of brain networks, and the role of engagement in off-task thought.

1. Introduction

The neuroscience of mind wandering has advanced appreciably over the past decade. By applying convergent methods that span self-reports, behavioral indexes, and neuroimaging (a process referred to as *triangulation*, Smallwood & Schooler, 2015), researchers have been able to gain an understanding of how the brain supports ongoing mentation that is unrelated to other tasks at hand. Whereas the default mode network (DMN) has been strongly implicated in supporting many of these processes, the role of multiple large-scale networks such as the dorsal attention network (DAN) and fronto-parietal network (FPN) and their underlying dynamics have more recently been highlighted (Christoff et al., 2016). Furthermore, researchers have reliably documented the impact that failures of attention have on the task at hand. At the same time, research has emerged that suggests not all instances of mind wandering are inherently harmful (Godwin et al., 2017; Mooneyham & Schooler, 2013).

However, limitations have remained in mind wandering research as well. For example, many mind wandering studies categorize thought during task performance as dichotomous “on-task” and “off-task” states (e.g., Christoff et al., 2009), despite the emerging recognition that there is a variety of attention states between which individuals can fluctuate, such as meta-cognitive thoughts about the task or drifting into states of inattention and drowsiness (e.g., Unsworth & Robison, 2016). In addition, instances that have typically been defined as off-task states can be driven by either internally-directed processes (e.g., spontaneous recollections) or externally-oriented stimuli (e.g., a loud noise; Stawarczyk, Majerus, Maquet, et al., 2011). Off-task states can be further characterized

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by their dynamics, such as the extent to which thoughts arise spontaneously (Christoff et al., 2016). As discussed later, emphasizing the dynamics of mind wandering and other thoughts has important implications and predictions for behavior and for the neural mechanisms underlying these processes.

The goal of the current study is to go beyond mind wandering as it has typically been defined (e.g., off-task thought) and examine the behavioral and neural characteristics of a broad range of attention states (e.g., task-related interference and inattention) and dynamics (e.g., constrained and spontaneous thoughts) that individuals experience. In particular, these broad attention states include 1) on-task 2) task-related interference (TRI), defined as thoughts that occur during task performance that are related to the task at hand (e.g., wondering how long it will take), 3) off-task thought, defined as thoughts unrelated to the task at hand, and 4) inattention, defined as drowsy or not paying attention to anything in particular. By addressing this broad range, we will potentially be able to capture differences such as when one is distracted because they are thinking about other topics that interest them (i.e., off-task) and when one is distracted because they are drowsy and not paying attention to anything (i.e., inattentive). In addition, including this range of attention states enables us to dive more deeply into the off-task attention state and study its dynamics and relationship with performance without this attention state confounded by instances of inattention or task-related thought. Regarding these attention states, some research has begun to address these additional attention states. For example, Stawarczyk, Majerus, Maquet et al. (2011) observed increased fMRI activity in the right ventral mPFC during task-related interference relative to on-task thoughts. However, additional research examining attention states across a broad range is needed.

To capture the behavioral characteristics of attention states, we employed a version of the metronome response task (MRT), first published by Seli and colleagues (2013). The MRT is a rhythmic tapping task in which individuals tap along to a metronome and continuous performance variability is measured. Compared to other sustained attention tasks such as the sustained attention to response task (SART), the MRT is not heavily influenced by response selection, inhibition, and speed-accuracy tradeoffs and so may provide a purer measure of the effects of mind wandering on behavior. In the MRT, increased variability over time in the difference between the metronome onset and the corresponding tap onset (referred to as rhythmic response time; RRT) provides a behavioral index of mind wandering. We incorporated Seli and colleagues' MRT with experience sampling consisting of an extended set of self-report attention categories to address the limitations described above.

Regarding thought dynamics, or how our kinds of thoughts change over time, in a framework proposed by Christoff and colleagues (2016), thoughts fall along a continuum and can range from weakly constrained (e.g., spontaneous) to strongly constrained (e.g., directed). Spontaneous thoughts are defined as thoughts that arise relatively freely and with minimal constraints on the contents of thought. Spontaneous thoughts include processes like daydreaming and creative thought. (Note that within this framework, the term mind wandering is used more narrowly and is considered a type of spontaneous thought.) On the other hand, constrained thoughts occur when deliberate (e.g., goal-directed) or automatic (e.g., ruminative) processes impose constraints onto the content and flow of thought.

The distinction between spontaneous and constrained thought has implications for the underlying neural mechanisms supporting thoughts along this continuum. For example, the generation and variability of spontaneous thoughts is thought to be linked to the medial temporal lobe regions of the DMN. In contrast, deliberate constrained thoughts may be driven primarily by the FPN or the salience network (Christoff et al., 2016). Recent research has examined the EEG correlates of these types of thoughts (Kam et al., 2021). In addition, research has begun to examine variation in constrained and spontaneous thought across different populations and contexts. For example, Alperin et al. (2021) examined ADHD patients and observed that adults with ADHD experienced more spontaneous off-task thoughts (as well as more off-task thought in general) compared to non-ADHD controls during the SART. In another study, researchers found using experience sampling in everyday life that spontaneous thoughts were positively associated with concurrent valence (Mills et al., 2021). However, to date no neuroimaging research has empirically investigated the neural correlates of these types of thoughts. One of the goals of this current research is to begin to explore the neural signatures of thought dynamics in the off-task attention state.

Along with the dynamics of thought, with our approach it is also possible to more closely investigate the relationship between objective performance and subjective attention state. In general, it is reasonable to believe that decreases in performance are associated with increases in mind wandering and the corresponding recruitment of brain networks supporting mind wandering. However, some research suggests it is not always this straightforward. Esterman and colleagues (2012) and Kucyi, Hove et al. (2016) examined reaction time (RT) performance variability in continuous performance tasks during fMRI. In each study, the researchers observed moderate increases of DMN activity during periods of low variability RT ("in the zone" performance). This increased activity was proposed to be beneficial for supporting performance of these types of continuous, attention-demanding tasks in an efficient manner. However, neither group of researchers asked participants about their attention state or mind wandering experiences during the studies.

Conversely, in a separate study Kucyi, Esterman, and colleagues (2016) examined mind wandering reports and behavioral performance simultaneously during fMRI. In this study, participants performed a continuous performance task that consisted of viewing gradually changing images of scenes. Participants were instructed to press a button for each city scene and withhold the button press for each mountain scene. After each block, participants rated the extent to which they were on-task or were mind wandering. When examining DMN activation preceding the thought prompts, Kucyi, Esterman and colleagues (2016) found that mind wandering was associated with greater RT variability and the DMN activity pattern was more complex than in Esterman et al. (2012) and Kucyi, Hove et al. (2016). Specifically, DMN activity was highest during off-task attention with stable RT and lowest during on-task attention with variable RT. To explain these complex results, Kucyi, Esterman, and colleagues (2016) speculated that DMN activity and its relation to both mind wandering and steady behavior may be driven by the additive effects of separate neurophysiological processes underlying BOLD activation and deactivation. Kucyi, Esterman, and colleagues (2016) further suggested that the relationship between variable behavior and decreased DMN activity could arise due to periods of perceived increases in cognitive demand, in which DMN deactivation increases.

Although these interpretations are speculative, the findings from Kucyi, Esterman, and colleagues (2016) indicate a complex relationship between performance and attention state. Simultaneous consideration of both self-reported attention states and behavior could yield insights into the function of the DMN and other brain networks (Kucyi, Esterman et al., 2016). In the current research, we take a similar approach with the MRT procedure to examine brain activity during stable and variable performance in both on-task and off-task attention states. We focus on the on-task and off-task attention states as it is conceptually interesting to compare performance extremes between attention states that both involve thinking (as opposed to, for example, being inattentive or drowsy), yet in one state (on-task) this thinking is directly on the task and in the other state (off-task) thinking is on topics unrelated to the task. In addition, we focus on the extreme ends of performance on the MRT (high and low variability) in both attention states, because instances where performance deviates from what is typical (e.g., low variability when off-task) may have interesting implications for how the brain supports and sustains performance as well as implications in real-world situations where attention lapses. Going forward, we refer to this as a *quadrant state analysis* to reflect the four possible attention/performance states: on-task with low performance variability, on-task with high performance variability, off-task with low performance variability, and off-task with high performance variability.

To summarize, the current study uses a triangulation approach by combining behavioral performance, thought sampling, and fMRI to examine the neural correlates and behavioral patterns of attention states. There are two primary objectives in this study, as follows.

1) Identify the performance differences and neural basis of attention states, specifically by going beyond the on-task/off-task characterization and examining a) four attention states that capture a range of focus (on-task) and distraction (task-related interference, off-task, and inattention), and b) the dynamic nature (e.g., spontaneous and constrained) of off-task attention states.
2) Examine the interrelationship between the off-task attention state, behavioral variability, and brain activity.

