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More than off-task: Increased freely-moving thought in ADHD

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ABSTRACT

Off-task thought has been found to occur at high rates and is related to impairment in ADHD. However, off-task thought is heterogeneous and it remains unclear which specific *dimensions* of off-task thought are more prevalent in this disorder. It is therefore important to dissociate different aspects of off-task thought in order to better understand the mechanisms underlying impairment. The current study focused on the dimension of constrained (focused) to freely moving off-task thought. Self-report and neurophysiological measures during a computerized attention task provided convergent evidence that individuals with ADHD not only have more off-task thought than those without, but also engaged in a greater proportion of *freely moving* off-task thought than non-ADHD controls. Overall, this work demonstrated differences in both the quantity and type of off-task thought in adults with ADHD. It provides novel insight into both the phenomenology of off-task thought, as well as potential mechanisms underlying impairment in ADHD.

1. Introduction

Thought unrelated to the task at hand, or off-task thought, is a ubiquitous mental phenomenon, yet has only recently become subject to intensive empirical study. In many cases, off-task thought is beneficial for things like planning and creativity (Baird et al., 2012; Mooneyham & Schooler, 2013). Yet in other instances, it can be quite maladaptive (e.g., when the frequency is too great or the timing is inappropriate) (McVay & Kane, 2012; Mrazek, Phillips, Franklin, Broadway, & Schooler, 2013). Further, higher levels of off-task thought have been tied to an array of psychiatric disorders (Franklin et al., 2017; Hoffmann, Banzhaf, Kanske, Bermpohl, & Singer, 2016; Mowlem et al., 2016; Seli, Smallwood, Cheyne, & Smilek, 2015; Smallwood, 2013), most notably ADHD (Biederman et al., 2017; Bozhilova, Michelini, Kuntsi, & Asherson, 2018; Franklin et al., 2017; Mowlem et al., 2016; Seli et al., 2015; Shaw & Giambra, 1993).

ADHD is a developmental disorder characterized by symptoms of inattention and hyperactivity/impulsivity (American Psychiatric Association, 2013). This disorder emerges in childhood, but impairment persists into adulthood in 40–60% of cases, even when full ADHD diagnostic criteria are not met (Fayyad et al., 2017; Rasmussen & Gillberg, 2000; van Lieshout et al., 2016). Accumulated impairments are substantial, including lower occupational attainment, as well as increased marital conflict, traffic accidents, drug and alcohol use, and comorbid mood and anxiety disorders (Adamou et al., 2013; Biederman et al., 1993; Biederman et al., 2006; Bioulac et al., 2016; Kessler et al., 2006).

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1.1. ADHD and dimensions of off-task thought

Off-task thought is often referred to as “mind-wandering” in the broad literature. However, due to current definitional debates and a general disagreement about what the term “mind-wandering” refers to (see Christoff et al., 2016, 2018; Seli et al., 2018, Seli et al., 2018 for definitional debates), we use the more specific term “off-task thought” to encompass thought that is unrelated to the task at hand. Regardless of the term used, a majority of work investigating off-task thought commonly measures the construct as a homogenous experience and focus on quantifying the frequency of off-task thought (e.g., how often does your attention shift away from a task). However, we know that not all thought is alike and this approach misses qualitative differences (e.g., qualities or dimensions of thought such as content or movement) that can help clarify how off-task thought relates to impairment in psychopathologies (Christoff, Irving, Fox, Spreng, & Andrews-Hanna, 2016; Kam et al., 2021; Mills et al., 2018, 2021; Smith, Brosowsky, Ralph, Smilek, & Seli, 2021).

In the context of ADHD, off-task thought is a paramount feature that influences impairment in work/school, life skills, and interpersonal relationships (Biederman et al., 2019; Bozhilova et al., 2018, 2020; Franklin et al., 2017; Mowlem et al., 2016; Seli et al., 2015; Shaw & Giambra, 1993). Although it is clear that those with ADHD engage in *more* off-task thought than those without (Biederman et al., 2017, 2019; Bozhilova, Kuntsi, Rubia, Michelini, & Asherson, 2021; Franklin et al., 2017; Mowlem et al., 2016; Seli et al., 2015; Shaw & Giambra, 1993) the nature of off-task within this population and whether it differs only quantitatively (i.e., increased frequency) or also qualitatively (i.e., is driven by distinct aspects of off-task thought) from typically developing populations is under studied. The few studies that have investigated qualities of off-task thought in ADHD have focused on the dimension of deliberate vs. automatic thought (Arabaci & Parris, 2018; Franklin et al., 2017; Seli et al., 2015). This work has found that those with ADHD engage in more automatic off-task thought than those without ADHD (Arabaci & Parris, 2018; Seli et al., 2015) and the degree to which they do this is related to functional impairment (Franklin et al., 2017). This work, although limited in scope, starts to suggest that off-task thought in ADHD may have distinct qualitative features that merit further investigation.

Because investigation of specific dimensions of off-task thought has rarely been applied to empirical studies of disorders like ADHD, a new opportunity exists to clarify cognitive and neurophysiological mechanisms in this population. Doing so has the translational potential to both (a) increase understanding of the basic cognitive mechanisms of off-task thought in general, and (b) improve understanding of ADHD, possibly contributing to identification of new targets for intervention for this disorder. The current study contributed to these goals by using a neuroscientifically-informed model proposed by Christoff et al. (2016) that captures the potentially multifaceted nature of off-task thought. This model defines thought as varying on two dimensions: (a) the extent to which thought is deliberately constrained (goal-directed) and (b) the extent to which thoughts are automatically constrained (from sources like affect, habits, or sensory salience). When both types of constraints are low, the framework predicts that thoughts should be more unguided and freely moving (e.g., switching from topic to topic) and less constrained (e.g., focused on a single train of thought). Freely moving thought ebbs, flows, and switches topics (e.g., thinking about the uncomfortable chair you’re sitting in, wondering what you’ll eat later, remembering a funny thing someone said earlier). In contrast, constrained thoughts are relatively stable and fixated on a specific topic (e.g., going over what you’ll say in an upcoming meeting). Although previous work has focused on how ADHD relates to the off-task dimension, Christoff et al. (2016) would predict that it may not be off-task alone, but rather that the off-task thought has a specific “freely-moving” quality to it.

