THE EXPERIENCE OF BRAIN POWER DURING A CONTINUOUS PERFORMANCE TASK: EXPLORING THE INFLUENCE OF TASK- AND PERSON-BASED FACTORS

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Abstract

The experience of brain power is a crucial element of collective flourishing and the regulation of cognition. However, essential questions regarding its mechanisms remain poorly understood, particularly concerning how person- and task-based factors influence the experience. This study explored how the experience of brain power during a continuous performance task (CPT) is associated with person-based (i.e., ADHD symptoms) and task-based (i.e., manipulations in interstimulus intervals (ISI)) factors. Participants reported the presence of ADHD symptoms and then were randomly assigned to one of three CPT ISI conditions (1000, 3000, or 6000 ms). Two-thirds of the way through the CPT, participants rated their experience of brain power. Both person- and task-based factors influenced the experience of brain power on two psychometrically distinct facets of the experience (task-elicited and volitionally exerted). Both factors interact to influence CPT performance. Implications of the findings and future directions are discussed.

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The experience of brain power during a continuous performance task: Exploring the influence of task- and person-based factors

Using mental effort to engage in cognitively demanding tasks is associated with a conscious experience, which serves as a regulatory mechanism to motivate behaviour change (Botvinick & Braver, 2015; Kool & Botvinick, 2014; Kurzban, 2016). Indeed, the conscious experience of using mental effort may inform heuristics that individuals use to minimize the expenditure of cognitive resources. This idea is the law of least mental effort, which describes the tendency to minimize cognitive expenditure (Ferrero, 1894) and is often linked to a resource-based account of effort in which effort is limited but nondepletable and, therefore, must be effectively managed (Kahneman, 1973; Kurzban et al., 2013; Tversky & Kahneman, 1974). However, the experience of engaging in mental effort may systematically vary depending on person-based factors (e.g., Bruya, 2010). For example, the experience of engaging in mental effort may be particularly aversive for individuals with Attention-Deficit/Hyperactivity Disorder (ADHD), a disorder for which avoiding or disliking tasks that involve sustained mental effort is a diagnostic criterion (American Psychiatric Association [APA], 2022). Moreover, the experience of engaging in mental effort may systematically vary depending on task factors (e.g., Robinson & Morsella, 2014). For example, previous research has shown that participants report different levels of effort for cognitive tasks that activate different underlying mental processes, such as computational complexity or compensatory control (Bambrah et al., 2019). Thus, to fully understand how the experience of mental effort regulates the expenditure of cognitive resources, it is critical to account for person- and task-based factors that alter the experience.

Conceptualizations of Mental Effort

Varied conceptualizations of mental effort have been proposed. Kahneman (1973) understood mental effort in terms of voluntary (i.e., chosen or applied by the individual) and involuntary (i.e., automatic or engaged by a task) processes, although Kahneman placed greater emphasis on the latter. For example, in a thought experiment, Kahneman (1973) described the difference between being asked to remember the number two for some time versus multiplying two larger numbers in your head. According to Kahneman, the phenomenological experience of remembering the number two is different from multiplying two numbers together in that you cannot try harder to remember the number two. Thus, Kahneman emphasizes task-based factors that influence mental effort while recognizing that the individual also plays a role in the expenditure of cognitive resources.

Others define mental effort as an aspect of executive control processes that manage energetic resources (Mulder, 1986). In this framework, Mulder (1986) states that information processing is affected by three energetic resources: arousal, activation, and mental effort adjustment. Arousal refers to tonic changes in physiological activity, while activation refers to phasic responding, which is time-locked to stimulus processing (Mulder, 1986). According to Mulder (1986), deficient task performance is caused by both person and task-based factors insofar as an individual may be unable to volitionally exert enough effort to maintain optimal activation and arousal when a task is not sufficiently arousing or activating. Thus, effort refers to that volitional component, while this model recognizes that task-based factors also influence performance. Indeed, both aspects of Mulder's model, task-elicited arousal or activation and volitionally exerted effort, are crucial to understanding performance on tasks that require compensatory control, wherein effort must be continuously applied volitionally to maintain adequate performance when the individual is not sufficiently activated or aroused by the task.

Bruya (2010) defines mental effort as the conscious experience that arises while engaged in mentally demanding activities. More specifically, under Bruya's (2010) conceptualization of mental effort, there is a contrast between experiences that are consciously effortful on the one hand and autotelic or effortless on the other hand. Activities, actions, or attention can be considered effortful when the subjective experience of using cognitive energy is present (Bruya, 2010). In this way, Bruya (2010) described the subjective experience of volitionally exerted mental effort as mental effort itself. In contrast, experiences can be autotelic, for which action and self-awareness merge because the activity provides sufficient stimulus for action, or put differently, the task automatically elicits energy from the individual (Bruya, 2010). Bruya (2010) proposes the idea of effortless attention or actions which are not experienced as volitionally effortful but require cognitive resources, nonetheless.

Mental effort has also been conceptualized in terms of the interrelation between volitionally exerted and task-elicited components (Hockey, 2011). According to Hockey (2011), volitionally exerted mental effort is a response to the perception and appraisal of task demands, desired performance, and actual performance. Therefore, although volitionally exerted mental effort is under the control of the individual, task demands also influence it. Moreover, individual differences in motivational goals and discrepancies between actual and desired performance influence volitionally exerted mental effort (Hockey, 2011). In general, according to Hockey, goals that an individual is motivated to pursue will be experienced as less effortful. Thus, in Hockey's view, mental effort should be understood not simply in terms of the demands of a task nor the energy volitionally applied but in terms of the interplay between the two and their interface with motivation.

These different approaches to understanding and defining mental effort highlight distinct but interrelated components. Mulder's definition underlines the importance of how the task engages the individual through activation and arousal. This relates to Kahneman's idea of involuntary mental effort or Bruya's idea of autotelicity—when a task engages and can activate the individual in line with task demands. Existing definitions also point to a component of effort that is applied voluntarily, and the focus here is on the actions and goals of the agent. This distinction between task-elicited and volitionally exerted mental effort components has been borne out empirically. For example, Mulert et al. (2007) found that task-elicited effort was proportionally linked with objective task difficulty, while volitionally exerted effort remained stable across difficulty levels. Given that existing theories and empirical work highlight the distinction between task-elicited and volitionally exerted effort, it is important to understand mental effort as a multi-dimensional construct.

Operationalizations of Mental Effort

In addition to varied conceptualizations, varied operationalizations of mental effort have been employed. Commonly, researchers operationalize mental effort using a variety of psychophysiological variables or via self-report. In terms of psychophysiology, researchers have used skin conductance response (Kahneman, 1973; Venables & Fairclough, 2009), pupil diameter (Beatty, 1982; Fairclough & Mulder, 2012), heart rate reactivity (Mulder & Mulder, 1981; Jorna, 1992; Mukherjee et al., 2011), cortisol (Veltman & Gaillard, 1993), blood glucose (Scholey et al., 2001, 2006), electroencephalogram frequency bands (e.g., Boksem et al., 2005; Gergelyfi et al., 2015; Venables & Fairclough, 2009) and event-related potentials, specifically the P300 component (Kaseda et al., 1998; Kato et al., 2009), to measure mental effort.

However, given that it is the conscious experience of engaging in mental effort that is thought to play a regulatory role, it is critical to assess this experience directly through self-report. Researchers have assessed mental effort with self-report scales that are either single-item or multi-faceted. For example, researchers have asked participants to rate their current level of effort using single-item scales (e.g., Hsu et al., 2017; Paas & Merrienboer, 1993; Zijlstra & van Doorn, 1985). By contrast, multi-faceted scales are designed to assess different aspects of the experience of mental effort. For example, the NASA Task Load Index (NTLX;

Hart & Staveland, 1988) includes an assessment of ‘frustration,’ and the Dundee State Stress Questionnaire (Matthews et al., 1999) includes an assessment of ‘stress.’ However, these scales fail to clearly distinguish between volitionally exerted (i.e., put forth by the individual) and task-elicited (i.e., elicited from the individual by a task) effort. Moreover, these multi-faceted scales are used retrospectively to assess participants' recall of engaging in mental effort.

Self-reports of the conscious experience of engaging in mental effort can be assessed either anticipatorily (e.g., Bambrah et al., 2019), in-the-moment (e.g., Hsu et al., 2017; Paas & Merrienboer, 1993; Zijlstra & van Doorn, 1985), or retrospectively (e.g., Hart & Staveland, 1988; Matthews et al., 1999), but more commonly in-the-moment and retrospectively. Retrospective measures require participants to reflect on their experience of mental effort after completing a task and are subject to biases like the peak-end effect (Redelmeier & Kahneman, 1996). The peak-end effect describes a phenomenon in which participants’ retrospective judgments are strongly determined by their ratings of an experience at its peak and the end, and this phenomenon has been observed with mental effort ratings (e.g., Bambrah et al., 2019; Finn & Miele, 2016; Hsu et al., 2017, 2018). Bambrah et al. (2019) found that salient moments of mental effort biased overall retrospective evaluations; moreover, this effect was stronger in individuals who exhibited more ADHD symptomology (Hsu et al., 2017, 2018). Thus, given that the peak-end effect has been observed in the recall of mental effort, it is critical to also examine the experience of mental effort in the moment.