To address the first objective, we examine MRT performance variability across the four attention states (on-task, TRI, off-task, and inattention). We also examine fMRI activation and functional connectivity within and between these attention states. Similarly, we examine MRT performance variability between the spontaneous and constrained attention states, as well as fMRI activation and functional connectivity. To address the second objective, we perform the quadrant state analysis described above, and compare high and low MRT performance variability in both on-task and off-task attentions states. In addition, we examine fMRI activation and percent signal change in the DMN in each of the four quadrants of the analysis to identify patterns of brain activity that vary based on both performance and attention state.

We predict that distinct patterns of brain activity will be identified across the different attention states (i.e., on-task, task-related interference, off-task, and inattentiveness). In addition, off-task thought dynamics (i.e., spontaneous vs constrained) will dissociate in manners similar to those proposed by Christoff and colleagues (2016). Furthermore, while variability in behavioral performance likely will increase during off-task states, additional differences may be observed when examining subjective state and performance simultaneously. Brain activity, particularly within the DMN, may lend support to these dissociations. Together, these results may further clarify findings in previous literature (e.g., Kucyi et al., 2016) and support our growing understanding of the complexities of the brain and behavior.

2. Method

2.1. Participants

A total of 35 participants (17 female, 17 male, 1 no response) were recruited from the Georgia Institute of Technology. Due to technical difficulties with the MRI scanner, the datasets from the first two participants were excluded. Two additional participants were excluded due to scanner contraindications. Therefore, 31 participants were included in behavioral and MRI analyses. The age of participants ranged from 18 to 23 ($M = 20$, $SD = 1.6$). All participants were right-handed, had normal or corrected-to-normal vision, were not contraindicated for MRI, and did not report any neurological or psychiatric conditions. In addition, eye tracking datasets were collected from a subset of these participants ($n = 24$) but were not included in the analyses presented here.

2.2. Metronome response task

Participants were instructed to keep their eyes open and focus on a fixation in the center of the screen. Participants performed the MRT across a series of tap periods. For each tap period, participants were instructed to tap along as synchronously as possible to a metronome sound. The metronome tone consisted of a 450-Hz sine wave presented for 75 ms (following parameters of Kucyi, Hove et al., 2016; Seli et al., 2013). Each metronome tone was preceded by 650 ms of silence and followed by 575 ms of silence (following the MRT procedures of Seli et al. 2013). Thus, across the tap periods the metronome sounded at a rate of approximately 0.77 Hz (one tone per 1300 s). Each tap period was preceded by a short baseline fixation with a 2 – 4 s variable duration. The fixation cross remained on the screen across the duration of the tap periods. The duration of the tap periods varied and the number of tap periods of each duration followed approximately an exponential distribution and ranged as follows for each block: six tap periods of 16 s; three tap periods of 20 s; two tap periods of 24 s; two tap periods of 28 s; one tap period of 32 s; and one tap period of 36 s. The order in which these tap periods occurred within each block was randomized. The exponential distribution of tap period durations was used to minimize expectancy effects from participants. Participants had a 4-button response box and were instructed to tap by pressing the button under their right index finger. After each tap period ended, the metronome stopped and participants were presented with the thought probes.

2.3. Thought probes

Participants were presented with a set of thought probes at the end of each tap period that asked them to classify the attention state they were in just prior to the onset of the probe. The first thought probe ("Attention Prompt") followed those from Stawarczyk, Majerus, and Maj et al. (2011) and Unsworth and Robison (2016): 1) on-task, 2) task-related thoughts, 3) off-task, and 4) not alert / drowsy. Participants had six seconds to select their response via button-press. After selecting the response, the prompt remained on the screen until the end of the six seconds, and participants could change their response if desired.

Following the first prompt, if participants did not select the off-task option, they were then presented with a fixation for the next 10 s. (These 10 s ensured consistent timing for MRI scan durations, and also discouraged participants from selecting one of these options to speed through the task.) If participants selected the off-task option, they were then presented with two additional prompts to further address the nature of off-task thought. The second prompt ("Environment Prompt") addressed the environmental nature of the off-task thought: 1) surrounding environment, 2) internal thoughts. The third prompt ("Dynamics Prompt") addressed the dynamics of thought, following theorizing by Christoff et al. (2016) and Mills et al. (2018): 1) freely moving, 2) constrained. Each of these prompts was presented for an additional 5 s and remained on the screen for the full length of time. Definitions for all attention state categories are summarized in Table 1.

2.4. fMRI Design

Imaging was conducted on a Siemens 3T Trio MRI scanner at the Georgia Institute of Technology. All participants completed a T1-weighted MPRAGE anatomical scan with the following acquisition parameters: FoV = 256 mm; 176 slices; $1.0 \times 1.0 \times 1.0$ mm^3 voxels; flip angle = 9°, TE = 3.98 ms; TR = 2250 ms; TI = 850 ms.

Participants then completed the main experiment over the course of five runs (run duration = 10 min, 33 s). During each run, functional T2*-weighted echo-planar scans were collected with the following acquisition parameters: FoV = 204 mm; slices = 37; $3.0 \times 3.0 \times 3.0$ mm^3 voxels; interleaved slice acquisition; gap = 0.5 mm; flip angle = 90°; TE = 30 ms; TR = 2000 ms.

2.5. Experimental procedure

The MRT was run using E-Prime software. All visual stimuli were presented in white font on a black background. In order to familiarize participants with the MRT, a practice session was held outside the scanner before the experiment began. The experimenter explained the meaning of each thought probe category and provided examples as needed (Appendix A). The participants then performed five trials at a desktop computer to familiarize themselves with the act of tapping and reporting attention states.

The main experiment consisted of five runs of 15 tap periods per run. At the start of each tap period, participants focused on a fixation cross in the center of the screen. This fixation served as the baseline with a variable duration (2 – 4 s). Following the baseline, the fixation remained on the screen and the metronome sound started. Participants were instructed to begin tapping as soon as they heard the metronome and to tap along as synchronously as possible for the duration of the tap period. At the end of the tap period, participants were presented with the first thought probe and had 6 s to enter their response. If participants selected the "off-task" option, they were then presented with two additional thought probes (described under "Thought Probes"). If participants selected any of the other three options, they were presented with a 10-s fixation period until the next baseline and tap period began. This fixation period was included to equate the duration of the entire probe period, regardless of the selection participants made to the first prompt. Upon completion of the main experiment, participants completed a questionnaire regarding their experience during the study.

Table 1
Definitions of each attention state and off-task thought category.

Attention State	Definition
on-task	Complete focus on the current task
task-related interference (TRI)	Thinking about topics related to the current task (e.g., how long it will take, one's performance, etc.)
off-task	Thinking about things unrelated to the task
internal	Thoughts that are internally directed and decoupled from the external environment (e.g., memories, problem solving, prospective thought)
external	Thoughts oriented to sights, sounds, scents, and other external stimuli in the immediate environment
spontaneous	Thoughts that arise relatively freely and are unconstrained / undirected. Example paraphrased from Christoff et al. (2016): while driving, one suddenly remembers to pick up dog food at the store, and then reminisces about winters from childhood
constrained	Goal-directed thoughts that arise in a constrained or directed manner. Example paraphrased from Christoff et al. (2016): while painting the house, one plans the afternoon chores and how to combine multiple errands into one trip
inattentive	Lack of attention toward any specific stimulus or topic; spacing out or feeling drowsy

Note. When participants were presented with the first prompt (Attention Prompt), they selected either the on-task, task-related interference (TRI), off-task, or inattentive state. When participants selected the off-task state, they were then presented with two additional prompts: the environment prompt, with the choices internal or external, and the dynamics prompt, with the choices spontaneous and constrained.

2.6. Data processing and analysis

All behavioral and fMRI analyses were based on the data of the last 5 to 10 s preceding the thought probes. This duration is similar to that of other mind wandering studies using experience sampling during fMRI (Christoff et al., 2009) and should reliably capture the behavioral and neural correlates of attention fluctuations. In addition, all analyses required that each cell contain a minimum of two reports per participant. Cells with only one report per participant were excluded from the respective analysis. Unless otherwise noted, all behavioral inferential statistics were computed using linear mixed-effects models with the *lme* function from the *nlme* package in R. Linear mixed-effects models are extensions of the general linear model, and both fixed and random effects are modeled. These models have the advantage of being able to handle unbalanced designs and missing cells and have previously been used in mind wandering research to address these concerns (Unsworth & Robison, 2016). Post-hoc comparisons with Tukey correction were run in R.