This freely moving to constrained dimension is of interest because ADHD is marked by enhanced attentional variability (i.e., a lack of attentional focus) during externally-focused attention (e.g., during cognitive tasks) (Huang-Pollock, Karalunas, Tam, & Moore, 2012; Kuntsi & Klein, 2012). Hypotheses suggest individuals with ADHD may have difficulty stabilizing attention (i.e., maintaining attentional focus) during off-task thought as well (Christoff et al., 2016; Smallwood, 2013), but no work has investigated attentional variability/freedom of thought movement during internal cognition. Understanding the fluctuation (or lack thereof) of internalized attention in ADHD is important not only for gaining a greater understanding of attentional impairment in this disorder, but also for providing a framework for designing and implementing interventions that target the mechanisms driving aspects of attention that may be problematic for the individual.

1.2. Measuring freely moving thoughts

Most literature on off-task thought has relied on self-report online experience sampling (Smallwood & Schooler, 2015). However, online experience sampling has rarely been used to distinguish between freely moving versus constrained thought. Recent work suggests such a distinction is possible using carefully framed questions, such as “how freely were your thoughts moving?” (Christoff et al., 2016; Mills, Raffaelli, Irving, Stan, & Christoff, 2018). Mills et al. (2018) demonstrated that off-task thought in typically-developing adults is constrained only 40% of the time and freely moving the other 60% of the time, highlighting that off-task thought is not inherently freely moving and that this dimension may be an important source of individual differences.

While self-report measures are valuable and reliable measures for capturing nuances of off-task thought (Schubert, Frischkorn, & Rummel, 2020; Varao-Sousa & Kingstone, 2019), they do come with limitations such as the impact of probe framing (Weinstein, De Lima, & van der Zee, 2018) and probe presentation rate (Seli, Carriere, Levene, & Smilek, 2013). Combining subjective self-report measures and objective physiological measurements (e.g., neurophysiology) can aid in providing convergent evidence across measurement types for findings as well as elucidating underlying mechanisms. In the current study, EEG complexity was used to provide additional insight into the nature of off-task thought (Bob, Golla, Epstein, & Konopka, 2011; Ibáñez-Molina & Iglesias-Parro, 2014, 2016; Liu, Yan, Chen, & Wang, 2013; Mölle et al., 1996, 1999). As the name suggests, EEG complexity reflects the complexity, or chaos, of the underlying dynamic neural system (Stam, 2005). While the underlying processes leading to EEG signal complexity are widely

debated (e.g., see [Tononi, Edelman, & Sporns, 1998](#)), many measures of EEG complexity may reflect the number of cell assemblies (e.g., functional networks of neurons) contributing to the EEG signal, with more assemblies reflecting higher complexity ([Elbert et al., 1994](#); [Lutzenberger, Preissl, & Pulvermüller, 1995](#); [Stam, 2005](#)).

Complexity measures have been a valuable tool for evaluating brain dynamics during various attentional states ([Bob et al., 2011](#); [Ibáñez-Molina & Iglesias-Parro, 2014, 2016](#); [Iglesias-Parro et al., 2020](#); [Liu et al., 2013](#); [Lutzenberger, Elbert, Birbaumer, Ray, & Schupp, 1992](#); [Mölle et al., 1996, 1999](#)). Studies have demonstrated greater complexity during rest (where attention is free to wander) ([Bob et al., 2011](#); [Liu et al., 2013](#)) and off-task thought ([Ibáñez-Molina & Iglesias-Parro, 2014, 2016](#); [Iglesias-Parro et al., 2020](#)) than in focused attention tasks. Constrained thinking tasks (e.g., doing mental arithmetic) are associated with less complexity across all EEG sites as compared to less-constrained thinking tasks (e.g., coming up with as many unusual uses for a credit card as you can) ([Mölle et al., 1996, 1999](#)). Further, simulation studies have shown that EEG complexity increases with increased default mode network activity ([Ibáñez-Molina & Iglesias-Parro, 2016](#)), a pattern of activation often associated with off-task or more freely moving thought ([Christoff et al., 2016](#); [Kucyi, 2018](#); [Mittner et al., 2014](#)). EEG complexity is a non-linear measure of the underlying EEG signal. While other non-linear EEG metrics have been used to investigate aspects of thought/attention (e.g., detrended fluctuation analysis ([Irrmischer, Poil, Mansvelder, Intra, & Linkenkaer-Hansen, 2018](#))), EEG complexity is used here as one of the few metrics that has demonstrated the ability to distinguish between constrained and freely moving thought ([Mölle et al., 1996, 1999](#)).

1.3. The current study

The current study tested whether individuals with ADHD show differences in amount and/or type of off-task thought compared to those without ADHD using self-report, cognitive performance, and EEG measures. Hypotheses were that those with ADHD would (1) self-report more off-task thought overall and a greater proportion of freely moving off-task thought, specifically, (2) show more variable reaction times and more errors on the attention task overall as well as a greater increase in reaction time variability and errors during off vs on-task trials than controls, (3) have a larger increase in EEG-measured complexity during off-task vs. on-task thought as compared to controls, consistent with more freely moving off-task thought. Although the primary goal of this study was to examine group-based differences in freely moving off-task thought, exploratory analyses were also run to investigate whether freely moving thought in ADHD predicted ADHD-related impairment. If so, this would suggest that this aspect of thought could become a potential target for intervention.

2. Methods

2.1. Participant recruitment

Adults (ages 18–40) were recruited via public advertisements as part of an ongoing study of adults with ADHD. Participants were told they were partaking in a study to better understand attention in those with and without ADHD and were not explicitly told it was a study on off-task thought. Participants provided written informed consent and all procedures were approved by the Institutional Review Board at Oregon Health & Science University.