A New Term and an Integrative Conceptualization of Mental Effort

Considering the disparate ways ‘mental effort’ has been conceptualized, operationalized, and measured, comparisons across different theorists and studies are fraught with confusion and misunderstanding. Thus, we suggest a novel term that is less likely to contain idiosyncratic connotations for different readers. We propose to use the umbrella term 'brain power' to refer to the task-elicited and/or volitionally exerted arousal, activation and attention processes that are required to accomplish mental tasks. The task-elicited and volitionally exerted components of brain power may be associated with distinct conscious experiences. Indeed, Bruya's (2010) work points to this possibility. In addition to the task-elicited and/or volitionally exerted arousal, activation and attention processes required to accomplish mental tasks, we suggest that the affective experience of employing brainpower, especially considering its critical regulatory function, should also be considered part of the broad phenomenon of brainpower. Therefore, we propose defining brain power as the task-elicited and/or volitionally exerted arousal, activation and attention processes required to accomplish mental tasks. We contend that task-elicited and volitionally exerted processes are consciously perceived and associated with affective experiences which regulate mental task initiation and persistence.

Although previous research has found that different cognitive tasks are associated with unique conscious experiences of effort (Bambrah et al., 2019), a direct assessment of task-elicited and volitionally exerted brain power has not been conducted. The State Brain Power Questionnaire (SBPQ) is a new measure of the in-the-moment experience of brain power designed to be administered mid-task to address existing gaps in the literature. Unlike existing measurements, the SBPQ captures perceptions of task-elicited and volitionally exerted brain power and the affective experience of brain power. Preliminary research developing and validating this scale has been conducted, and final analyses are underway. In forthcoming work (Wagner & Eastwood, in preparation), we have shown that participants can reliably report task-elicited and volitionally exerted brain power while engaged in a task requiring sustained attention and that these components are psychometrically distinct. Using the SBPQ in the present study will allow for the direct assessment volitionally exerted and task-elicited brain power during a task requiring sustained attention (alternatively termed compensatory control).

Task-Based Factors Impacting the Experience of Brain Power

The experience of brain power may systematically differ depending on task-based factors (Bruya, 2010; Robinson & Morsella, 2014). Indeed, previous research has compared individuals' experience of brain power when completing different types of cognitive tasks (Bambrah et al., 2019) or when completing different difficulty levels within the same task (Hsu et al., 2018). Hsu et al. (2018) found that participants reported higher levels of effort with increasing difficulty levels on a working memory task, while Bambrah et al. (2019) found that ratings of in-the-moment effort were higher when participants completed a compensatory control task compared to when completing a working memory task. These findings highlight that task-based factors may influence the experience of brain power and that exploring manipulations within compensatory control tasks may help elucidate this observation.

Within experimental cognitive paradigms that assess compensatory control, such as sustained attention tasks, task-based factors can be manipulated to alter demands on different cognitive processes. One task commonly used to study sustained attention, which also allows for manipulations of task demands, is the Continuous Performance Task (CPT; Rosvold et al., 1956). In a CPT, participants must maintain concentration throughout the task and correctly identify target stimuli within a continuous stream of distractors. The CPT can be modified by changing response patterns (i.e., withholding responses for different target stimuli; Conners, 1985), increasing memory demands by changing the target from a single stimulus to a cue-probe pair (Cohen et al., 1999), changing the ratio of target to non-target stimuli, or by manipulating the event rate of the stimuli. These manipulations offer an avenue for exploring how task-based factors influence the experience of brain power.

Person-Based Factors Impacting the Experience of Brain Power

The regulation of brain power may differ between individuals depending on their perception of brain power that arises while engaged in cognitively demanding tasks. Previous research has found that the experience of brain power correlates with personality traits, such as conscientiousness. More specifically, highly conscientious individuals report lower ratings of effort and frustration on the NTLX when engaged in cognitively demanding tasks than low conscientious individuals (Bates, 2024). Additionally, the experience of mental effort and the avoidance of mental effortful tasks has been identified as an essential area of research within clinical populations (Wolpe et al., 2024). Indeed, mental effort avoidance has been shown to have a transdiagnostic structure associated with traits such as lack of perseverance and impulsiveness (Patzelt et al., 2019).

One such clinical population, or dimensional clinical presentation, that may be important for understanding how person-based factors influence the experience of brain power is ADHD. Indeed, a diagnostic criterion for ADHD includes avoiding or disliking tasks that involve sustained mental effort (APA, 2022). In a recent review of the literature exploring the experience of brain power in ADHD, Wagner et al. (2024) suggest that individuals with ADHD or who self-report ADHD symptoms may not be sufficiently activated by cognitively demanding tasks and, therefore, may need to volitionally exert additional brain power to maintain performance (Sergeant 2000, 2005). However, they highlight that existing literature has produced mixed results, mainly stemming from different operationalizations and measurements of the experience of brain power (Wagner et al., 2024). Wagner et al. (2024) recommend measuring the self-reported experience of task-elicited and volitionally exerted brain power while engaged in cognitively demanding tasks, such as compensatory control tasks (see also Mies et al., 2019).

There is a history of using compensatory control tasks to explore performance differences between individuals with ADHD and those without. Much of this research has focused on inhibition but has also been used to test Sergeant's Cognitive Energetic Model (CEM; Sergeant, 2000; 2005; Sergeant & Oosterlaan, 1999), which is also called the State Regulation Deficits (SRD) model (van der Meere & Sergeant, 1998) of ADHD. This model proposes that the interplay between task-based factors (i.e., the task at hand and associated goals) and state processes or individual-based factors (i.e., individual levels of arousal and activation) determines the efficiency of information processing. To test this model, researchers have manipulated the event rate of stimuli (also called inter-stimulus intervals), which alters demands on information processing during CPTs (see Sergeant, 2005; Sonuga-Barke, Wiersema, et al., 2010 for review). Concerning cognitive performance, Metin et al. (2012) conducted a meta-analysis of studies exploring event rate effects using a type of CPT (the Go/No-Go paradigm) in ADHD and found disproportionate slowing of reaction times (RTs) and higher commission error rates for fast (1250-2300 ms) and slow (4250-8300 ms) event rates in the ADHD sample compared to controls. Thus, this person-based factor seems to interact with task-based manipulations to produce performance differences. Critically, this research did not include in-the-moment measures of the experience of brain power, which raises the question of whether the experience of brain power is an important mediating factor between ADHD symptoms and performance.

Additionally, despite the existing research exploring the interaction between ADHD diagnosis and event rate manipulations, there is a dearth of research exploring how task demands interact with continuous measures of hyperactivity/impulsivity and inattention in non-clinical samples and how, in turn, this may influence the experience of brain power. Recent studies have called into question the validity of some diagnostic categorizations, such as ADHD (e.g., Kushki et al., 2019), and proposed a move toward transdiagnostic approaches

(Insel et al., 2010; Mahjoob et al., 2024). To this end, there is a recognition of the importance of conducting research across the full range of attentional abilities (Crosbie et al., 2013; Dupuis et al., 2022). Therefore, measurements of the presence of ADHD symptoms, such as hyperactivity/impulsivity and inattention, allow for an investigation into how person-based factors influence the processes underpinning the experience of brain power. One study found that individuals high in ADHD traits performed worse on a CPT, with poorer response inhibition and slower response latencies than those with fewer ADHD traits (Crosbie et al., 2013). However, this study did not manipulate event rates or measure the experience of brain power. Therefore, there is limited research using a dimensional approach to hyperactivity/impulsivity and inattention (a person-based factor) while exploring how event rate manipulations (a task-based factor) influence the experience of brain power and, in turn, cognitive performance.

The Present Study

In summary, existing literature underscores crucial gaps in our understanding of the experience of brain power depending on person- and task-based factors. Notably, previous studies exploring the experience of brain power in ADHD have relied on self-report measures that tend to conflate two conceptually and theoretically essential aspects of brain power (i.e., task-elicited and volitionally exerted brain power). For instance, Mies et al. (2019) measured "effort" with the NTLX, which was defined as the work put forth by the individual, while Hsu et al. (2017) measured effort, which was defined as the experience of being taxed or burdened. Moreover, previous studies have typically only assessed the experience of using brain power with retrospective measures (Johnstone et al., 2010; Mies et al., 2019) rather than assessments of the in-the-moment experience of doing a task, which is critical for determining task persistence. One study measured the in-the-moment experience of task-elicited brain power; however, it did not systematically vary task demands (Hsu et al., 2017).