Preprocessing and Analysis of Behavioral Data. All behavioral analyses were conducted on the performance data from the last five metronome tones preceding the thought prompts (Seli et al., 2013); this makes up approximately the last 6.5 s of the tapping period. Before statistical analysis, performance accuracy was calculated for these five taps preceding each tapping period. All missing taps were counted as errors. To be included in analysis, each trial needed to have at least three correctly performed taps out of the five total. With these exclusion criteria, an average of 3.53 % ($SEM = 1.39$ %) of trials were removed from each participant's data. In addition, trials that had no responses to the attention prompt were removed from analysis as well. On average, 2.51 % ($SEM = 0.84$ %) of these trials had no response.

The steps for behavioral data analysis of the MRT followed the procedures of Seli and colleagues (2013). For each participant for each tap period, the RRT was calculated from the last five metronome tones. The RRT was obtained by calculating the difference between the onset of the metronome tone and the corresponding time of key press. From here, the RRT variance was calculated from these values. Because the distribution of RRT variance is typically skewed right, a natural log transformation was applied to these values (Seli et al., 2013). Transformed RRT variance served as the dependent variable in the behavioral data analysis.

The frequency of each attention state in the attention prompt was calculated as a proportion out of all valid trials. Because the environment and dynamics prompts are nested within the off-task response of the attention prompt, the frequency of each attention state from these prompts was calculated as a proportion out of all valid off-task trials. The arcsine transformation (defined as $\sin^{-1}\sqrt{p}$ where p is the proportion) was applied to all proportion values before running inferential statistics. For interpretability, all descriptive statistics and figures depict the raw values.

*Quadrant State Analysis***.** This analysis focused on the on-task and off-task attention states from the attention prompt. The top and bottom third trials were identified based on RRT variance and organized into the following four conditions: on-task + high variance (on-high), on-task + low variance (on-low), off-task + high variance (off-high), and off-task + low variance (off-low). A linear mixed effects analysis was run to compare RRT variance across performance variability (high vs low) and attention state (on-task vs off-task).

Preprocessing and Analysis of fMRI Data. Data preprocessing was performed using Analysis of Functional NeuroImages (AFNI). Standard preprocessing was conducted, including despiking, slice time correction, motion correction, spatial smoothing (FWHM of 6.0 mm), structural–functional alignment, and normalization to MNI space. Individual analysis was conducted using AFNI. Group level analyses were conducted using AFNI and custom scripts in MATLAB. Individual and group analyses were conducted separately for each of the three prompts.

Individual Analysis. Design matrices were created for each participant with covariates for each attention state. For the attention prompt, covariates of interest were on-task, task-related interference (TRI), off-task, and inattentive states. For the environment prompt, covariates of interest were external and internal states. For the dynamics prompt, covariates of interest were spontaneous and constrained states. For all analyses, covariates of no interest consisted of trials with no/incorrect responses, the probe period when participants reported their attention states, and the fixation period at the start of each tapping period. For each analysis, the last 5.2 s (corresponding to the last four taps) preceding the thought prompt were convolved with an idealized hemodynamic response function and modeled with a generalized linear model in AFNI.

Whole-Brain Group Analysis. Data were analyzed at the group level with a linear mixed-effects model using the 3dLME function in AFNI. Like with the behavioral analyses, this model is an alternative to the traditional ANOVA but includes a random intercept and allows for missing data. The 3dLME function uses the coefficients modeled for each variable of interest in the individual analysis. Group-level general linear tests were run for the following contrasts from the attention prompt: on-task vs all distraction states; on-task vs TRI; on-task vs off-task; on-task vs inattentive; TRI vs off-task; TRI vs inattentive; and off-task vs inattentive. In addition, two conjunction analyses were run to further isolate neural activity pertaining to individual distraction states in the attention prompt. The first analysis tested which voxels were significant in both the off-task and inattentive states compared to the on-task state (off-task > on-task ∩ inattentive > on-task). The second analysis tested which voxels were significant in the off-task state compared to both the inattentive and on-task conditions (off-task > on-task ∩ off-task > inattentive). For the environment prompt, a general linear test was run for the contrast internal vs external. For the dynamics prompt, a general linear test was run for the contrast spontaneous vs constrained. A threshold of FDR corrected $q = 0.05$ was set for statistical analyses.

Quadrant State Analysis. A separate individual and group analysis was conducted for the quadrant state analysis. Data were analyzed in the same manner as described for the three prompts. The trials from the upper and lower third of behavioral performance from on-task and off-task attention states were included in analysis. Design matrices were created for each participant with covariates for on-high, on-low, off-high, and off-low trials. Covariates of no interest were included for the other two attention states (task-related interference and inattention) along with the on-task and off-task trials not included in this analysis. In addition, covariates of no interest were created for trials with no/incorrect responses, the probe period when participants reported their attention states, and the fixation period at the start of each tapping period.

The group-level analysis was performed by running general linear tests for the following contrasts: on-low vs on-high; off-low vs off-high; on-low vs off-low; and on-high vs off-high. In addition, student t-tests were run to test the last two contrasts, on-high vs off-low, and on-low vs off-high, as these could not be implemented with the 3dLME syntax. A threshold of FDR corrected $q = 0.05$ was set for statistical analyses.

Previous research (Kucyi, Esterman et al., 2016) found independent contributions of attention state and behavioral performance to BOLD signal in the DMN. Therefore, to directly test for this effect in the current study, percent signal change was examined between each condition in the DMN. The DMN here was defined *a priori* based on the 7-network estimate parcellation from Yeo et al. (2011). A mask was then used to extract the average beta coefficients generated for each condition. At the group level, a 2x2 linear mixed effects model was run in R to test the effect of performance and attention with DMN percent signal change as the dependent variable.

Functional Connectivity Analysis. Seed-based, beta-series functional connectivity analyses (Rissman et al., 2004) were conducted to more closely examine the neural correlates of the attention states in the attention prompt and of spontaneous and constrained thought measured with the dynamics prompt. For the attention prompt, individual GLM analyses were run for each participant following procedures described above, with the addition that the trials from the four attention states (on-task, TRI, off-task, and inattention) were modeled individually. For the dynamics prompt, individual GLM analyses were run for each participant, with the addition that the trials from constrained and spontaneous attention states were modeled individually. Analysis was based on a set of ROIs comprising the DMN and FPN taken from previous literature (Godwin et al., 2017; Spreng et al., 2013). There were 17 nodes in the DMN and 15 nodes in the FPN, and each node was a 5-mm spherical ROI. For each participant, the time series of individual beta estimates were averaged across the voxels for each node to create one average beta series per node per attention state. Large-scale network connectivity was examined for each attention state from the attention prompt as well as for the spontaneous and constrained attention states from the dynamics prompt. For both of these analyses, connectivity matrices were calculated from the mean beta series of each node. Following previously published procedures (Godwin et al., 2017), within-network functional connectivity was calculated for the DMN and FPN by taking the triangular half of the correlation matrix of all nodes for each network. The average of these fisher-transformed correlation coefficients was used as the measure of within-network connectivity. Between-network functional connectivity was calculated by correlating all DMN nodes with all FPN nodes and averaging the fisher-transformed correlation coefficients. In addition, functional connectivity between each node was examined within the correlation matrices and multiple comparisons were corrected for by using FDR (This correction was applied separately for each family, specifically for DMN, FPN, and between-network.) In these functional connectivity analyses, all datasets contained a minimum of five trials per condition to ensure sufficient signal to noise in analysis.

3. Results

3.1. Self-Report measures

Attention Prompt. The proportions of each reported attention state collapsed across blocks are shown in Fig. 1. Overall, off-task thoughts were most frequent and inattentive states were least frequent. To test for significant differences between proportions, a linear mixed-effects model was run with the attention prompt as a factor and the four attention states from the prompt as the levels. There was a significant main effect of attention state, $F(3,90) = 9.34$, $p < .001$. Post-hoc comparisons indicated that there was a significantly smaller proportion of inattentive states ($M = 0.15$, $SEM = 0.02$) compared to on-task ($M = 0.25$, $SEM = 0.03$; $z = -3.00$, $p = .014$), TRI ($M = 0.27$, $SEM = 0.02$; $z = -3.80$, $p < .001$), and off-task ($M = 0.32$, $SEM = 0.03$; $z = -5.20$, $p < .001$). No other comparisons were

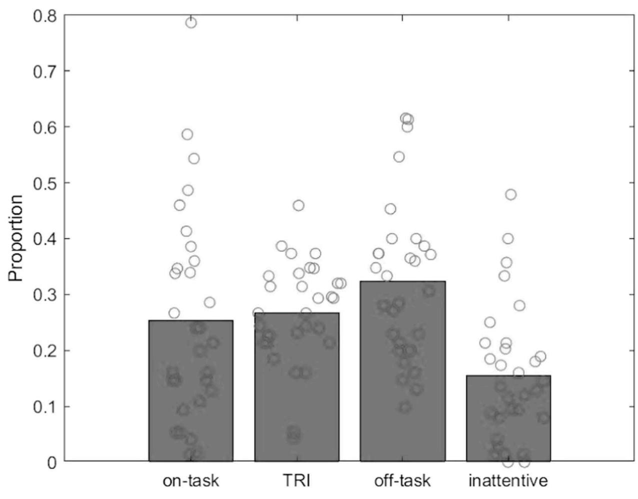

Fig. 1. Frequency of attention states. *Note*. The mean proportion of each attention state reported (on-task, task-related interference (TRI), off-task, and inattentive) from the attention prompt, shown with individual data points overlayed. There was a main effect of attention state, and significantly fewer inattentive states reported compared to the other states.

significant, $0.79 < \text{all } zs < 2.20$, all $ps > 0.17$. In general, participants reported that their attention state was typically focused on something, whether it was on the task, task-related interference, or off-task thoughts. These attention states were reported relatively equally and more frequently compared to the inattentive state.