After an initial screening phone call, enrolled adults reported on their ADHD symptoms. Self-report of current and childhood ADHD symptoms was assessed with a semi-structured interview with a masters-degree level clinician (DSM-5 Adult ADHD Clinical Diagnostic Scale [ACDS] ([Adler & Spencer, 2004](#))) as well as standardized questionnaires (Barkley Adult ADHD Rating Scale (BAARS) and Connors' Adult ADHD Rating Scale (CAARS)) ([Barkley, 2011](#)). Informant measures of clinical symptoms were also obtained for diagnostic assignment ([Kooij et al., 2008](#); [Zucker, Morris, Ingram, Morris, & Bakeman, 2002](#)). To further validate past childhood symptoms of ADHD, a parent or former guardian of the participant was asked to complete the BAARS ([Barkley, 2011](#)) rating symptoms of the participant during childhood. An additional informant (e.g., spouse or close friend) was also asked to complete the BAARS ([Barkley, 2011](#)) rating current ADHD symptoms. This method conforms to best practices for determining validity of ADHD in adults ([Sibley et al., 2012](#)).

The Mini International Neuropsychiatric Interview (MINI ([Sheehan et al., 1998](#))), a structured clinical interview, was also administered by a masters-degree-level clinician to assess other psychiatric disorder symptoms.

2.1.1. Exclusion criteria

Participants were excluded from the current study if they had a self-reported history of neurological impairment such as seizures or head injury with loss of consciousness; a prior diagnosis of intellectual disability, autism spectrum disorder, fetal alcohol syndrome, Tourette's disorder, PTSD, or psychosis; left-handedness; and any non-stimulant psychotropic medications (with the exception of SSRIs and SNRIs for those with an ADHD assignment). Additional exclusionary criteria determined by a clinical interview and neuropsychological testing included currently experiencing a major depressive episode, meeting criteria for substance use disorder, or having an estimated IQ < 80..

2.2. Determining diagnostic grouping

In line with DSM-5 criteria, in order to be assigned to the ADHD group, participants needed to have ≥ 5 current inattentive or hyperactivity symptoms, at least mild impairment resulting from these symptoms, as well as evidence that the onset of symptoms occurred prior to the age of 12 ([American Psychiatric Association, 2013](#)). Symptom counts were determined using the following rules:

(a) at least one reporter (informant or self) must have endorsed ≥ 5 current symptoms on either the BAARS or ACDS; (b) and at least one reporter must endorse ≥ 3 childhood inattentive or hyperactive symptoms also on either the BAARS or ACDS; (c) the participant must report at least mild impairment on the ACDS; (d) for both the child and adult symptom domains, both reporters must report a minimum of 2 symptoms within the inattentive or hyperactive domain on either the BAARS or ACDS; and (e) participants must have a T-score > 65 on at least one ADHD related scale on the CAARS.

To be in the control group, (a) both reporters (participant and informant) must agree that the participant has ≤ 3 total current inattentive and hyperactive symptoms on the ACDS and BAARS (b) and < 3 total childhood inattentive and hyperactive symptoms on the ACDS or BAARS; (c) the participant must report no impairment on the ACDS; and (d) the participant must have T-scores < 60 on all ADHD related scales on the CAARS.

Only participants who fell into ADHD or Control groups were eligible for the study.

2.3. Experimental procedure

All participants were assessed for state sleepiness (Stanford Sleepiness Scale) (Hoddes, Zarcone, & Dement, 1972) and if they indicated they were considerably tired (denoted as a 5 or higher on the 8 point scale), their visit was rescheduled. Participants with ADHD taking stimulant medications (51%) were included in the study. Participants were asked to discontinue stimulant medication use and refrain from recreational drug use for at least 24 h prior to their visit. Abstinence was confirmed through oral report as well as through a urine screen (iCUP). If the urine screen came back positive, the visit was rescheduled. An exception was made for THC if the participant reported abstinence for the last 24 h.

2.3.1. Sustained attention to response task (SART)

The SART (Robertson, Manly, Andrade, Baddeley, & Yiend, 1997) is a well-established attentional task (Smallwood, Beach, Schooler, & Handy, 2008; Smilek, Carriere, & Cheyne, 2010). The task was programmed using Python 2.7. Participants responded with a button press to a pseudorandom series of digits 1–9 and withheld that response to the digit, “3”, appearing 11% of the time. Fig. 1 depicts an example of an experimental run. Each digit appeared one at a time for 250 ms followed by a centrally located fixation cross presented for 900–1100 ms. 500 Hz tones (distractors) were presented 400–650 ms after the offset of each visual stimuli for 75% of the trials. Participants were told to ignore these tones. The auditory distractors were included to address questions about the stimulus-dependence of off-task thought and are not included in analyses in the current study. A total of 45 blocks were presented, each varying in length from 30 to 90 s. The task was ~ 60 min in duration including short voluntary breaks.

Performance measures on the SART demonstrated high internal consistency using split-half correlation methods on odd versus even trials for RT, SDRT, and errors of commission. Spearman-Brown Coefficients were 0.99, 0.99, 0.94 respectively. Coefficients remained high when assessing internal consistency within each group as well (all coefficients > 0.92).

2.3.1.1. Thought probes. At the end of each block, participants answered questions assessing their attentional state (Mills et al., 2018). The following questions were analyzed in the current study:

1. Were you thinking about something other than what you were doing?
2. Were your thoughts moving about freely?

Participants responded using a slider bar on a continuous scale from (1) *not at all* to (7) *very much* for each question. Prior to the task, participants were provided with an explanation of each of the thought probes with examples. See [Supplementary Material](#) for the full script used.

After completing the thought probes,¹ the task continued to the next block. Participants were told they could take short breaks to drink water or stretch after responding to the thought probes and before continuing on to the next block.

No-go trials (i.e. trials with a “3” presented) did not occur within 5 trials (6 s) preceding a thought probe. This was in order to be able to analyze only go trials preceding thought probes (more details provided in the analysis section).

2.3.2. Thought probe confidence

After completing the SART, participants completed a single thought probe confidence rating scale which asked about their confidence in responding to the thought probes. Participants answered each question on a 4-point likert scale with (1) *not confident* (2) *somewhat confident* (3) *confident* and (4) *very confident*. All participants were included in all primary analyses; however, sensitivity analyses were conducted only including those who rated their confidence as a 2, 3 or 4.²

2.3.3. Functional impairment

Functional impairment was assessed using the Weiss functional impairment rating scale self-report (WFIRS-S). This 70-item

¹ Of note, three additional probes were administered asking “were you thinking about your surroundings?”, “How negative or positive were your thoughts?”, and “How strong was that emotion?”. However, they were not analyzed in the current work.