Yet previous research has shown that varying task demands may elicit different experiences of brain power (e.g., Johnstone et al., 2010) and that varying task demands, like event rates, may be necessary for understanding ADHD (Metin et al., 2014). Lastly, past research has typically assigned participants to dichotomous groups, either based on a diagnosis of ADHD or scores on symptom screeners. Still, there is a range of individuals who fail to meet the criteria for a diagnosis of ADHD who are struggling with hyperactivity/impulsivity and inattention. Self-reported hyperactivity/impulsivity and inattention measured with scales that assess symptoms of ADHD offer a means of measuring a continuum of attentional struggles while bearing no implication for diagnosis. By including continuous measures of hyperactivity/impulsivity and inattention, as evident in self-report assessments of ADHD symptoms, additional variability in this identified person-based factor can speak to the mechanisms underscoring brain power as well as the experience of those who are neurodiverse.

Using the SBPQ, which is an in-the-moment, multi-faceted measurement of the experience of brain power, in conjunction with manipulations of event rates and assessments of hyperactivity/impulsivity and inattention, will address several critical gaps in the existing literature. Specifically, the present study will explore how the in-the-moment experience of using brain power in a compensatory control task (i.e., Continuous Performance Task), measured with the SBPQ, may vary as a function of hyperactivity/impulsivity and inattention and interstimulus interval (i.e., 1000 ms, 3000 ms, and 6000 ms ISIs), and how, in turn, this relates to performance.

Hypotheses

All hypotheses were preregistered on the Open Science Framework (https://osf.io/). To access the preregistration for this study, please visit https://osf.io/zmgny. All hypotheses and results are presented in Table S1 of the Appendix.

Brain Power Rating Hypotheses

Given that event rate manipulations alter the demands on information processing, the researchers hypothesize that ISI will affect the experience of using brain power, such that there will be higher ratings of task-elicited brain power in the 1000 ms ISI than the 3000 and 6000 ms ISI conditions and higher ratings of task-elicited brain power in the 3000 ms ISI than the 6000 ms ISI conditions. Moreover, it is hypothesized that the slower tasks will result in higher ratings of volitionally exerted brain power than the faster tasks, such that there will be higher ratings of volitionally exerted brain power on the 6000 ms ISI condition compared to the 1000 ms and 3000 ms ISI conditions.

Despite some mixed findings in the literature, the researchers are guided most by the findings of Hsu et al. (2017), which found that an ADHD probable group reported higher levels of effort during a compensatory control task than a control group. Therefore, we hypothesize that higher ratings of self-reported hyperactivity/impulsivity and inattention will be associated with lower ratings of task-elicited and higher ratings of volitionally exerted brain power across all ISI conditions.

Task Performance Hypotheses

The hypotheses preregistered for task performance were macro-level predictions. More specific hypotheses are presented in line with the macro-level descriptive performance predictions preregistered.

It is hypothesized that task conditions will have an effect, with faster reaction times on non-X trials and higher commission error rates in the 1000 ms ISI condition compared to the 3000 and 6000 ms ISI conditions. Additionally, it is hypothesized that there will be faster reaction times on the non-X trials and higher commission error rates on the 3000 ms ISI condition compared to the 6000 ms ISI condition.

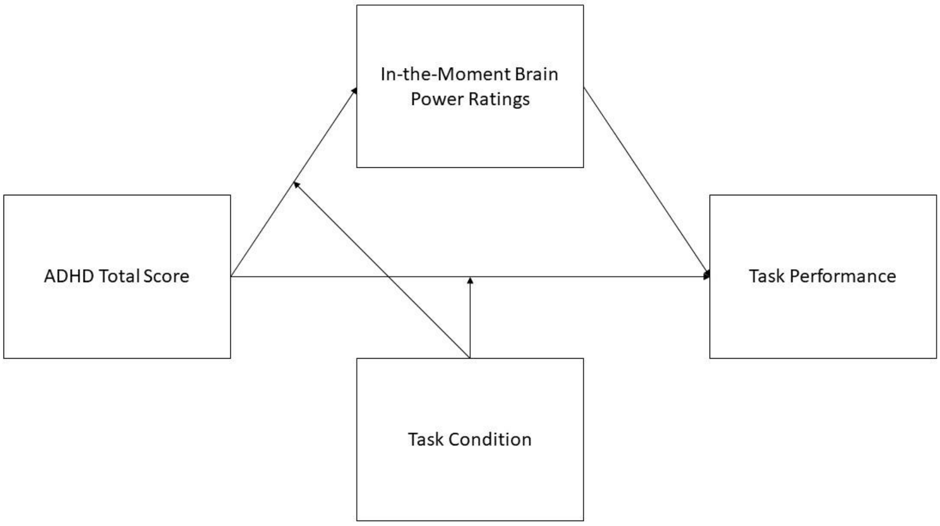
Given that past results have found anss interaction between ADHD status and event rate (ISIs) on cognitive performance, we sought to explore how differences in hyperactivity/impulsivity and inattention (a person-based factor) will interact with manipulations in event rates (a task-based factor). It is hypothesized that self-reported hyperactivity/impulsivity and inattention will interact with task condition to predict performance on the CPT (e.g., commission errors and non-X trial latency), such that the effect of hyperactivity/impulsivity and inattention on CPT performance will be moderated by task condition. Specifically, higher self-reported hyperactivity/impulsivity and inattention will predict worse performance on the CPT (e.g., commission errors and non-X trial latency), especially on the 1000 and 6000 ms ISI conditions. We expect that hyperactivity/impulsivity and inattention will have a smaller correlation with CPT performance in the 3000 ms ISI condition.

Overall Moderated Mediation Model

Building on the hypotheses above, the researchers hypothesize that hyperactivity/impulsivity and inattention will predict CPT performance (i.e., commission error rates and non-X trial latency), and this will be moderated by task condition (i.e., 1000, 3000, or 6000 ms ISI). Moreover, brain power ratings (i.e., task elicited, volitionally exerted) will (at least partially) mediate the relationship between hyperactivity/impulsivity and inattention and CPT performance (commission error rate and non-X trial latency). Lastly, the researchers hypothesize that task condition (i.e., 1000, 3000, or 6000 ms ISI) will moderate the relationship between hyperactivity/impulsivity and inattention and brain power ratings (task elicited, volitionally exerted). Relative to the other conditions, the researchers hypothesize that there will be larger magnitudes of effects in the 1000 ms and 6000 ms ISI conditions relative to the 3000 ms ISI condition. See Figure 1 for a depiction of this model.

Figure 1

Visual Depiction of the Moderated Mediation Model



Note. ADHD Total score = sum of ASRS-5 total and WURS total. In-the-moment brain power ratings = task-elicited or volitionally exerted, run as separate models. Task performance = either commission errors or non-X trial latency, run as separate models. Task condition = 1000, 3000, or 6000 ms ISI.

Brain Power Ratings and Task Performance Hypotheses – Moderated Mediation Model. In the 1000 ms ISI condition, the researchers hypothesize that higher self-reported hyperactivity/impulsivity and inattention will predict less task-elicited brain power and, in turn, lower task-elicited brain power will predict worse performance on both indicators of CPT performance. Additionally, in the 1000 ms ISI condition, higher self-reported hyperactivity/impulsivity and inattention will predict greater volitionally exerted brain power, and, in turn, greater volitionally exerted brain power will predict worse performance on both indicators of CPT performance.

In the 3000 ms ISI condition, the researchers hypothesize that higher self-reported hyperactivity/impulsivity and inattention will predict less task-elicited power and, in turn, lower task-elicited brain power will predict worse performance on both indicators of CPT.

Additionally, the researchers hypothesize that in the 3000 ms ISI condition, higher self-reported hyperactivity/impulsivity and inattention will predict greater volitionally exerted brain power, and, in turn, greater volitionally exerted brain power will predict worse performance on both indicators of CPT performance.

In the 6000 ms ISI condition, the researchers hypothesize that higher self-reported hyperactivity/impulsivity and inattention will predict less task-elicited brain power and, in turn, lower task-elicited brain power will predict worse performance on all indicators of CPT performance. The researchers also hypothesize that in the 6000 ms ISI condition, higher self-reported hyperactivity/impulsivity and inattention will predict greater volitionally exerted brain power, and, in turn, greater volitionally exerted brain power will predict worse performance on both indicators of CPT performance.