When examining the proportions of each reported attention state across blocks, there was no significant main effect of block, $F(4, 570) = 0.098$, $p = .983$, nor a significant interaction, $F(12, 570) = 1.392$, $p = .165$ between block and the attention states. As described above, there was a significant main effect across the attention states, $F(3, 570) = 29.168$, $p < .001$.

Environment and Dynamics Prompts. Overall, more internal ($M = 0.66$, $SEM = 0.03$) than external ($M = 0.34$, $SEM = 0.03$) thoughts were reported. This comparison was significant, $t(30) = -4.77$, $p < .001$. In addition, more spontaneous ($M = 0.61$, $SEM = 0.03$) than constrained ($M = 0.39$, $SEM = 0.03$) thoughts were reported. This comparison was significant, $t(30) = 3.38$, $p = .002$.

3.2. Rhythmic response time measures

A linear mixed-effects model was run to examine the effect of block on overall RRT variance. There was a significant main effect of block, $F(4, 120) = 7.01$, $p < .001$. Post-hoc comparisons indicated that RRT variance was significantly lower in the first compared to the second, third, and fourth blocks (all $zs > 3.4$, all $ps < 0.01$). RRT variance also decreased in the fifth compared to the second block ($z = 2.799$, $p = .041$). In general, RRT variance was lowest in the first block, increased during the next three blocks, and decreased during the final block.

Attention Prompt. A linear mixed-effects model was run with the attention prompt as a factor and the four attention states as the levels. There was a significant main effect of attention state, $F(3, 83) = 17.78$, $p < .0001$ (Fig. 2). Results of post-hoc comparisons are summarized in Table 2. RRT variance was significantly greater during each distraction state compared to being completely on-task. However, most distraction states did not differ significantly from each other.

Quadrant State Analysis. A significant main effect of performance was observed, indicating that RRT variance in the high variability condition was significantly greater than in the low variability condition, $F(1, 80) = 807.91$, $p < .0001$. In addition, there was a significant main effect of attention state, $F(1, 80) = 21.114$, $p < .0001$, where off-task thoughts had greater mean RRT variance than on-task thoughts. The interaction between attention state and performance was not significant, $F(1, 80) = 0.201$, $p = .655$.

To further understand the relationship between each attention state and performance level, post-hoc tests were conducted for all paired comparisons. This resulted in six paired comparison tests. All comparisons were significant, all $zs > |3|$, all $ps < 0.013$ after Tukey correction was applied. Results are illustrated in Fig. 3.

Overall, there were large significant differences between trials with the highest variance compared to the lowest variance, along with differences between on-task and off-task trials. As hypothesized, the most extreme low-variance trials were reported on average as on-task, and the most extreme high-variance trials were reported on average as off-task. Interestingly, however, off-low trials were significantly more variable than on-low trials, even though both were characterized by low variance. Furthermore, off-high trials were significantly more variable than on-high trials, even though both were characterized by high variance. Together, these contrasts suggest that over and above objective behavioral performance, an individual's subjective attention state can provide additional information regarding attention and performance. These findings are further addressed in the Discussion.

Environment and Dynamics Prompts. To examine the main effects and interactions between environment (external versus internal) and dynamics (spontaneous versus constrained) on performance variability, a 2x2 linear mixed effects model was run.

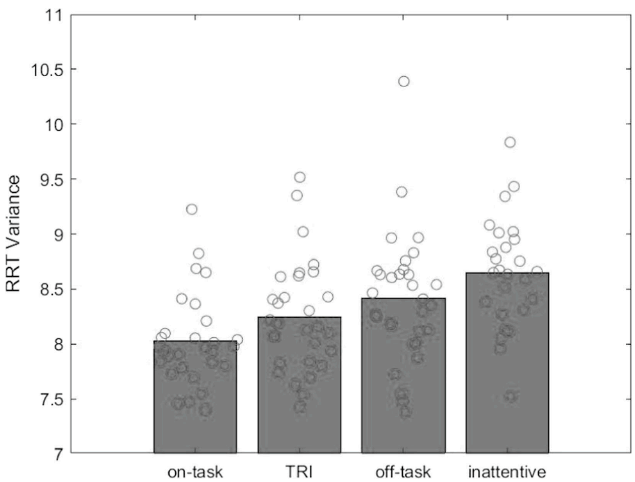

Fig. 2. Performance variability across attention states. *Note*. Mean rhythmic response time (RRT) variance for each attention state (on-task, task-related interference (TRI), off-task, and inattentive) in the attention prompt, with individual data points overlayed. There was a significant main effect of attention state.

Table 2
Post-hoc comparisons of RRT variance between each attention state in the attention prompt.

Pair		z	*p*-value
on-task	- TRI	2.749	0.030 *
	- off-task	4.900	<0.001 *
	- inattentive	7.084	<0.001 *
TRI	- off-task	2.198	0.124
	- inattentive	4.585	<0.001 *
off-task	- inattentive	2.511	0.058

Note. *: Significant after Tukey multiple comparison correction.

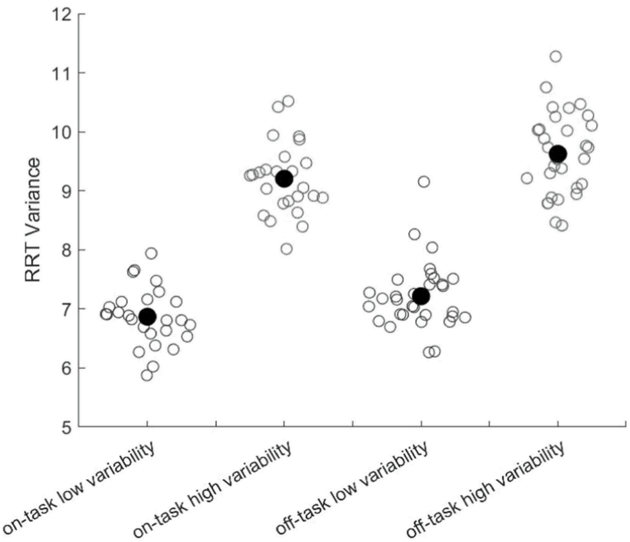

Fig. 3. Performance variability in the quadrant state analysis. *Note.* Quadrant State Analysis is depicted here, showing the mean rhythmic response time (RRT) variance from the top and bottom third of the on-task and off-task attention states, with the individual data points overlayed.

However, there were no significant effects of environmental attention state, $F(1, 62) = 0.389$, $p = .535$, or dynamic attention state, $F(1, 62) = 0.985$, $p = .325$. In addition, there was no significant interaction between environmental and dynamic attention states, $F(1, 62) = 2.495$, $p = .119$.

3.3. *fMRI analysis*

Attention Prompt: Whole Brain Analysis. A whole brain analysis was run in AFNI using a linear mixed effects model to examine BOLD response across the different attention states. The first general linear test examined brain activity during the on-task state compared to all forms of distraction (task-related interference, off-task, and inattentive states). In general, significant activation in BOLD signal was observed during distraction states across the orbital frontal gyrus near the medial PFC and in the left inferior frontal gyrus. In addition, activation was observed in the right lingual gyrus, the left postcentral gyrus, and supplementary motor area during distraction states. No activation associated with on-task thoughts survived whole-brain correction. Significant clusters of activation associated with the distraction states are listed in Table 3.

A series of additional general linear tests were run to compare each pair of attention states. When contrasting off-task thoughts with on-task thoughts (Fig. 4), there was significant activation in many DMN regions along with the left precentral and postcentral gyrus. Significant activation for on-task thoughts compared to off-task thoughts was observed in the right inferior parietal lobule. When contrasting off-task thoughts to the inattentive state, there was activation observed in regions including the left middle frontal gyrus, left precuneus, left inferior parietal lobule, bilateral caudate nucleus, and bilateral cuneus (Fig. 4). Activation was observed in the right inferior frontal gyrus for the inattentive state. Significant clusters of activation are listed in Table 3. There was no significant activity when contrasting on-task and TRI attention states.