² This included the exclusion of two control participants who were not confident in their responses to the probe asking about freely moving thought. The exclusion of these participants from all analyses did not alter any of the reported results.

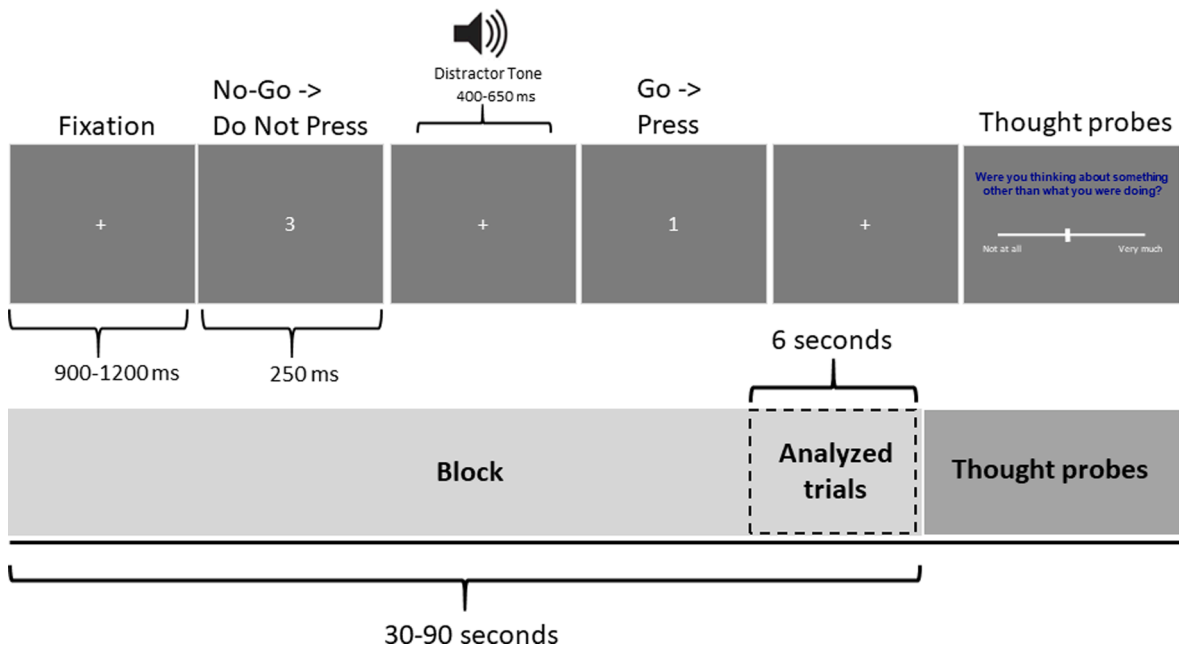


Fig. 1. Depiction of a SART experimental run.

questionnaire assesses seven domains of functioning (family, work, school, life skills, self-concept, social, and risk). For each of the items, participants indicated how much difficulty they have had in that area using a 4-point scale with responses ranging from never to very often. Global impairment was used in the current study which is an average of scores across the seven domains. All scales have been previously shown to have adequate internal consistency (Cronbach's alpha = 0.84–0.93) as has the global impairment score (average of all scales) (Cronbach's alpha = 0.96). Construct, predictive, and discriminant validity have also all been previously documented (Canu, Hartung, Stevens, & Lefler, 2016; Weiss, McBride, Craig, & Jensen, 2018).

2.4. EEG recording and preprocessing

EEG was recorded during the SART from each adult at a sampling rate of 500 Hz with 96 Ag-AgCl active electrodes using the open source software PyCorder v1.0.9. The electrode array is based on the international 10–20 system centered at Cz. EEG signals were amplified by a BrainVision actiCHamp2 amplifier.

EEG data was analyzed using ERPLAB (Lopez-Calderon & Luck, 2014) and EEGLAB (Delorme & Makeig, 2004) toolboxes. Raw EEG data was referenced offline to the average of all channels. EEG signals were filtered using an IIR filter with a bandwidth of 0.01–50 Hz. Eye artifacts were removed by independent component analysis. Epochs were time-locked to the onset of the go-correct visual stimuli. The sampling epoch for each trial was 1,200 ms, including a 200 ms pre-stimulus period that was used to baseline correct the epoch. Trials were discarded from the analyses if they contained baseline drift or if the amplitude of movement artifacts was $\pm 90 \mu\text{V}$. Individual channels responsible for rejecting greater than 20% of trials were interpolated using EEGLAB's interpolation function.

2.5. Data analysis

2.5.1. Determining off-task and on-task blocks

Responses to thought probes were on a continuous scale in order to reduce framing effects such as acquiescence and satisficing (Weinstein, 2018; Weinstein et al., 2018); however, categorization was necessary in order to complete analyses which required a dichotomous assignment. This method is consistent with other studies (Christoff, Gordon, Smallwood, Smith, & Schooler, 2009; Kam et al., 2021; Kirschner, Kam, Handy, & Ward, 2012; Mills et al., 2018; Qin, Perdoni, & He, 2011). Each block was categorized as off-task or on-task based on the participant's response to the first thought probe which asked "were you thinking about something other than what you were doing?" Blocks preceding responses of 1–3.5 on that thought probe were categorized as on-task blocks. Blocks preceding responses of 4.5–7 on that thought probe were categorized as off-task blocks. Blocks preceding responses between 3.5 and 4.5 were not categorized due to the ambiguous nature of a response that lies in the middle of this scale, similar to prior studies (Christoff et al., 2009; Mills et al., 2018). To measure frequency of off-task thought, the percentage of blocks reported as off-task was calculated.

For off-task blocks, responses to the thought probe "were your thoughts moving about freely?" were also dichotomized. Responses between 1 and 3.5 were coded as constrained off-task thought, while responses between 4.5 and 7 were coded as freely moving off-task thought. For each participant, the percentage of self-reported constrained and freely moving off-task thought was calculated.