Method

Participants

Participants were students from a metropolitan university in Canada who participated for course credit. The sample included 221 participants between the ages of 18 and 25 (M = 19.39, SD = 1.30). Most participants were assigned female at birth (n = 183 female, n = 38 male) and identified as women (n = 180 women, n = 37 men, n = 3 prefer not to say). Ninety-one participants had completed high school, 122 had completed some college or university, five had completed a college certificate or university degree, and one had completed a graduate or professional degree. One participant identified as Indigenous Canadian or First Nations, ten identified as Chinese Canadian, 16 as Black Canadian, 22 as English Canadian, 17 as European descent, 60 as South Asian, eight as West Asian, 48 as “other,” and five preferred not to say. Fourteen participants identified as mixed-ethnicity. York University’s Office of Research Ethics approved all study procedures.

Table 1 presents mean scores for all 221 participants' Adult ADHD Self-Report Scale-5 (ASRS-5), Wender Utah Rating Scale (WURS), ADHD total score (summed value of the ASRS-5 and WURS), and task performance metrics. Sixty-one participants (27.6%) scored above the threshold on the ASRS-5 (i.e., above 14), ninety-one participants (41.2%) scored above the threshold on the WURS (i.e., above 36), and forty-four participants (19.9%) scored above the threshold on both ADHD symptom screeners. The results pattern showed a ceiling effect for non-X trial accuracy. A summary of the hypotheses and results is in Table A1 in the Appendix.

Table 1

Mean Scores of Background and Outcome Variables.

	Condition		
	1000 ms	3000 ms	6000 ms
ASRS-5 Score	11.15	10.64	11.01
WURS Score	33.91	33.42	32.03
ADHD Total Score	45.06	44.06	43.04
CPT Performance			
Non-X Accuracy	0.97 (0.05)	0.96 (0.11)	0.96 (0.09)
Non-X Trial Latency	339.18 (67)	541.00 (331)	830.95 (575)
Commission Error Rate	0.52 (0.25)	0.38 (0.25)	0.39 (0.29)

Procedure

After consenting to participate in the study online, participants completed a demographics questionnaire, the ASRS-5, and the WURS on Qualtrics (https://www.qualtrics.com/). They then watched a three-minute video describing our conceptualization of brain power (https://youtu.be/OiSXFuC2yUY). In this video, participants watch animated people perform various tasks, such as mental math or reading. The experience of using brain power is compared to using muscle power to illustrate further how brain power is conceptualized. Importantly, this video describes the phenomenological distinction between task-elicited and volitionally exerted brain power. Following the video, participants were automatically forwarded to Inquisit 6 Player (https://www.millisecond.com/), where they were randomly assigned to one of three task conditions (1000 ms, 3000 ms, or 6000 ms interstimulus intervals) and completed the Continuous Performance Task and State Brain Power Questionnaire described below.

Continuous Performance Task

The experiment was conducted online using Inquisit 6 Player (https://www.millisecond.com) to present stimuli on participants' computers, with an average refresh rate of 60 Hz. The present study's Continuous Performance Task (CPT) is like the Conners' Continuous Performance Task-III, also called the not-X CPT. However, the task is manipulated such that participants are randomly assigned to one of three versions of this task. In all versions, participants are presented with a sequence of white sans-serif letters, each for 250 ms, in the centre of a black screen. The difference between the versions of the tasks was the interstimulus intervals (ISI); thus, ISI is a between-subjects manipulation. Three ISIs were used in the present study: 1000 ms, 3000 ms, and 6000 ms. Participants in all task versions are directed to respond quickly and accurately to all letters, except X, by pressing the spacebar. Participants are asked to withhold responding if they see an X. In both versions of the task, non-X trials occurred 90% of the time and X trials appeared 10% of the time. The frequencies of the two trial types replicate those used in previous studies using the Conners' CPT (Conners, 1985).

The task begins with two practice blocks, each comprising 30 trials matching the 90:10 proportion of the experimental blocks. The practice block is followed by an experimental block composed of 100 trials, of which 90 were non-X and 10 were X trials. No feedback was provided after the practice block. Following the first experimental block, participants are asked to complete the State Brain Power Questionnaire, described below. Upon finishing the questionnaire, participants returned to another experimental block of the same version of the task they completed before the questionnaire. This final experimental block comprises 50 trials, 45 of which were non-X trials and 10 of which were X trials.

State Brain Power Questionnaire

After 100 trials of the CPT, participants complete the State Brain Power Questionnaire (SBPQ). The SBPQ is a 10-item scale that employs the words "brain power" to help overcome the problem of under-specificity of the term "mental effort." The SBPQ addresses two facets of the experience of brain power: (1) how much brain power participants apply at will (i.e., volitionally exerted brain power), and (2) how much the task engages their brain power (i.e., task-elicited brain power). In the SBPQ, participants indicate their conscious rating of the volitionally exerted (3 items) and task-elicited (3 items) effort on an 11-point scale from "Only a little" (0) to "A great deal" (10). The SBPQ is presented in the Appendix.

Adult ADHD Self-Report Scale-5

The Adult ADHD Self-Report Scale (ASRS) is a self-report measure assessing the presence and severity of adult ADHD symptoms (Kessler et al., 2005; Ustun et al., 2017). The scale requires the presence of ADHD symptomatology based on DSM-5 ADHD criteria within the past six months. This six-item scale presents items on a 5-point Likert-type scale from 0 (never) to 4 (very often). Scores can range from 0 to 24, but an ADHD screener cut-off score of 14 has been shown to have a sensitivity of 91%, specificity of 96% and yield few false positives (Utsun et al., 2017). The responses on the ASRS-5 were summed to create a score of present self-reported hyperactivity/impulsivity and inattention.

Wender Utah Rating Scale

The Wender Utah Rating Scale (WURS) is a self-report measure assessing the retrospective presence and severity of childhood ADHD symptoms in adult samples (Ward et al., 1993). The WURS is based on the Utah ADHD criteria (Wender, 1995), which requires a childhood history of inattentive and hyperactive ADHD symptoms, in addition to persistent struggles in adulthood in one of the following domains: emotional lability, hot temper, stress intolerance, disorganization, and impulsivity (Ward et al., 1993). The WURS consists of 25 items on a 5-point Likert-type scale from 0 (not at all/very slightly) to 4 (very much). Scores can range from 0 to 100, but an ADHD screener cut-off score of 36 has been shown to have a sensitivity and specificity of 96% (Ward et al., 1993). The responses on the WURS were summed to create a score of historical hyperactivity/impulsivity and inattention.

Analysis Plan

First, a composite hyperactivity/impulsivity and inattention score was calculated by summing each participant's ASRS and WURS scores. Critically, the two measures do not overlap in their assessment of symptoms and their severity. The timeframe used as an anchor for the ASRS is in the past six months, while the timeframe anchor for the WURS is in childhood. Given that the ASRS and WURS assess hyperactivity/impulsivity and inattention for different life periods (current and during childhood), the summing of the scores assesses the presence and severity of hyperactivity/impulsivity and inattention across the lifespan. For brevity, this variable is called “ADHD Total Score” in the analyses and results.

Second, outcome variables, latency and commission error rates were scaled to match the magnitude of the other variables. This made the variances of all variables included in the models consistent, and therefore, parameters could be more accurately estimated.

Third, two 1x3 analyses of variances (ANOVA) were run to explore how the in-the-moment ratings of brain power differ between task conditions. A separate analysis was run for each task-elicited and volitionally exerted brain power.

Fourth, two separate regression analyses explored how hyperactivity/impulsivity and inattention (ADHD total score) predict in-the-moment brain power ratings. A separate analysis was run for each task-elicited and volitionally exerted brain power.

Fifth, two 1x3 ANOVA were run to explore how task performance (i.e., commission error rates and non-X trial latency) differs between task conditions. A separate analysis for commission error rates and non-X trial latency was run.

Sixth, regression analyses examined how hyperactivity/impulsivity and inattention (ADHD total score) predict CPT performance (i.e., commission error rates and non-X trial latency). Regression analyses with task conditions entered as a moderator were run to check whether the present study's results match those of past literature.

Seventh, moderated mediation analyses were run to test if the experience of brain power (task-elicited and volitionally exerted) mediates the relationship between self-reported hyperactivity/impulsivity and inattention and performance on the CPT and if ISI manipulations moderate this relationship. A separate analysis was run for each outcome variable (commission errors and non-X trial latency) and each aspect of the experience of brain power (the perception of volitionally exerted and task-elicited brain power). Hyperactivity/impulsivity and inattention (ADHD total score were included as the exogenous variable, and task performance (commission errors, non-X trial latency) was the outcome variable. The mediator between hyperactivity/impulsivity and inattention and task performance was in-the-moment ratings of the experience of brain power (i.e., volitionally exerted and task-elicited brain power). Task conditions (i.e., 1000 ms, 3000 ms, and 6000 ms ISIs) were used as a potential moderator of the relationship between hyperactivity/impulsivity and inattention and in-the-moment ratings of the conscious experience of brain power. Additionally, task condition was entered as a potential moderator of the relationship between hyperactivity/impulsivity and inattention and task performance (commission error rate and non-X trial latency).