Two conjunction analyses were performed to further examine patterns of neural activity pertaining to individual distraction states. The first analysis tested which voxels were significant in both the off-task and inattentive states compared to the on-task state (off-task $>$ on-task $\cap$ inattention $>$ on-task). Shared activity in both states was observed in the left inferior frontal gyrus and left ACC. Relative to the on-task state, activity in the off-task state, which was not present in the inattentive state, was observed in a large set of DMN and MTL regions, including the precuneus, parahippocampal gyrus, and inferior frontal gyrus. Activation in the insula was also observed. Activity in the inattentive state, which was not present in the off-task state, was observed in subregions of both the ventral and dorsal

Table 3
Attention prompt: whole brain analysis.

Contrast	Number of Voxels	x	y	z	Hemisphere	Region	Condition
on-task vs all distraction states							
	220	−45	−24	63	left	postcentral gyrus	all distraction states
	23	−42	24	21	left	inferior frontal gyrus	all distraction states
	11	6	−87	−3	right	lingual gyrus	all distraction states
	9	−12	51	−12	left	middle orbital gyrus	all distraction states
	8	−18	−60	27	left	cuneus	all distraction states
	6	−6	21	54	left	SMA	all distraction states
on-task vs TRI							
	n/a	n/a	n/a	n/a		n/a	n/a
on-task vs off-task							
	653	−33	−72	45	left	inferior parietal lobule	off-task
	450	−45	−24	69	left	postcentral gyrus	off-task
	299	−9	51	−12	left	mid orbital gyrus	off-task
	193	−48	24	24	left	inferior frontal gyrus	off-task
	142	−21	−24	−9	left	hippocampus	off-task
	131	60	−30	54	right	inferior parietal lobule	on-task
	127	−6	18	51	left	SMA	off-task
	125	21	−87	−33	right	cerebellum	off-task
	101	3	−87	0	right	calcarine gyrus	off-task
	63	−30	−54	60	left	superior parietal lobule	off-task
	59	−9	3	−3	left	pallidum	off-task
	33	−18	63	15	left	superior frontal gyrus	off-task
	30	−24	36	−15	left	middle orbital gyrus	off-task
	27	21	−33	−39	right	cerebellum	off-task
	19	−45	45	−3	left	inferior frontal gyrus	off-task
	17	21	−51	−18	right	cerebellum	off-task
	14	12	15	3	right	caudate nucleus	off-task
	14	−51	18	48	left	middle frontal gyrus	off-task
	13	−24	21	−9	left	insula	off-task
	10	−36	33	0	left	inferior frontal gyurs	off-task
	6	45	−69	−45	right	cerebellum	off-task
	6	39	−72	−36	right	cerebellum	off-task
	6	−45	−90	6	left	middle occipital	on-task
	5	54	−57	−27	right	cerebellum	off-task
on-task vs inattentive							
	147	−15	−102	3	left	cuneus	on-task
	88	−39	−24	60	left	precentral gyrus	inattentive
	68	15	−102	6	right	cuneus	on-task
	49	−6	0	−3	left	pallidum	inattentive
	32	−3	33	24	left	anterior cingulate cortex	inattentive
	19	−24	36	−9	left	inferior frontal gyrus	inattentive
	14	−6	30	0	left	anterior cingulate cortex	inattentive
	9	−21	−18	27	left	caudate nucleus	on-task
	5	−18	15	21	left	caudate nucleus	on-task
	3	−3	60	21	left	superior medial gyrus	inattentive
	2	−21	9	−24	left	parahippocampal gyrus	inattentive
	2	−42	−36	69	left	postcentral gyrus	inattentive
TRI vs off-task							
	n/a	n/a	n/a	n/a		n/a	n/a
TRI vs inattentive							
	313	15	−102	6	right	cuneus	TRI
	207	−15	−102	3	left	middle occipital gyrus	TRI
	66	−3	−6	0	left	thalamus	inattentive
	47	−3	36	3	left	anterior cingulate cortex	inattentive
	32	−6	27	24	left	anterior cingulate cortex	inattentive
	23	−3	60	21	left	superior medial frontal	inattentive
	11	−39	−93	−12	left	inferior occipital gyrus	TRI
	11	48	24	18	right	inferior frontal gyrus	inattentive
	9	−63	−45	−12	left	middle temporal gyrus	TRI
	4	−27	36	−9	left	inferior frontal gyrus	inattentive
	4	21	33	−18	right	superior orbital gyrus	inattentive
	3	−12	18	48	left	superior frontal gyrus	TRI
off-task vs inattentive							
	495	−18	−99	3	left	middle occipital gyrus	off-task
	209	−36	21	60	left	middle frontal gyrus	off-task
	47	−33	−75	45	left	inferior parietal lobule	off-task
	44	39	−72	−36	right	cerebellum	off-task
	33	−9	−66	54	left	precuneus	off-task

(*continued on next page*)

Table 3 (*continued*)

Contrast	Number of Voxels	x	y	z	Hemisphere	Region	Condition
	17	12	30	−6	right	anterior cingulate cortex	off-task
	7	−12	9	21	left	caudate nucleus	off-task
	6	−18	−12	18	left	caudate nucleus	off-task
	4	63	−57	9	right	middle temporal gyrus	inattentive
	4	−66	−36	36	left	supramarginal gyrus	inattentive
	3	−15	0	27	left	caudate nucleus	off-task
	2	9	−78	−36	right	cerebellum	off-task
	2	−24	−18	−9	left	hippocampus	off-task
	2	45	27	12	right	inferior frontal gyrus	inattentive
	2	60	6	18	right	precentral gyrus	inattentive
	2	−57	−24	24	left	supramarginal gyrus	inattentive
	2	−33	3	27	left	inferior frontal gyrus	off-task
	2	57	−33	30	right	supramarginal gyrus	inattentive
	2	63	−30	45	right	supramarginal gyrus	inattentive

Note. Regions with significant activation (FDR correction $q = 0.05$) for each contrast of the attention prompt whole brain analysis. The number of voxels pertains to the size of each cluster identified in AFNI. The peak of each cluster is indicated with MNI coordinates. The region is the anatomical region of the cluster peak identified with the CA_ML_18_MNIA atlas in AFNI.

ACC and left inferior frontal gyrus. To further isolate off-task activity, a second conjunction analysis was performed on the off-task state compared to both the inattentive and on-task conditions (off-task > on-task ∩ off-task > inattention). Activation associated with the off-task state in both contrasts was observed in the left middle frontal gyrus, left precuneus, right lingual gyrus, left superior medial gyrus, and right cerebellum.

In summary, as predicted and replicating much previous research, increased DMN activation was observed during off-task thoughts and distraction states in general. Increased activity during the distraction states, in particular the off-task and inattention states, was also observed in left motor areas, perhaps associated with increased behavior variability when attention oriented away from the task. In addition, activation in frontoparietal “task-positive” regions was observed in the off-task state compared to inattention, in line with the role these regions have in off-task thought such as planning and problem solving.

Functional Connectivity Analysis. To further examine the neural correlates of these attention states, beta series functional connectivity analyses were run on the four states: on-task, TRI, off-task, and inattention. To broadly examine the roles of the DMN and FPN in these attention states, network functional connectivity was examined by averaging across pairwise correlations within the DMN and FPN connectivity metrices. However, there was no difference within the DMN or FPN when comparing between different attention states after correcting for multiple comparisons (all $ps > 0.05$). In addition, when comparing functional connectivity between each pair of nodes across attention states, no correlations survived multiple comparison correction (all $ps > 0.05$). The lack of significant functional connectivity results is possibly due to limited power and is addressed further in the Discussion.

*Quadrant State Analysis***.** To examine brain activity across high and low performance variability and on-task and off-task attention states, a separate whole brain analysis was run with a linear mixed effects model. A set of six contrasts were run to compare brain activity across each combination of attention state and performance, as in the behavioral analysis: on-high, on-low, off-high, and off-low. No significant activity survived whole-brain correction in the following general linear contrasts: on-low versus on-high; off-low versus off-high, and on-low versus off-low. In addition, there was no significant activity in the contrast on-high versus off-low.

Whereas most whole-brain contrasts did not yield significant results, when comparing the off-high trials to the on-high trials, there was extensive activity in the off-high condition throughout the brain (Fig. 4). Similar to the results of the attention prompt described above, this activity was observed in areas belonging to the DMN, including the precuneus, medial prefrontal cortex, inferior frontal gyrus, inferior parietal lobule, and angular gyrus. In addition, activation was observed over the bilateral motor cortex as well as regions including the insula, superior parietal lobule, and occipital regions. When comparing activation in off-high to on-low trials, a similar but less extensive pattern of significant activity was observed. Activation during the off-high condition was observed in the precuneus and inferior parietal lobule, as well as the middle and superior frontal gyrus, superior parietal lobule, and motor cortex.