Trials that occurred 6 s (5 trials) prior to a thought probe were used in behavioral and EEG analyses. While many other studies tend

to use a slightly larger time window (e.g., 10–20 s), this is often to balance capturing the reported attentional state with the need to have adequate numbers of trials for reliable EEG/ERP analysis (Baird, Smallwood, Lutz, & Schooler, 2014; Kam et al., 2012, 2021; Smallwood et al., 2008). However, there is no such restriction for EEG complexity analysis. Rather, reliability of complexity measures is dependent on the number of data points in the time-series with a recommended low limit of 128 time points. In the current study, we have 500 time points per epoch (1 s sampled at 500 Hz) (Lutzenberger et al., 1995). Since it is acknowledged that a smaller time window would more reliably capture the subsequent attentional state (Kam et al., 2011; Smallwood et al., 2008), a slightly smaller time window was used here. Trials that occurred in an off-task block were considered off-task trials while trials that occurred within an on-task block were considered on-task trials (Kam et al., 2012, 2013; Kam et al., 2021; Smallwood et al., 2008). See Fig. 1 for a depiction.

2.5.2. Task performance

Mean reaction time (RT), standard deviation of reaction time (SDRT; a measure of reaction time variability), errors of omission, and errors of commission were calculated for the overall task. Additionally, RT, SDRT, and errors of omission were also calculated separately for off-task and on-task trials. Errors of commission could not be calculated for off-task and on-task trials since there were no no-go stimuli within the 6 s prior to the thought probes.

2.5.3. EEG complexity

EEG segments were averaged and the 200 ms baseline was not included when calculating complexity values. Complexity was calculated for off-task and on-task trials separately. Because complexity is sensitive to signal noise (Skinner, Molnar, & Tomberg, 1994; Stam, 2005), 30 epochs were randomly selected from each condition for each subject to ensure more similar signal-to-noise ratio as has been used in other work (Müller & Lindenberger, 2012).

Complexity values were calculated with the Skinner's algorithm to calculate pointwise correlation dimension (PD2) (Skinner, Molnar, Vybiral, & Mitra, 1992, 1994) using the Dataplore software package (Datan Software and Analysis GmbH, Teltow, Germany). PD2 is a mathematical measure derived from non-linear system theory that has frequently been used to measure overall complexity of EEG brain dynamics, particularly during various attentional states (Lutzenberger et al., 1992; Mölle et al., 1996, 1999). First, the system dynamics were reconstructed with the time delay (τ) of 1 (2 ms) consistent with similar work (Müller & Lindenberger, 2012). The maximum embedding dimension was set to 12 (Aftanas et al., 1998). The dimensionality of the resulting attractor was calculated using the following formula: $PD2(i) = \log C(r,i)/\log(r)$. The pointwise correlation integral ($C(r,i)$) was calculated based on:

$$C(r, i) = \frac{1}{N-1} \sum_{j=0; j \neq i}^{N-1} \theta(r - \|\hat{x}_i - \hat{x}_j\|)$$

where r is the radius of the state space neighborhood around x , \hat{x}_i and \hat{x}_j are the state space coordinates with the delay τ , N is the length of the signal, and θ is the Heavyside function defined as:

$$\theta(x) = \begin{cases} 0 & \text{if } x < 0 \\ 1 & \text{if } x \geq 0 \end{cases}$$

The PD2 value is the dimension of an attractor of the time-series which reflects the system's dynamic complexity. A PD2 value was calculated for the signal generated from each electrode across the scalp and an average was created to reflect global complexity (i.e., complexity across the entire scalp) (Ibáñez-Molina & Iglesias-Parro, 2016).

2.5.4. ADHD symptom counts

Symptom counts were determined by combining participant ratings and informant ratings on the BAARS using an "OR" algorithm such that a symptom was counted if either the participant OR the informant reported it as present (Pelham, Fabiano, & Massetti, 2005). The BAARS has high internal consistency for self-report (Cronbach's alpha = 0.92) and good interobserver agreement (Cronbach's alpha = 0.67–0.70) as well as high test–retest reliability over a 2–3 week period (Cronbach's alpha = 0.75) (Barkley, 2011).

2.6. Statistical analysis

2.6.1. Behavioral data

To determine whether those with ADHD engaged in a larger proportion of freely moving to constrained off-task thought as compared to controls, the percentage of constrained and freely moving off-task thoughts were submitted to a 2×2 linear mixed model with off-task thought type (constrained vs. freely moving) as the within-subjects variable and group (ADHD vs. control) as the between-subjects variable.

2.6.2. EEG data

To determine whether those with ADHD engaged in a larger proportion of freely moving off-task thought than control subjects, complexity values were submitted to a 2×2 linear mixed model with attentional state (off-task vs. on-task) as the within-subjects variable and group (ADHD vs. control) as the within-subjects variable.

2.6.3. Assessing the relationship between EEG and self-report measures

In order to gain further insight into the relationship between EEG complexity and aspects of off-task thought, linear regressions were used with EEG complexity (regardless of attentional state) as the independent variable and percentage of off-task thought or percentage of freely-moving thought as the dependent variable.

2.6.4. Predicting impairment and symptom severity

To determine the relationship between off-task thought and impairment in ADHD, linear regression analyses were used with the measurement of off-task thought (percentage off-task or percentage freely moving and EEG complexity) as the independent variable and ADHD impairment or symptom severity (global score from the WFIRS-S or total ADHD symptoms) as the dependent variable. Four separate regression models were run: (1) frequency of off-task thought predicting impairment; (2) frequency of off-task thought predicting symptom severity; (3) frequency of freely moving thought and EEG complexity predicting impairment; (4) frequency of freely moving thought and EEG complexity predicting symptom severity. These regressions were run *within* the ADHD group to specifically examine whether within-group heterogeneity in symptom severity is related to differences in off task thought.

2.6.5. Missing data

Participants needed 30 clean trials in order to calculate complexity measures. 11 participants were missing off-task complexity data ($n_{ADHD} = 5$; $n_{Control} = 7$) and 14 were missing on-task complexity data ($n_{ADHD} = 8$; $n_{Control} = 6$). Of those 11 and 14 participants, 5 participants never reported being on-task ($n_{ADHD} = 1$; $n_{Control} = 4$) and 3 participants never reported being off-task ($n_{ADHD} = 3$) and were therefore missing behavioral data in the on- or off-task conditions, respectively. Linear mixed models were used here due to their ability to better accommodate missing data using pairwise, as opposed to listwise, deletion.