Results

Brain Power Ratings

We conducted two 1x3 ANOVAs to examine whether in-the-moment brain power ratings differed between ISI conditions. First, we hypothesized that there would be higher ratings of task-elicited brain power in the 1000 ms ISI than the 3000 and 6000 ms ISI conditions and higher ratings of task-elicited brain power in the 3000 ms ISI than the 6000 ms ISI conditions. However, we did not find a significant difference in task-elicited brain power ratings between the ISI conditions in task-elicited brain power, $F(2,219) = 3.45$, $p = .065$ ($M_{1000} = 16.78$, $SD_{10000} = 8.03$; $M_{3000} = 16.14$, $SD_{30000} = 7.96$; $M_{6000} = 14.33$, $SD_{60000} = 8.46$).

Second, we hypothesized that there would be higher ratings of volitionally exerted effort in the 6000 ms ISI condition compared to the 1000 ms and 3000 ms ISI conditions, and we did find a significant difference between conditions, $F(2,218) = 4.28$, $p = .015$. Comparisons were analyzed using Tukey's Honest Significant Difference test, which revealed higher ratings in the 6000 ($M = 21.01$, $SD = 7.46$) ms condition than the 1000 ($M = 17.5$, $SD = 8.78$) ms condition, $p = .02$, as well as a higher rating in the 6000 ($M = 21.0$, $SD = 7.46$) ms condition than the 3000 ($M = 17.87$, $SD = 7.82$) ms condition, p = .04.

Brain Power and ADHD Total Score Regression

We conducted two separate regression analyses to explore whether hyperactivity/impulsivity and inattention predicted task-elicited and volitionally exerted brain power ratings. First, as predicted, higher self-reported ratings of hyperactivity/impulsivity and inattention (ADHD total score) were associated with lower ratings of task-elicited brain power, $F(1, 219) = 3.945$, $p = 0.04$, $R^2 = 0.012$, $\beta = -.047$. Second, as predicted, higher ADHD total scores were associated with higher volitionally exerted brain power ratings, $F(1, 219) = 27.46$, $p < .001$, $R^2 = 0.11$, $\beta = .12$.

Task Performance

Task Effects

To explore if task conditions influenced CPT performance, two 1x3 ANOVAs were run. First, we explored how task conditions affected commission error rates and found a significant difference between conditions, $F(2, 218) = 5.70$, $p = 0.004$. Comparisons were analyzed using Tukey's Honest Significant Difference test, which revealed there were higher commission error rates on the 1000 ($M = 0.52$, $SD = 0.25$) ms condition than the 3000 ($M = 0.38$, $SD = 0.25$) ms condition, $p = .008$, as predicted. There were higher commission errors on the 1000 ($M = 0.52$, $SD = 0.25$) ms condition than the 6000 ($M = 0.39$, $SD = 0.25$) ms condition, $p = .01$. However, a difference between these two conditions was not hypothesized. No significant difference between the 3000 ms and 6000 ms conditions was observed, failing to confirm that hypothesis.

Second, we explored if task conditions influenced non-X trial latency, revealing a significant difference between conditions, $F(2, 218) = 28.77$, $p < 0.001$. Contrasts between conditions were analyzed using Tukey's Honest Significant Difference test, which, as predicted, revealed a significant difference between all three conditions, with faster reaction times in the 1000 ms ISI condition ($M = 339.16$, $SD = 67$) than the 3000 ms condition ($M = 541.00$, $SD = 331$), $p = 0.005$, as well as the 6000 ms condition, ($M = 830.95$, $SD = 575$), $p < 0.001$. Reaction times on the 3000 ms condition ($M = 541.00$, $SD = 331$) were also significantly faster than those on the 6000 ms condition ($M = 830.95$, $SD = 575$), $p < 0.001$.

ADHD Symptoms and Task Effects

We aimed to investigate how variations in hyperactivity/impulsivity and inattention, a personal factor, interact with changes in event rates (ISIs), a task factor, building on previous findings showing an interaction between ADHD status and event rates on a cognitively demanding task. More specifically, a previous meta-analysis found higher commission error rates on trials with fast event rates for ADHD groups relative to controls (Metin et al., 2012). Therefore, we conducted a regression analysis with ADHD total score predicting commission error rate moderated by task condition. However, no significant relationship was observed, $F(3, 217) = 2.49$, $p = 0.061$, $R^2 = 0.03$. The means of the ADHD total scores and task performance metrics by task condition are presented in Table 1.

Additionally, we sought to explore if the present study replicates past meta-analytic findings, which have found an interaction between event rates (ISIs) and ADHD status, with a significant slowing of reaction times in non-target trials (non-X trials) in ADHD groups relative to controls on CPT trials with slow event rates (Metin et al., 2012). We conducted a regression analysis with ADHD total score predicting non-X trial latency, moderated by task condition. The overall model was significant, $F(3, 217) = 2.43$, $p = 0.036$, $R^2 = 0.05$; however, contrary to the hypothesis, no significant interaction between ADHD total score and task condition was observed. As predicted, task condition significantly predicted non-X trial latency. Further examination of the model revealed significantly slower non-X trial reaction times in the 3000 ms condition ($M = 541.00$, $SD = 331$) than in the 1000 ms condition ($M = 339.18$, $SD = 67$), p = 0.001. Additionally, as predicted, there was significantly slower non-X trial latency in the 6000 ms condition ($M = 830.95$, $SD = 575$) than in the 1000 ms condition ($M = 339.18$, $SD = 67$), $p < 0.001$. There were also significantly slower non-X trial reaction times in the 6000 ms condition ($M = 830.95$, $SD = 575$) than in the 3000 ms condition ($M = 541.00$, $SD = 331$), as predicted. No other significant effects were observed, suggesting that non-X trial latency was predicted by task condition. However, no unique effect of ADHD total scores nor the interaction between ADHD total score and task condition was observed.

In summary, the above analyses revealed several significant effects. First, ratings of volitionally exerted brain power differed between ISI conditions, with higher ratings on the 6000 ms condition than the 1000 and 3000 ms conditions. Second, ratings of task-elicited brain power were not found to be significantly different between conditions, although the means of the ratings for the 1000 and 3000 ms conditions were higher than the 6000 ms conditions. Hyperactivity/impulsivity and inattention (ADHD total score) predicted lower ratings of task-elicited and higher ratings of volitionally exerted brain power. When examining task effects, there were higher commission error rates and faster latencies on the 1000 ms condition than the 3000 and 6000 ms conditions and faster latencies on the 3000 ms condition than the 6000 ms condition. Finally, hyperactivity/impulsivity and inattention (ADHD total score), when moderated by ISI condition, did not predict commission error rates but did predict non-X trial latency; however, this effect was not driven by the interaction between ADHD total score and ISI condition. Although significant effects were not found in all analyses, a moderated mediation analysis is still justified to understand the patterns in the data better. Specifically, since ADHD total score predicted ratings of task-elicited and volitionally exerted brain power, and since these ratings may differ depending on ISI manipulation, it is crucial to see if these effects combine to influence CPT performance.

Moderated Mediation Model Results

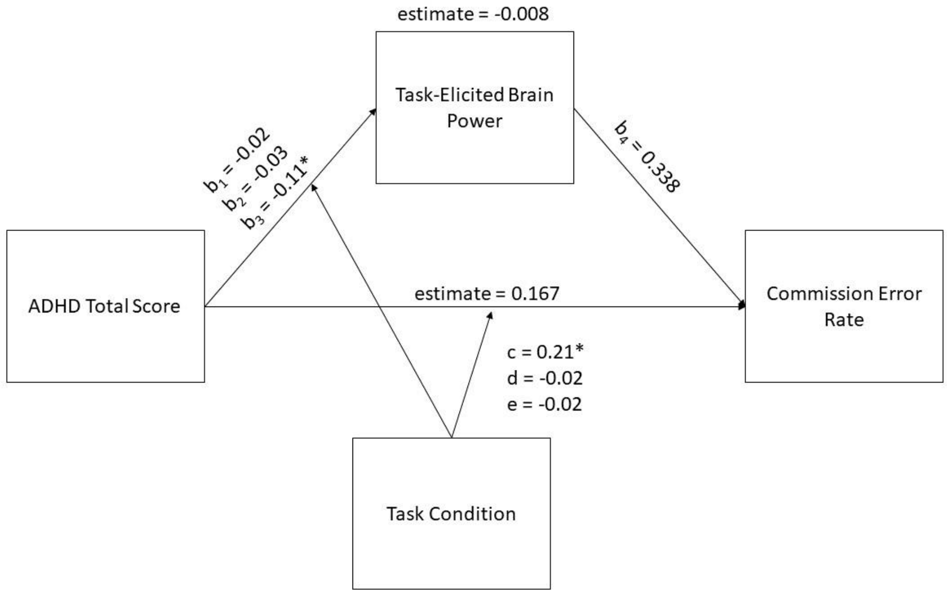
The researchers hypothesized that hyperactivity/impulsivity and inattention (ADHD total score) would predict CPT performance (i.e., commission errors and non-X latency), and the relation would be moderated by task condition (i.e., 1000, 3000, or 6000 ms ISI). Moreover, it was predicted that brain power ratings (i.e., task elicited, volitionally exerted) would (at least partially) mediate the relationship between ADHD total score and CPT performance. Lastly, the researchers hypothesized that task condition (i.e., 1000, 3000, or 6000 ms ISI) would moderate the relationship between ADHD total score and brain power ratings (task elicited, volitionally exerted). See Figure 1 for a depiction of this model, which included 9 parameters and was based on data from 221 observations. Many of the results presented here overlap with the results presented already. Only the moderated mediation model's results are presented here to limit overlap and improve readability. The figures of each model include all of the analysis results despite not appearing in written form.