When examining the percent signal change in the DMN between each condition, there was a significant main effect of attention state, $F(1, 80) = 4.42$, $p = .039$. There was a trending but nonsignificant interaction between attention state and performance variance, $F(1, 80) = 2.83$, $p = .096$. There was no main effect of performance variance, $F(1,80) = 0.040$, $p = .843$. Overall, there was decreased signal in the DMN during the on-task attention state compared to off-task, and the greatest difference in activation was observed between the off-high trials and the on-high trials. Results are summarized in Fig. 5.

Environment Prompt: Whole Brain Analysis. This contrast examined the effect of environmental orientation of attention state on brain activity. There was no significant activity associated with internally orientated attention. Significant activity associated with externally oriented attention included right inferior parietal lobule and right insula, consistent with external attention and saliency processing. Significant activity in externally oriented attention was also observed in right Heschl’s gyrus, consistent with auditory processing.

Dynamics Prompt: Whole Brain Analysis. The contrast for the dynamics prompt focused specifically on the dynamics of internally-directed thoughts. There were too few trials categorized as externally oriented to run a factorial analysis examining environment by dynamics. In addition, it was theoretically interesting to constrain the dynamics prompt analysis to internally-directed thoughts, as this would provide insight to the dynamics of classically defined “task-unrelated and stimulus independent” mind

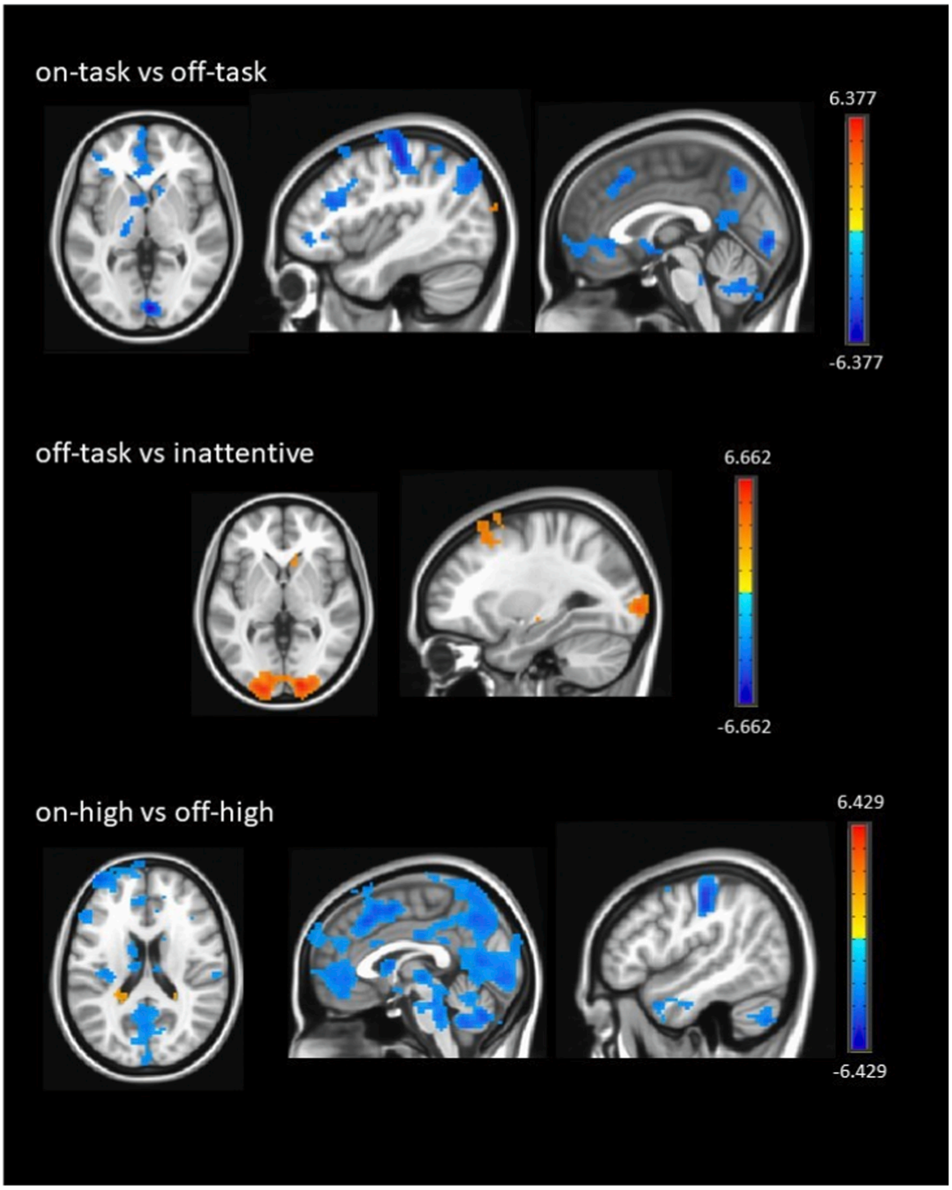

Fig. 4. Whole-brain fMRI analyses of attention prompt and quadrant state analysis. *Note*. Row 1: Axial, lateral (left hemisphere), and medial (right hemisphere) views of on-task (orange) vs off-task (blue) contrast; Row 2: Axial and lateral (left hemisphere) views of off-task (orange) vs inattentive (blue) contrast; Row 3: Contrast of on-high (orange) > off-high (blue) from the quadrant state analysis from axial, medial (right hemisphere), and lateral (right hemisphere) views. All results are FDR-corrected $q < 0.05$. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

wandering instances (Christoff, 2012; Christoff et al., 2016). No significant activity was observed for spontaneous thoughts. However, for constrained thoughts, a significant cluster of activity was observed in the left hippocampal region (MNI coordinates of peak activation at −21, −36, 9).

4. Functional connectivity Analysis.

To broadly examine the roles of the DMN and FPN in thought dynamics, network functional connectivity was examined by averaging across pairwise correlations within the correlation matrices. To increase the signal to noise in analysis, a minimum of five trials was required for each condition, which decreased the sample size for the functional connectivity analyses to $n = 11$. However, there was no significant difference in connectivity in the DMN when comparing spontaneous ($M. = 0.336$, $SEM = 0.029$) to constrained thoughts ($M = 0.501$, $SEM = 0.130$), $t(10) = -1.243$, $p = .242$.There was also no significant difference in connectivity in the FPN when

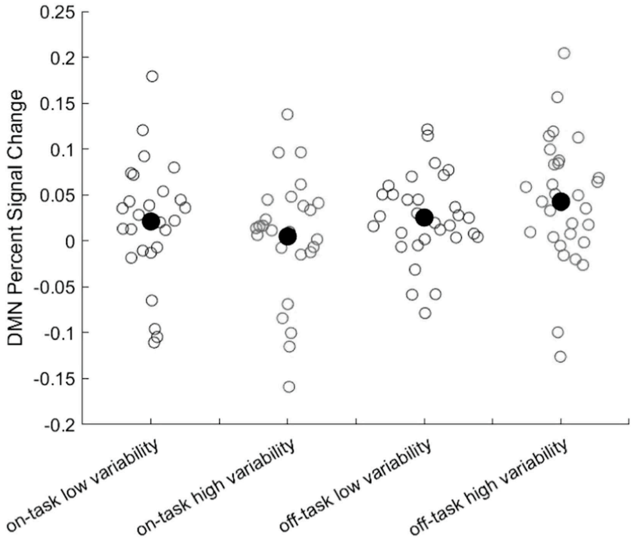

Fig. 5. Default mode network percent signal change analysis. *Note.* Quadrant State Analysis. DMN percent signal change as a function of attention state and performance variance, with individual data points overlayed. There was a main effect of attention state and a trending but nonsignificant interaction between attention state and performance.

comparing spontaneous ($M = 0.457$, $SEM = 0.062$) to constrained thoughts ($M = 0.433$, $SEM = 0.124$), $t(10) = 0.046$, $p = .964$.

Pairwise ROI connectivity analyses were run to more closely examine functional connectivity between the nodes of the DMN and FPN. Within the DMN, there was increased connectivity between the left STS and right TPJ during the constrained compared to spontaneous thoughts ($p < .05$, FDR corrected). No other pairwise comparisons survived FDR correction.

5. Discussion

By combining a continuous performance task with novel thought prompts, we were able to examine the interrelationship between attention states, behavioral variability, and brain activity. We went beyond the on-task/off-task characterization of mind wandering and identified the behavioral differences and neural basis of several types of attention states. In addition, we examined the dynamic nature of off-task attention states using fMRI analysis and functional connectivity metrics. Overall, participants reported fewer instances of being in an inattentive state compared to on-task and the other forms of distraction, indicating that most of the time, participants were at least paying attention to something if not the task itself (Fig. 1). In addition, the frequency of off-task thoughts was relatively steady across blocks, and frequencies were similar to those reported elsewhere (e.g., Unsworth & Robison, 2016). Importantly, results from the attention prompt replicated those of Seli and colleagues (2013): RRT variance was significantly smaller when participants reported that they were in the on-task attention state compared to the off-task state, indicating that overall, performance decreased during the off-task state compared to on-task. Additionally, across all distraction states (TRI, off-task, and inattention), RRT variability increased compared to on-task, confirming that each of these attention states is a form of distraction when defined both subjectively and behaviorally (Fig. 2).