3. Results

3.1. Participants

79 individuals participated in this study (40 controls, 39 ADHD). 82.3% of the participants identified as being Caucasian, 8.9% as Multiracial, 6.3% as Asian, 1.3% as Black, and 1.3% as Pacific Islander. Additionally, 6.3% identified as Hispanic. Distribution of race and ethnicity did not differ between ADHD and control groups. See [Table 1](#) for other participant demographics and clinical scores.

3.2. Task performance

As expected, on the entire task (regardless of on/off-task report) those with ADHD had significantly more variable reaction time, more errors of commission and omission, as well as poorer accuracy. See [Table 2](#). Of note, these results did not change when adding off-

Table 1
Demographic information and clinical scores.

	Control	ADHD	F	Effect Size (95% CI)
n	40	39		
Age (years)	28.67 (4.97)	29.71 (5.69)	0.72	0.20 (-1.40-3.48)
IQ	116.50 (11.33)	111.44 (14.37)	3.03	0.40 (-10.85-0.73)
Sex (male:female)	18:22	20:19	$\chi^2 = 0.31$	
Education (years)	17.18 (2.67)	15.87 (2.41)	5.18*	0.51 (-2.44 to -0.16)
Sleepiness	1.63 (0.67)	1.92 (0.62)	4.20*	0.46 (0.009-0.59)
<i>Inattention Symptoms</i>				
ACDS	0.13 (0.52)	5.54 (2.65)	156.17**	2.90 (4.55-6.28)
BAARS (self-report)	0.10 (0.38)	5.26 (2.22)	209.43**	3.30 (4.45-5.87)
BAARS (informant report)	0.51 (1.43)	4.05 (2.78)	49.54**	1.64 (2.54-4.54)
<i>Hyperactivity/impulsivity Symptoms</i>				
ACDS	0.05 (0.32)	4.16 (2.70)	88.95**	2.19 (3.24-4.98)
BAARS (self-report)	0.28 (0.51)	4.15 (2.37)	102.56**	2.31 (3.12-4.64)
BAARS (informant report)	0.51 (1.48)	2.84 (2.56)	21.81**	1.09 (1.27-3.17)
<i>Other Psychiatric Disorders</i>				
Major Depressive Disorder (met criteria:did not meet criteria)	8:32	22:17	$\chi^2 = 11.11^{**}$	
Generalized Anxiety Disorder (met criteria:did not meet criteria)	1:39	7:32	$\chi^2 = 5.18^*$	
<i>Medication Use</i>				
Prescribed Stimulant Medication (yes:no)	0:40	21:18	$\chi^2 = 29.34^{**}$	
Prescribed SSRI/SNRI (yes:no)	0:40	2:37	$\chi^2 = 2.11$	

ACDS = Adult ADHD Clinical Diagnostic Scale; BAARS = Barkley Adult ADHD Rating Scale; SSRI = selective serotonin reuptake inhibitor; SNRI = serotonin norepinephrine reuptake inhibitor II symptom counts are for current symptoms.

Sleepiness measured from the Stanford Sleepiness Scale and ranged from 1 (wide awake) to 4 (somewhat foggy)

* $p < 0.05$

** $p < 0.001$

Table 2
Task performance.

	Control	ADHD	F	Effect Size (95% CI)
RT (ms)	365.61 (38.81)	362.93 (47.85)	0.07	0.06 (−22.28 to 16.92)
SDRT (ms)	79.13 (22.54)	88.94 (26.60)	3.10 [†]	0.40 (1.28 to −20.91)
Errors of commission (%)	3.82 (1.55)	4.81 (1.62)	7.50 ^{**}	0.62 (0.27–1.70)
Errors of omission (%)	1.81 (3.08)	4.17 (6.79)	3.99 [*]	0.45 (0.006–4.72)
Accuracy (%)	94.36 (4.18)	91.02 (7.63)	5.84 [*]	0.54 (−6.10 to −0.59)
<i>Off-task trials only</i>				
RT	365.22 (48.04)	350.13 (48.04)	1.83	0.31 (−38.27 to 6.44)
SDRT	34.94 (15.73)	37.61 (22.03)	0.36	0.14 (0.46–14.54)
Errors of omission	2.17 (4.11)	6.23 (9.04)	6.08 [*]	0.58 (0.45–7.15)
Accuracy	97.83 (4.11)	93.77 (9.04)	6.08 [*]	0.58 (−7.15 to −0.45)
<i>On-task trials only</i>				
RT	376.14 (46.95)	365.82 (56.50)	0.78	0.20 (−40.36–8.01)
SDRT	26.83 (13.26)	29.22 (19.20)	0.41	0.14 (−2.47–14.11)
Errors of omission	1.33 (2.32)	3.56 (6.01)	4.85 [*]	0.49 (3.00–39.16)
Accuracy	98.67 (2.32)	96.44 (6.01)	4.85 [*]	0.49 (−39.16 to −3.00)

[†] p < 0.1

^{*} p < 0.05

^{**} p < 0.01

task thought frequency as a covariate.

A series of 2 attentional state (off-task vs. on-task trials) by 2 group (ADHD vs. control) linear mixed model revealed significant attentional state effects for RT ($F(1,72.17) = 11.64, p = 0.001$), SDRT ($F(1,76.01) = 8.92, p = 0.004$), and errors of omission ($F(1,73.77) = 11.14, p = 0.001$). Faster RTs, larger SDRTs, and more errors of omission occurred during off-task trials. There was main effect of group for errors of omission ($F(1,68) = 6.46, p = 0.01$). Those with ADHD made more errors of omission than those without ADHD. There were no other main effects of group (all p s > 0.16) and no group × attentional state interactions were significant (all p s > 0.11).

3.3. Thought probes

The number of blocks removed from analyses (responses that occurred between 3.5 and 4.5) were minimal. On average, 7 blocks were removed per participant for the thought probe assessing off-task thought and 3 blocks were removed per participant for the thought probe assessing freely moving thought. The number of blocks removed for each of the thought probes did not differ between ADHD and control groups (all p s > 0.76).