Task-Elicited Brain Power and Commission Error Rate

We conducted a moderation mediation analysis to examine the relationships among ADHD total score, task-elicited brain power, task condition, and commission error rate on the CPT. We hypothesized that a higher ADHD total score will predict lower ratings of task-elicited brain power, and, in turn, these lower ratings will predict higher rates of commission errors in all three task conditions (1000, 3000, 6000 ms ISIs), with larger effects in the 1000 and 6000 ms condition compared to the 3000 ms condition. Although there were significant paths within the model (see Figure 2), we failed to observe a significant moderated mediation model. The hypothesis for the model was not confirmed, suggesting that task-elicited brain power does not mediate the relationship between hyperactivity/impulsivity and inattention and commission error rates and that ISI manipulations do not moderate this relationship.

Figure 2

Moderated Mediation Model with Task-Elicited Brain Power as the Mediator between ADHD Total Scores and Commission Error Rate



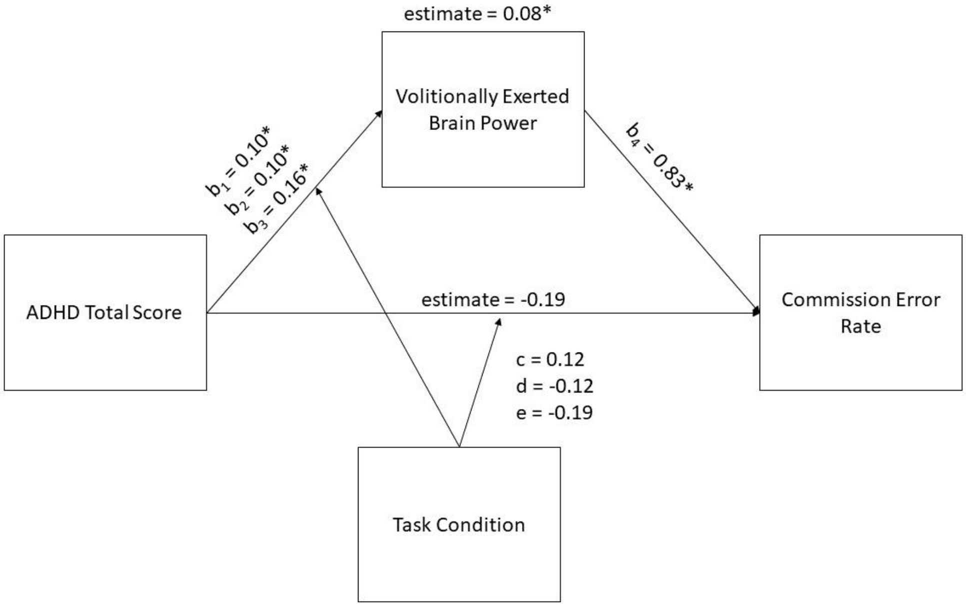
Note. * indicates a significant result with $p < 0.001$. Parameters are as follows: b_1 and c = 1000 ms ISI condition; b_2 and d = 3000 ms ISI condition; b_3 and e = 6000 ms ISI condition.

Volitionally Exerted Brain Power and Commission Errors Rate

We conducted a moderation mediation analysis to examine the relationships among hyperactivity/impulsivity and inattention (ADHD total score), volitionally exerted brain power, task condition, and commission error rate on the CPT. We hypothesized that a higher ADHD total score will predict higher ratings of volitionally exerted brain power, and, in turn, these higher ratings will predict higher rates of commission errors in all three task conditions (1000, 3000, 6000 ms ISIs), with larger effects in the 1000 and 6000 ms conditions than the 3000 ms condition. The indirect effect of ADHD total score on commission error rates through volitionally exerted brain power, moderated by task condition, was significant, *estimate* = 0.08, *SE* = 0.03, $z = 2.64$, $p = 0.008$, indicating mediation. The magnitude of the effect was largest in the 6000 ms condition ($b_3 = 0.16$, $p < 0.01$), while the magnitude of the effects in the 1000 ($b_1 = 0.10$, $p < 0.01$) and 3000 ($b_2 = 0.10$, $p < 0.01$), ms conditions were equal. This confirmed the hypothesis regarding the magnitude of effects for the 6000 ms condition but not the 1000 ms condition. The direct effect of ADHD total scores on commission error rate, independent of volitionally exerted brain power, was not significant, *estimate* = -0.19, *SE* = 0.24, *z* = -0.79, *ns*¸ when ratings of volitionally exerted brain power were included in the model. Overall, these findings confirm the moderated mediation hypothesis that volitionally exerted brain power mediates the relationship between hyperactivity/impulsivity and inattention (ADHD total score) and commission error rates on a CPT, and this mediation effect is moderated by task condition. This suggests that the positive relationship between ADHD total score and commission error rates can be explained through volitionally exerted brain power. Please see Figure 3 for a visual depiction of the results.

Figure 3

Moderated Mediation Model with Volitionally Exerted Brain Power as the Mediator between ADHD Total Scores and Commission Error Rates



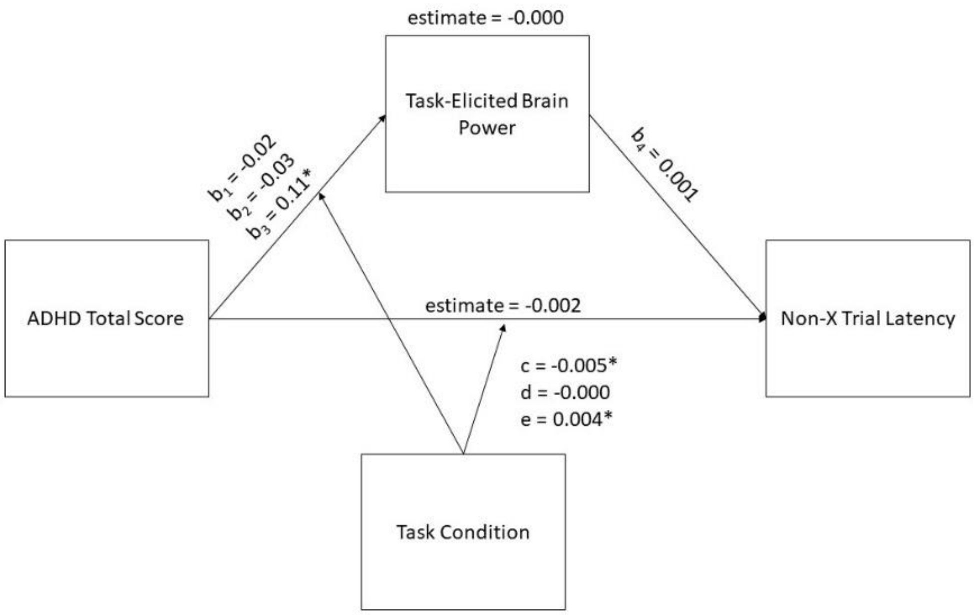
Note. * indicates a significant result with $p < 0.01$. Parameters are as follows: b_1 and c = 1000 ms ISI condition; b_2 and d = 3000 ms ISI condition; b_3 and e = 6000 ms ISI condition.

Task-Elicited Brain Power and Non-X Trial Latency

The same analysis was conducted to examine the relationship among hyperactivity/impulsivity and inattention (ADHD total score), task-elicited brain power, task condition, and non-X trial latency on the CPT. We hypothesized that a higher ADHD total score will predict lower ratings of task-elicited brain power, and, in turn, these lower ratings will predict faster reaction times in the 1000 ms and 3000 ms conditions but slower reaction times in the 6000 ms condition, with large effects in the 1000 and 6000 ms conditions than the 3000 ms condition. Neither the indirect effect (mediate) of ADHD total score on non-X trial latency through task-elicited brain power nor the direct effect of ADHD total score on non-X trial latency, independent of task-elicited brain power, were significant. Although there were significant paths within the model (see Figure 4), the findings suggest no significant mediation effect between ADHD total score and non-X trial latency through task-elicited brain power; thus, the results fail to confirm the moderated mediation hypothesis.