Performance also differed between some of the pairs of distraction states, as well. For example, in the inattentive state, RRT variance was greater than in the TRI state. Similarly, RRT variance in the inattentive state was greater than in the off-task state; however, this effect did not reach significance ($p = .058$). These findings provide support for the hypothesis that different forms of distraction have different effects on performance, perhaps as a function of task disengagement (discussed below). These findings also align with previous research that has documented similar relative decreases in performance during inattentive states (Unsworth & Robison, 2016). At the same time, these results indicate that other forms of distraction have similar consequences in terms of performance. Specifically, there was no difference in RRT variance between the off-task and TRI states. This result suggests that even when one is indirectly focused on the task (i.e., by thinking about topics related to the task), these thought processes can be similarly detrimental to performance.

More broadly, RRT variance followed a monotonic increase from on-task to inattentive (Fig. 2). Although the attention states of the attention prompt were defined categorically, the overall pattern is consistent with the concept of varying disengagement during task performance. For example, using a visual version of the MRT, researchers observed increased performance variability with increased reported depth of mind wandering (Laflamme et al., 2018). In addition, Cheyne et al. (2009) described mind wandering in terms of disengagement over the course of distinct states. These distinct states ranged from transient disengagement from a task where the individual can typically re-focus effectively and avoid overt errors, to full “decoupling” from the task where serious behavioral errors can occur. Another group of researchers (Schad et al., 2012) proposed the levels of inattention hypothesis, which predicts that reductions in attention and other cognitive processes can occur at different hierarchical levels (e.g., early perceptual versus higher-order abstract processing). The attention state categories from the attention prompt may have captured similar levels of disengagement ranging from full engagement (on-task) to severe decoupling (inattention).

5.1. Neural correlates of attention states

As in previous research, the fMRI whole brain analysis of the attention states from the attention prompt demonstrated increased activation in several DMN regions when participants were off-task (Fig. 4). When collapsing across all forms of distraction, activation was observed across the brain and concentrated in several DMN regions, including the left inferior frontal gyrus and middle orbital/medial PFC. A small but significant cluster of activity was also observed in the left parahippocampal gyrus of the MTL during distraction states. There was also a large cluster of activation observed in the left motor regions, which may have been driven by increased cognitive load associated with time on task (Derosière et al., 2013) and the challenges of tapping synchronously while losing focus.

Despite previous findings (Stawarczyk, Majerus, Maquet, et al., 2011), there was no significant activity in the TRI attention state compared to on-task. Furthermore, there was no significant activity in the TRI state when compared to the off-task state. This may be due to overlap in the processes occurring in the TRI state, which could be characteristic of either on-task and off-task, and thus the detection of unique TRI-related brain regions was hampered. That is, the TRI state is characterized by thoughts related to the task, such as how well one is performing or the purpose of the task. Although specific thoughts likely varied across participants, the general nature of this attention state suggests that it may recruit a set of mechanisms consisting of frontoparietal regions to guide evaluation and question formation as well as DMN regions to guide the generation of TRI thought content and related topics.

Using the on-task attention state for comparison, a conjunction analysis revealed similarities and differences between the off-task and inattentive states. Unique activity in the off-task state, which was not present in the inattentive state, was observed in a large set of DMN and MTL regions, including the precuneus, parahippocampal gyrus, and inferior frontal gyrus. Activation in the insula was also observed in the off-task state relative to the inattentive state. Furthermore, a second conjunction analysis testing for unique activation in the off-task state compared to both the inattentive and on-task conditions found a significant cluster of voxels in the left middle frontal gyrus, part of the FPN. Together, these results replicate previous research associating DMN regions with off-task thought and highlight the involvement of executive function regions during off-task thought (Christoff et al., 2009). These results also emphasize the role these regions may have specifically in off-task thought in contrast to other forms of distraction (e.g., inattentiveness) or distraction in general.

Compared to on-task, both the off-task and inattention states yielded activation in the left inferior frontal gyrus and left ACC. In addition, unique to the inattentive state were patterns of activation in subregions of the ventral and dorsal ACC and left inferior frontal gyrus which were not overlapping with the off-task state. In support of these findings, research linking fMRI with behavioral microsleeps during a vigilance task found increased activity in frontal and parietal regions, including the inferior frontal gyrus (Poudel et al., 2014). The researchers speculated that this activity may be related to attempts to stay awake and restore responsiveness, as opposed to reflecting general drowsiness. A similar mechanism may have occurred in the participants of the current study. In addition, the ACC is a major node of the ascending arousal system (Poudel et al., 2014). Previous research linking BOLD signal with EEG-vigilance states found increased activation in the ACC and throughout the frontal cortex during the transition between wakefulness and sleep onset (Olbrich et al., 2009).

In mind wandering research, attention states have been typically dichotomized into on-task or off-task, although a growing body of research has further examined the diverse contents and dynamics that characterize attention (Andrews-Hanna et al., 2018). However, explicitly asking participants about their experience of inattentiveness is less common – even though participants can indeed be drowsy during experiments, as reported in other studies (Unsworth & Robison, 2016). Differentiating between general inattentiveness and active, off-task thought is important both theoretically and in practice. The current study revealed that a subset of brain regions (viz., the left inferior frontal gyrus and left ACC) is associated with both off-task thought and inattentiveness, but that unique brain regions (viz., the precuneus, parahippocampal gyrus, and inferior frontal gyrus for off-task and subregions of the ventral and dorsal ACC and left inferior frontal gyrus for inattentiveness) can be tied to each attention state.

5.2. Dissociation of performance and attention states

Overall, the MRT procedure demonstrated that, as predicted, RRT variance increased in distracted states and that this variance tended to increase as individuals lapsed further into distraction (e.g., TRI → off task → inattentive states; Fig. 2). Despite these overall patterns, there were instances where participants reported being on task but their performance was relatively variable, and instances where participants reported being off task but their performance was relatively stable. Examining on-task and off-task attention states under conditions of high and low performance variability in the quadrant state analysis provided a more nuanced understanding of subjective and objective measures of attention and highlighted important considerations regarding subjectively and objectively-defined attention states. In particular, we observed periods of greater RRT variance during off-low trials compared to that of on-low trials (Fig. 3). Conversely, the RRT variance of on-high trials was significantly lower compared to that of off-high variance trials (Fig. 3). Although these differences are small, these results have important theoretical implications. For example, it may be the case that off-low and off-high trials reflect two distinct cognitive states. In support of this, a recent neural model of mind wandering (Mittner et al., 2016) proposed a conceptual distinction between 1) an off-focus state characterized by "tuning out" (e.g., Seli et al., 2013) where behavioral variability is moderately increased relative to on-task; and 2) an active mind-wandering state characterized by engagement with an internal stream of thought, where behavioral variability is highest relative to on-task. Perhaps the off-low trials in the current study correspond with the off-focus state of Mittner et al. (2016), whereas the off-high trials correspond with the active mind wandering state. It is also possible these conditions reflect somewhat of a “flow state” and the process of fluctuating between “in the zone” and “out of the zone” (Esterman et al., 2012; Kennedy et al., 2014). Overall, it is not clear the implication of the on-high trials. However, in general it is possible that this condition reflects periods of task performance where participants noticed they were off-task, and actively concentrated on the task to attempt to steady their performance (similar to that described by Hasenkamp et al., 2012).

Along with performance variability, neural activity was also examined in the quadrant state analysis. Although most whole-brain contrasts did not yield significant results, comparing off-high to on-high trials showed extensive activity throughout the brain in the off-high condition. Similar to the results of the attention prompt described above, this activity was observed in areas belonging to the DMN as well as the FPN, DAN, and motor cortex. Similar but less extensive results were observed when comparing activation in off-high to on-low trials.

The percent signal change analysis within the DMN provided a closer look at how activity in this network changed across the different task-variability conditions. As expected, there was increased DMN activity during the off-task state compared to on-task. In addition, although not significant, there was a trend in the interaction between attention state and performance. Interestingly, the current findings diverge from Kucyi, Esterman et al. (2016) in that DMN activation was greater for off-high than off-low attention states. Although this direction was just a trend and current results should be interpreted cautiously, the difference between this study and what was observed by Kucyi, Esterman et al. (2016) may be due to differences in the cognitive load of the tasks. The MRT used here was rather monotonous and low in cognitive demand, and the DMN signal may have been more strongly driven by spontaneous activations.