As expected, those with ADHD reported more off-task thought on the SART ($M = 59.77\%$ of trials) than controls ($M = 44.62\%$ of trials) ($F(1,76) = 6.40, p = 0.01$). A 2 attentional state (constrained blocks vs. freely moving blocks) by 2 group (ADHD vs. control) linear mixed model was run to determine whether adults with ADHD engaged in proportionally more freely moving off-task thought

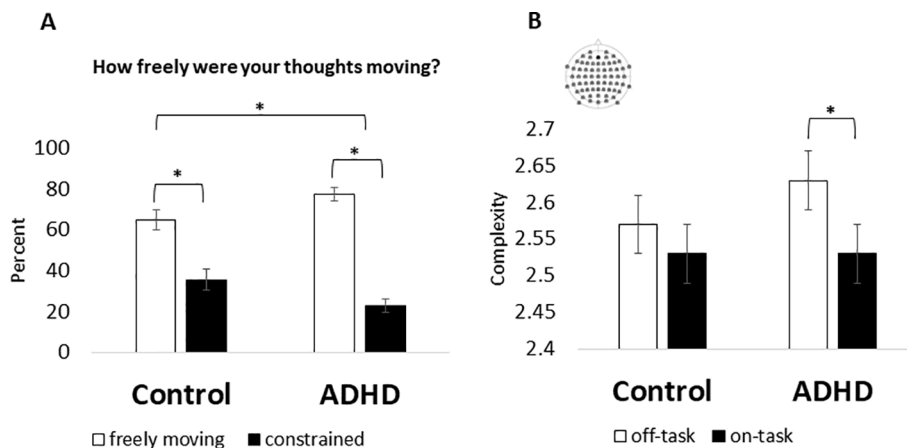


Fig. 2. (A) Bar graph representing the percentage of thought probes responded to as either freely moving or constrained for Control and ADHD groups. (B) Bar graph of complexity scores during off-task and on-task trials for Control and ADHD groups. Complexity was calculated across the entire scalp. The distribution of the electrodes is depicted in the upper left corner.

than controls (group \times attentional state interaction). A main effect of attentional state demonstrated that all participants reported engaging in more freely moving than constrained off-task thought ($F(1,73.00) = 51.45, p < 0.001$). This was qualified by a group \times attentional state interaction ($F(1,73.00) = 4.63, p = 0.04$). While both the control and ADHD group demonstrated more freely moving than constrained thought, this effect was of greater magnitude in the ADHD group ($F(1,38) = 71.50, p < 0.001, d = 5.86$) than in the control group ($F(1,35) = 8.67, p = 0.006, d = 2.71$). These results support the hypothesis that those with ADHD engaged in a greater proportion of freely moving off-task thought than controls. See Fig. 2 for a depiction of the results.

3.4. Complexity

3.4.1. SART

2 Attentional state (off-task vs. on-task) by 2 group (ADHD vs. control) linear mixed models were used to determine whether the EEG complexity for off-task and on-task trials differed between those with and without ADHD during the SART.

As expected, there was a significant effect of attentional state ($F(1,59.77) = 10.04, p = 0.002, d = 0.35$) where complexity was greater during off-task than on-task trials. There was also an interaction between group and attentional state ($F(1,59.77) = 4.96, p = 0.03$). In line with the hypothesis, the attentional state effect for the control group did not reach significance ($F(1,27.65) = 0.46, p = 0.50, d = 0.20$), whereas in the ADHD group, complexity while off-task was greater than complexity while on-task ($F(1,31.62) = 10.79, p = 0.002, d = 0.48$). See Fig. 2 for a depiction of results.

3.5. Relationships across variables

3.5.1. Complexity and thought probes

EEG complexity regardless of attentional state (i.e., EEG complexity over the entire task) was positively related to the percentage of time participants reported being off-task ($\beta = 0.28, p = 0.02$) as well as the percentage of time they reported being engaged in freely moving thought ($\beta = 0.29, p = 0.01$).

3.5.2. ADHD impairment and off-task thought

Within the ADHD group, neither frequency of off-task thought nor freely moving off-task thought predicted ADHD related impairment as measured on the WFIRS-S (all $ps > 0.22$).

However, frequency of off-task thought marginally predicted ADHD symptom severity ($\beta = 0.31, p = 0.06$). For freely moving thought, the overall model for the multiple regression was not significant ($F(1,35) = 2.39, p = 0.11$). See Table 3 for a full output of these models.

4. Discussion

Frequency of off-task thought is higher in ADHD than typical development (Franklin et al., 2017; Mowlem et al., 2016; Seli et al., 2015; Shaw & Giambra, 1993); however, clarifying whether off-task thought is qualitatively different in ADHD as well is relatively poorly studied. The current work aimed to determine whether those with ADHD engage not only in quantitatively more off-task thought, but also qualitatively different (i.e., the features of off-task thought are different), specifically focusing on if those with ADHD would engage in proportionally more freely moving off-task thought than those without. Consistent with our hypotheses, results of both self-report and neurophysiological measures confirmed that adults with ADHD engage in more freely moving off-task thought than controls. This work demonstrates for the first time that ADHD-related difficulties maintaining focused attention are seen not just in externally-focused attention, but also in internally-focused attention as reflected by an increase in freely moving off-task thought.

As expected, those with ADHD performed worse on the SART than controls (Willcutt, Doyle, Nigg, Faraone, & Pennington, 2005) and all participants performed more poorly during off- vs. on-task trials (Bozhilova et al., 2020a, 2020b; McVay & Kane, 2009, 2012). However, hypotheses that off-task thought would more negatively affect cognitive performance in the ADHD group were not

Table 3

Off-task thought frequency, freely moving thought frequency, and EEG complexity prediction of impairment and symptom severity.

	β	p	F	df	p	R^2
Global Impairment						
Off-task frequency	-0.20	0.22	1.53	1,37	0.22	0.04
Global Impairment						
Overall model			0.60	2,35	0.55	0.04
Freely moving frequency	-0.12	0.31				
EEG complexity	0.07	0.70				
ADHD symptom severity						
Off-task frequency	0.31	0.06	3.90	1,37	0.06	0.10
ADHD symptom severity						
Overall model			2.39	2,35	0.11	0.13
Freely moving frequency	0.24	0.14				
EEG complexity	0.25	0.14				

supported. Current findings may be due to the relatively low attentional demand of the task as off-task thought has been shown to differentially impact performance in ADHD in studies employing a higher load task (Bozhilova et al., 2020a, 2020b, 2021). Future work should continue to investigate the role of off-task thought on task performance measures in ADHD.