Figure 4

Moderated Mediation Model with Task-Elicited Brain Power as the Mediator between ADHD Total Scores and Non-X Trial Latency



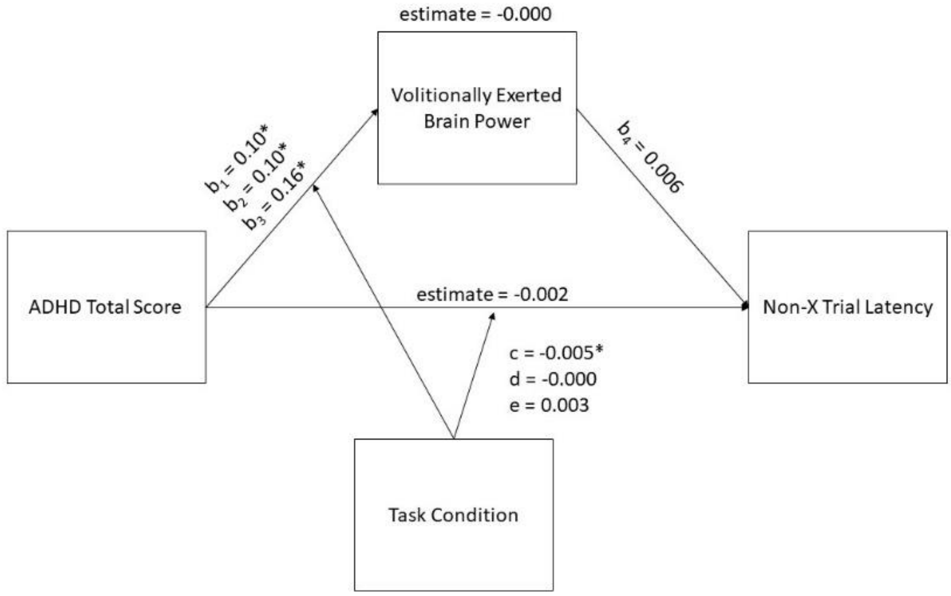
Note. * indicates a significant result with $p < 0.01$. Parameters are as follows: b_1 and c = 1000 ms ISI condition; b_2 and d = 3000 ms ISI condition; b_3 and e = 6000 ms ISI condition.

Volitionally Exerted Brain Power and Non-X Trial Latency

The final analysis examined the relationship among hyperactivity/impulsivity and inattention (ADHD total score), volitionally exerted brain power, task condition, and non-X trial latency on the CPT. We hypothesized that a higher ADHD total score would predict higher ratings of volitionally exerted brain power, and, in turn, these higher ratings would predict faster non-X trial latency in the 1000 and 3000 ms conditions and slower non-X trial latency in the 6000 ms condition. The parameter estimates revealed several significant effects within the model, the results of which are presented in Figure 5. Neither the indirect effect (mediate) of ADHD total score on non-X trial latency through volitionally exerted brain power nor the direct effect of ADHD total score on non-X trial latency, independent of volitionally exerted brain power, were significant. These findings suggest no significant mediation effect between ADHD total score and commission error latency through volitionally exerted brain power, failing to confirm this hypothesis. Please see Figure 5 for a visual depiction of the results.

Figure 5

Moderated Mediation Model with Volitionally-Exerted Brain Power as the Mediator between ADHD Total Scores and Non-X Trial Latency



Note. * indicates a significant result with $p < 0.001$. Parameters are as follows: b_1 and c = 1000 ms ISI condition; b_2 and d = 3000 ms ISI condition; b_3 and e = 6000 ms ISI condition.

In summary, only one moderated mediation analysis revealed a significant full mediation—when volitionally exerted brain power was the mediator between hyperactivity/impulsivity and inattention and commission error rates. The magnitude of the effects was larger in the 6000 ms ISI condition compared to the other ISI manipulations. None of the other analyses revealed significant mediate or direct paths.

Discussion

Although the experience of brain power is thought to play a critical role in regulating cognition, there is a limited understanding of how person- and task-based factors influence that experience. The present study sought to explore the experience of brain power while accounting for person and task-based factors. More specifically, the present study included measures of hyperactivity/impulsivity and inattention as a measure of a person-based factor that is thought to impact the experience of brain power. To that end, hyperactivity/impulsivity and inattention predicted lower task-elicited and higher volitionally exerted brain power ratings, discussed further below. Additionally, the present study included manipulations of task demands to explore how changes to stimulus event rates influence the experience of brain power. Ratings of volitionally exerted brain power were higher in the 6000 ms condition compared to the 1000 ms and 3000 ms conditions; however, task-elicited brain power ratings did not significantly differ between conditions. When examining the joint effects of person- and task-based factors on cognitive performance, only one moderated mediation analysis revealed a significant full mediation. Specifically, full mediation was observed when volitionally exerted brain power mediated the relationship between hyperactivity/impulsivity and inattention and commission error rates, with larger effects in the 6000 ms condition compared to the other ISI conditions. No other analyses showed significant mediation or direct effects. Given the large scope of this study, several hypotheses were put forth, some of which were confirmed.

First, it was hypothesized that in-the-moment ratings of brain power would differ depending on task condition and type of brain power measures (i.e., task-elicited or volitionally exerted). We hypothesized that there would be higher ratings of task-elicited brain power in the 1000 ms condition compared to the 3000 and 6000 ms conditions and higher ratings of task-elicited brain power in the 3000 ms condition compared to the 6000 ms condition. These hypotheses were not confirmed. Despite preliminary analyses showing that task-elicited brain power is a psychometrically distinct factor (Wagner & Eastwood, in preparation), the present study failed to validate our measure of task-elicited brain power because manipulations task factors did not give rise to differentiated ratings of task-elicited brain power. Alternatively, it may be the case that the cognitive demand manipulations included in the present study failed to evoke differences in the experience of task-elicited brain power. Although the present study included a 1000 ms condition, relatively faster than the 3000 and 6000 ISI conditions, event rates on CPTs can be as quick as 500 ms (see Ballard (2001) for review). Indeed, event rates of less than 1000 ms on a CPT have produced individual differences or symptom-specific performance patterns (e.g., Riccio et al., 2002). Therefore, future research should further assess the experience of task-elicited brain power associated with faster event rates. Additionally, exploring other task-based factors, such as task duration, may further elucidate the underpinnings of the experience of task-elicited brain power.

We also hypothesized and confirmed that there would be lower ratings of volitionally exerted brain power in the 1000 ms condition compared to the 6000 ms condition and lower ratings of volitionally exerted brain power in the 3000 ms condition compared to the 6000 ms condition. We also hypothesized but failed to confirm that there would be lower ratings of volitionally exerted brain power in the 1000 ms condition compared to the 3000 ms condition. Taken together, the present study provides evidence for the validity of our measure of volitionally exerted brain power factor and suggests that the experience of volitionally exerted brain power differs depending on task-based factors. The longer ISI condition of 6000 ms was associated with an increased level of volitionally exerted brain power, while the experience of volitionally exerted brain power did not differ between the 1000 and 3000 ms conditions. Previous research has found that the subjective experience of mental effort varies depending on the type of task, namely working memory versus compensatory control (Bambrah et al., 2019). Bambrah et al. (2019) found that compensatory control tasks were experienced as more effortful than working memory tasks. Moreover, Mies et al. (2019) failed to find differences in the experience of mental effort induced by manipulations in task demands within a working memory task. Therefore, taken together, the present study extends previous research while reinforcing the notion that compensatory control, in particular, is associated with high levels of volitionally exerted brain power.

Second, we hypothesized that self-reported ratings of hyperactivity/impulsivity and inattention would be associated with differential relationships to task-elicited and volitionally exerted brain power. We hypothesized and confirmed that higher ADHD total scores (i.e., the sum of ASRS and WURS scores) would be associated with lower ratings of task-elicited brain power when completing a compensatory control task, namely, the CPT. We also hypothesized and confirmed that higher ratings of hyperactivity/impulsivity and inattention would be associated with higher ratings of volitionally exerted brain power when completing a compensatory control task. Previous research exploring the experience of brain power in ADHD or in association with self-reported symptoms has primarily done so with dichotomous comparisons between an ADHD group and a control group. A recent scoping review found that these studies using dichotomous groups have yielded mixed results in the self-reported experience of brain power (Wagner et al., 2024). Only one study, included in the scoping review, has explored the continuous relationship between hyperactivity/impulsivity and inattention and the experience of brain power—Brown et al. (2020) found that self-reported hyperactivity/impulsivity and inattention accounted for 7% of the variance in self-reported mental effort. However, this study only used a retrospective single-item measure of the experience of mental effort, failing to differentiate between task-elicited and volitionally exerted brain power (Brown et al., 2020). The present study provides evidence for a relationship between self-reported hyperactivity/impulsivity and inattention and differential experiences of brain power (i.e., task-elicited or volitionally exerted).