The behavioral results indicate a small but significant dissociation between subjective attention state and performance (viz., off-high vs off-low). The pattern of behavioral performance here is similar to the relationship between performance and depth of mind wandering observed by Laflamme et al. (2018) and also fits well with the model of disengagement proposed by Cheyne et al. (2009). In general, this pattern may simply reflect an extension of the four broad attention states examined in the attention prompt. However, the same pattern did not extend to DMN activity. There are several reasons why this may have occurred. One reason is that there may not have been enough power to detect further differences, as suggested by the trending but nonsignificant interaction. Because the on-task and off-task attention states were subsequently divided into high and low variability performance based on the upper and lower thirds of RRT data, there were relatively few trials that went into analysis. In addition, the DMN was defined broadly, based on the parcellation of Yeo et al. (2011). However, as proposed by Mittner et al. (2016) and others (Andrews-Hanna et al., 2018), subsystems of the DMN along with other large-scale networks may drive differences in attention state and performance, whereas core DMN regions may be common to many off-task thoughts and attention states in general. While the functional connectivity analysis of the attention prompt did not yield significant results, likely due to limited power, future research could explore these subsystems more in depth (e.g., using the 17-network parcellation of Yeo et al., 2011). In general, it is possible that neural activity as measured here provides a coarser assessment of off-task states in relation to behavior, where DMN activity tracks overall, general differences in on-task and off-task states. In contrast, the simple, continuous nature of the MRT procedure captures subtle but important fluctuations within attention states.

5.3. Dynamic characteristics of the Off-task attention state

The framework proposed by Christoff et al. (2016) predicts that spontaneously directed thoughts are supported primarily by the medial temporal lobes and DMN regions. However, increased fMRI activation was observed in the left hippocampus for constrained thoughts as opposed to spontaneous thoughts. In addition, there were very few differences observed in functional connectivity between the two attention states. When examining functional connectivity within the DMN and FPN as a whole, no differences between attention states emerged. When examining pairwise connectivity between individual nodes that comprise the networks, a small increase in functional connectivity between two DMN nodes, the left STS and right TPJ, was observed for constrained compared to spontaneous thoughts. Although it is not directly clear why functional connectivity was increased between these nodes, or why there was increased activation within the left hippocampus during constrained thought, it is possible that it is reflective of roles that the DMN more in general may play in driving constrained thinking. For example, it is possible that during constrained thought, participants were engaging in rumination rather than general constrained thought, which has been associated with DMN hyperconnectivity (Christoff et al. 2016). Although these results provide a glimpse into the dynamics of attention states as predicted by previous theorizing (Christoff et al., 2016), in general, the minimal results observed in functional connectivity between these attention states more likely reflects the limited statistical power that was available in analysis, in particular due to the limited number of trials and the inherent noise due to categorizing trials based on self-reported attention states.

Finally, there were no significant differences in RRT variability within environments or dynamics, nor was there a significant interaction between the two. Regardless of the orientation of one’s off-task thought, performance was not affected. Although this null result does not rule out the possibility that behavioral performance differs between these attentions states in other contexts, the findings here demonstrate how an integrative, multimodal approach in neuroscience can elucidate differences between cognitive processes. Although RRT variance did not differ across environments or dynamics, BOLD signal metrics helped begin to clarify the neural mechanisms of thought dynamics.

5.4. Concluding remarks

In general, people engage in off-task thoughts when the topics of those thoughts are more attractive or compelling than the task that one is performing (Mittner et al., 2016; Godwin et al, 2017). The mechanisms supporting these thoughts as well as the task at hand are driven by a complex set of processes that likely involve a dynamic balancing between cognitive representations (e.g., task files; Bezdek et al., 2019) of one's current goals, interests, and concerns (Klinger, 1999; Klinger et al., 2018; McVay & Kane, 2009). As described in Bezdek and colleagues (2019), over the course of cognitive processing, these representations compete with each other to further drive mental contents and behavior. In this sense, one's "off-task" attention state may very much be considered "on-task" to the individual if the thoughts align with the individual's true goals and not the task at the moment. Content related to these thoughts may be driven spontaneously, perhaps by neural mechanisms within the hippocampus and medial temporal lobes (Ellamil et al., 2016). Alternatively, one may choose to shift their thoughts away from the task at hand, and thus content related to these thoughts can become driven in a goal-directed manner by executive control regions (Christoff et al., 2016). Ultimately, a more general perspective of the relation between off-task thought and performance can be gained by thinking of off-task thought as encompassing one of many goals of the individual (Bezdek et al., 2019; Klinger et al., 2018), the extent to which one engages in the task or in off-task thought, and the balance between brain networks supporting the execution of each of these goals. The current study did not explicitly ask participants regarding their level of engagement across the task or the extent to which their off-task thoughts aligned with other personal goals. However, as discussed above, the distinctions outlined by Mittner and colleagues (2016) align nicely with the differences in RRT variance observed in the quadrant analysis, along with the monotonic pattern of behavioral performance across the attention states of the attention prompt. Future research could measure or actively manipulate the level of engagement throughout tasks to further study these processes.

The MRT procedure applied in the current research yielded many advantages, as described above. In addition, the inclusion of multiple attention states in the thought prompts provided the ability to carefully assess the characteristics of off-task thought while avoiding confounding inattentive states, off-task thoughts, and task-related thoughts. However, there is large variability across individuals in terms of their ability to focus and tendencies to mind wander in different tasks and contexts (Godwin et al., 2017). Future research could build on the findings here and examine the role of individual differences. For example, individual differences such as working memory capacity (Levinson et al., 2012) and state characteristics such as current motivation and interest (Kane et al., 2017; Seli et al., 2015) can play substantial roles in the occurrence of mind wandering and its effect on performance. Ultimately, a complete understanding of off-task thoughts, their effect on performance, and their neural mechanisms will be generated with research across a range of diverse contexts, measures, and individuals.

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Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

Data will be made available on request.

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Appendix A

Below is the script that is read to participants so they can learn about the different off-task thought states. Most of these examples were taken from Christoff et al. (2016). The examples illustrate how external/internal and constrained/spontaneous are independent dimensions, and thoughts can be either external or internal AND constrained or spontaneous.

—

When we are thinking about things other than the task we're doing, it's possible for our thoughts to be oriented either 'externally' or 'internally'. Externally-oriented thoughts are focused on things surrounding us in our environment, such as sights, sounds, smells, and bodily sensations (hunger/thirst/temperature). Internally-oriented thoughts are focused on things in our mind, such as thinking about the upcoming weekend or your last vacation.

Here are some examples:

Internally-oriented:

-While re-painting the walls of their room, a person plans their afternoon, figuring out how to combine multiple errands into a single car ride.

-Despite their best attempts to write a paper, a student keeps fixating on a harsh comment from their teacher.

- While driving in their car, a writer suddenly thinks of a line for the book they are writing, then remembers that they must pick up dog food on the way home, before reminiscing about the winters of their childhood.

Externally-oriented:

-to stay awake during a boring lecture, a student tries to estimate who has the most expensive shoes in the room.

-While listening to harsh criticism by the teacher, a student starts counting the tiles on the floor of the classroom as a means to stop from crying.

-While studying in a quiet library, a student finds himself unable to ignore a buzzing fly.

-While hiking on a forest trail, a hiker's thoughts move from the gravel on the path to a slug crawling up a stump, and then to a leaf floating in a puddle.

In addition, when we are thinking about things other than the task we're doing, it's possible for our minds to move about 'freely' or for our thoughts to be 'constrained'. When thoughts move about freely, thinking may appear more spontaneous and may jump from one content to another. When our thoughts are constrained, thinking may feel more deliberate or goal-directed, or driven by a particular topic, concern, or stimulus.

Here are some examples:

Freely-moving:

- While driving in their car, a writer suddenly thinks of a line for the book they are writing, then remembers that they must pick up dog food on the way home, before reminiscing about the winters of their childhood *(internal)*.

-While hiking on a forest trail, a hiker's thoughts move from the gravel on the path to a slug crawling up a stump, and then to a leaf floating in a puddle *(external)*.

-As the child gazes out the window on the long plane flight, his thoughts drift from the clouds to the soothing motion of the plane, to the taste of ice cream leftover from a snack earlier *(external)*.

-While cleaning the kitchen, a student daydreams about their upcoming weekend getaway, and then thinks about the midterm exam they took the day before, and then remembers they should give their parents a call before leaving *(internal)*.

Constrained:

-While re-painting the walls of their room, a person plans their afternoon, figuring out how to combine multiple errands into a single car ride *(internal)*.

-While studying in a quiet library, a student finds himself unable to ignore a buzzing fly *(external)*.

-Despite their best attempts to write a paper, a student keeps fixating on a harsh comment from their teacher *(internal)*.

-While listening to harsh criticism by the teacher, a student starts counting the tiles on the floor of the classroom as a means to stop from crying *(external)*.

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