Although results confirm different patterns of off-task thought in those with ADHD as compared to typically developing adults, more research is needed to understand whether this is an epiphenomenal feature of the disorder or whether it is directly related to core features of the disorder. Our own results did not support strong associations between off-task thoughts and ADHD symptoms or ADHD-related impairment. Impairment ratings, in particular, were based only on self-report and use of other informants to assess impairment will be important. Another possibility is that the patterns of thought observed here reflect a type of cognitive strength in ADHD and future studies should focus on whether this type of thought supports increased creativity or other positive traits in ADHD.

4.1. Contributions to the field of off-task thought

Current findings of the percentage of off-task thought engaged in by control participants (~45%) is consistent with lab-based and experience-sampling studies with off-task thought occurring ~50% of the time (Killingsworth & Gilbert, 2010; Smallwood & Schooler, 2015). Similarly, although a more limited body of research, frequency of off-task thought in ADHD in the current study (~60%) is comparable with what is reported in the literature (50–70%) (Bozhilova et al., 2020a, 2020b; Van den Driessche et al., 2017).

The relative proportions of freely moving and constrained off-task thought in typically-developing adults seen in the lab for the current study is consistent with prior work using probes in daily life (Mills et al., 2018). We further demonstrate that, at least in the lab, this effect is even larger in ADHD. These findings add to an extremely limited number of studies directly examining the freely moving nature of off-task thought and suggest that off-task thought is largely freely moving under both lab-based and real-world conditions. Despite off-task thought being largely encompassed by freely moving thought (~70% of the time) the remaining 30% of reports were those of constrained thoughts. Restricting off-task thought to be defined as freely moving thought would mean misclassifying or neglecting to capture 30% percent of off-task thought.

The current findings also add to the limited body of work suggesting that specific aspects of off-task thought are more prominent in ADHD. Other studies, although not focused on the constrained to freely moving dimension of thought, have examined whether off-task thought in ADHD is automatic or deliberate and have found that those with ADHD engage in more automatic/unintentional off-task thought than those without ADHD (Arabaci & Parris, 2018; Seli et al., 2015). Clarifying and classifying specific qualities of off-task thought will continue to be a critical step for understanding the relationship between thought and psychopathology.

4.2. Limitations & future directions

One potential issue with the thought probe method is that participants become aware of the content that they are being evaluated on which could result in a bias in their responses. With the current experimental design, it is not possible to eliminate this potential bias; however, the convergence of self-report with physiology is reassuring. Identifying non-self-report-based measures of specific aspects of off-task thought (e.g., activation of the medial temporal lobe subcomponent of the default mode network (Christoff et al., 2016)) can inform future studies and potentially help mitigate participant reporting biases.

The neural mechanisms driving EEG complexity measures are widely debated (Tononi et al., 1998), however; studies strongly suggest that this metric can be used to distinguish between constrained and freely moving attentional states (Bob et al., 2011; Ibáñez-Molina & Iglesias-Parro, 2014, 2016; Iglesias-Parro et al., 2020; Liu et al., 2013; Mölle et al., 1996, 1999). In the current study, EEG complexity was related to both occurrence of off-task thought as well as freely moving thought calling into question whether this is a measurement that reflects off-task thought in general, or freely moving thought specifically. Because a majority of off-task thought is freely moving, it is difficult to disentangle these two dimensions in the current study. However, if EEG complexity merely reflected off-task thought, we would expect to see increased complexity during off-task thought in the control group as well as the ADHD group, which we did not find. Rather, the complexity findings parallel the behavioral findings suggesting increased freely moving off-task thought in ADHD. In order to further solidify this finding, future work should use other neurophysiological metrics that might reflect freely moving thought (e.g., alpha power variability (Kam et al., 2021)) as well as attentional fluctuations (e.g., long-range temporal correlation (Irrmischer et al., 2018)).

This study focused on a single dimension of off-task thought: freely moving to constrained. However, thought does not vary along a single dimension and future work should consider investigating how multiple dimensions of thought (e.g., freely moving to constrained and deliberate to automatic) interact to contribute to psychopathology both within and beyond ADHD. Future work investigating whether stimulant medication alters the dynamics of off-task thought in those with ADHD will also be informative. The current work focused specifically on adults with ADHD. This is a critical, and understudied, population; however, this disorder is prevalent across the lifespan. While there is some work investigating off-task thought in children and adolescents with ADHD (Frick, Asherson, & Brocki, 2020; Van den Driessche et al., 2017), additional work is needed to fully understand potential developmental changes in dimensions of off-task thought. The predominantly Caucasian sample in the current study is representative of the greater prevalence of ADHD in White adults as compared to other racial groups (Kessler, 2006). However, there are recognized socially-influenced issues of quantifying rates of ADHD (as well as other psychiatric disorders) in minority populations (Chung et al., 2019; Shi et al., 2021). As such, future work should aim to increase the racial diversity of their participants in order to obtain data applicable to all humans rather than a select subset.

4.3. Conclusions

Off-task thought is not only more frequent in those with ADHD, but is also less constrained to a single topic. Both quantitative and qualitative differences are likely to be important for understanding ADHD-related impairment. An increased understanding of how off-task thought occurs in ADHD has the potential to clarify mechanisms underlying psychopathology and provide novel treatment targets to reduce maladaptive thought patterns.

CRedit authorship contribution statement

Brittany R. Alperin: Conceptualization, Methodology, Software, Validation, Formal analysis, Investigation, Data curation, Writing - original draft, Visualization, Project administration, Funding acquisition. **Kalina Christoff:** Conceptualization, Writing - review & editing. **Caitlin Mills:** Conceptualization, Writing - review & editing. **Sarah L. Karalunas:** Resources, Writing - review & editing, Supervision, Project administration, Funding acquisition.

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.

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Appendix A. Supplementary material

Supplementary data to this article can be found online at <https://doi.org/10.1016/j.concog.2021.103156>.

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