Third, the present study conducted analyses guided by previous research exploring the interaction between ADHD status and event rate manipulations in the prediction of cognitive performance. Expected task effects were observed; namely, we observed faster responses and higher commission error rates on trials with faster event rates and slower responses and lower commission error rates on trials with slower event rates. However, we failed to find a statistically significant unique effect of hyperactivity/impulsivity and inattention or an interaction with manipulations in event rate when examining commission errors as a dependent variable with event rate conditions entered as moderators. Few participants in the present study (19.9%) met the threshold scores on both ADHD screeners used to determine probable ADHD status, and this may explain why we did not find results that mirror those found in meta-analytic studies comparing ADHD and control groups. A future study exploring how a diagnosis of ADHD influences the experience of brain power and, in turn, performance on a CPT may help clarify the findings from the present study.

Fourth, we hypothesized that brain power ratings (i.e., task-elicited and volitionally exerted) would mediate the relationship between hyperactivity/impulsivity and inattention and task performance (i.e., commission error rates, non-X trial latency) and that this relationship would be moderated by task condition (i.e., 1000, 3000, 6000 ms). No statistically significant moderated mediation relationships were observed when exploring task-elicited brain power as the mediator between hyperactivity/impulsivity and inattention and either outcome variable (i.e., commission error rates and non-X trial latency). Nor was a statistically significant moderated mediation relationship observed when exploring volitionally exerted brain power as the mediator between hyperactivity/impulsivity and inattention, and non-X trial latency. However, volitionally exerted brain power was found to fully mediate the relationship between ADHD symptoms and commission error rates, and this relationship was moderated by task condition.

No previous research has explored how the experience of brain power is influenced by person-based (i.e., hyperactivity/impulsivity and inattention) and task factors (i.e., event rate manipulations) and how, in turn, this experience is related to cognitive performance. Previous research has found that ADHD-probable individuals differ in their experience of brain power and perform worse on compensatory control tasks compared to controls (Hsu et al., 2017). Additionally, Hsu et al. found that within the ADHD-probable group, there was a significant negative correlation between in-the-moment ratings of the experience of being taxed or burdened and accuracy (Hsu et al., 2017). However, Hsu et al. (2017) did not explore how the experience of the experience of being taxed or burdened mediates the relationship between ADHD group status and task performance. Moreover, Hsu et al. (2017) did not measure brain power using multiple dimensions of the experience. Therefore, the present study builds on the foundational work done by Hsu et al. (2017) by exploring how the experience of brain power mediates the relationship between a person-based factor (i.e., hyperactivity/impulsivity and inattention) and cognitive performance while accounting for how task-based factors (i.e., manipulations in event rate) moderate this relationship.

Since the presence of ADHD has been identified as a potential person-based factor that may influence the experience of brain power, a promising next step would be to explore how the experience of brain power may influence performance metrics on the CPT for those with and without an ADHD diagnosis. A future study exploring how the experience of brain power, while engaged in a CPT, differs for those with ADHD versus controls may help clarify some of the findings from the present work where effects were not observed for self-reported hyperactivity/impulsivity and inattention. Focusing on diagnostic groups may provide a more robust signal when seeking to understand the processes underpinning brain power.

It would be remiss not to acknowledge that the conceptualization of brain power presented in the present study is only one way of understanding this critical regulatory mechanism. As previously highlighted, many different ways of conceptualizing and understanding mental effort, or what we are calling ‘brain power’ exist. Metacognition, as it relates to mental effort, involves appraisals of work put into a task, task performance, abilities, and the task itself (Ackerman, 2019). Indeed, effort regulation has been proposed as a central metacognitive control function that modulates cognitive effort investment (Ackerman, 2013; Fiedler et al., 2019; Richter et al., 2016). According to the Diminishing

Criterion Model, individuals continue to invest cognitive effort until they reach a target level of success (Ackerman, 2013). However, this investment is influenced by time and confidence, such that as the process or task is prolonged, individuals become less willing to invest cognitive effort, less motivated to succeed, and less confident in their problem-solving responses (Ackerman, 2013). Thus, this framework emphasizes the individual's goals, motivations, and performance appraisals related to the engagement and use of brain power. Following this line of thought is the idea that what we have termed ‘brain power’ is regulated, in part, in a goal-driven manner and may be influenced by time spent on a task and shifting goals as a task is prolonged. Understanding the experience of brain power as a metacognitive process may allow for additional explorations of how it is influenced by person- and task-based factors. For example, a future study should explore how the in-the-moment experience of brain power, both volitionally exerted and task-elicited, relates to self-assessments of performance and confidence mid-task, as well as the performance goals of participants when engaged in a problem-solving task.

It is important to note that while providing valuable insights, the present study did not include measures of the motivation for engaging in a task, which may interact with the experience of brain power. According to Motivational Intensity Theory, mental effort is exhibited when the actor believes that success is possible and that the rewards of success outweigh the costs of employing mental effort; under such circumstances, the amount of mental effort employed is proportional to the actor’s perception of task difficulty (Richter et al., 2016). Therefore, the in-the-moment experience of what we call ‘brain power’ may interact with an individual's motivations and goals. This framework provides a rationale for the decision to engage in tasks requiring brain power—a potentially important facet not included in the present study. Future work should include assessments of the importance of succeeding in the task, the goals of the individual, and perceived task difficulty to understand how these potentially important person-based factors influence the experience of brain power (Richter et al., 2016). This research gap presents a clear call to action for future studies to explore the complex relationship between brain power, motivation, and perceived task difficulty, which could significantly advance our understanding of these processes.

Another way of framing the current work on the experience of brain power is to conceptualize it as a noetic feeling, which can inform an individual about cognitive processes and, therefore, decision-making (Dorsch, 2023). Noetic feelings can be understood as affective experiences about cognitive states (Dokic, 2012). It may be the case that distinct affective characteristics are associated with the experience of brain power, such that affective feelings monitor the quality of cognitive processes (Dokic, 2012) and serve to regulate cognition (Kurzban, 2016). Indeed, this understanding was emphasized previously such that noetic feelings related to brain power serve a critical regulatory role. However, the present study did not include explicit measures of feelings that arise in association with the experience of brain power. Future studies should include such affective characteristics, which may further illuminate the mechanisms underlying brain power.

Likely, the experience of brain power does not have a one-to-one correlation with cognitive processes. Including measures of affective characteristics has the potential to uncover the affective processes that may impact the experience of brain power. For example, recognizing the role of affective processes has been instrumental in furthering our understanding of pain. According to the Gate Control Theory of pain, affective processes influence the 'gate,' or transmission station in the spinal cord, influencing nerve impulse flow to the brain (Melzack & Wall, 1965). Thus, the experience of pain is influenced by affective processes, like previous experiences, past conditioning, the meaning attached to pain-producing situations, and catastrophizing (Melzack, 1961; Sullivan et al., 1995). Given that brain power, much like pain, is thought to be aversive, previous experiences, past conditioning, the meaning attached to activities that require brain power, reactivity or catastrophizing, and difficulties in regulating emotions in the face of aversive feelings may be important affective process underlying the experience of brain power. Hsu et al. (2017) found that in-the-moment ratings of effort and discomfort were moderately correlated, underscoring the need to explore affective processes that might contribute to the uncomfortable experience of engaging in mental effort. Comparable lines of inquiry have been explored in ADHD specifically, which have found that the subjective experience of tasks, specifically delays and past conditioning in the experience of delays, impacts performance over and above explanations based on cognitive processes like inhibition (Sonuga-Barke, Bitsakou, et al., 2010). Thus, affective processes ought to be explored when it comes to understanding the basic mechanisms of brain power and the regulation of cognition.

Affective reactions and the perception of cognitive factors concerning the experience of brain power do not occur in a vacuum, nor does the regulation of brain power. Accordingly, when considering affective and cognitive processes intertwined with the experience of brain power, it is also critical to consider the structural, cultural, and socio-economic factors that may influence the experience. Both socioeconomic background and national culture have been found to influence the experience of brain power. D'Angiulli et al. (2012) found that adolescents from a lower socioeconomic context perceived more mental effort in a selective auditory attention task when compared to those from a higher socioeconomic background. Additionally, Widyanti et al. (2013) found that culture influenced responses on the NTLX, with Indonesian participants using a narrower range of responses when compared to Dutch participants. More broadly, related traits, such as effortful control (i.e., the ability to regulate impulses and behaviours and motivate action towards a goal) and emotional self-regulation, are impacted by structural factors, such as school and peer environments, family context, socioeconomic context, and ethnic discrimination

(Atherton et al., 2020; Morris et al., 2007; Raver, 2004). Therefore, future research should examine structural, cultural, and socio-economic factors that may influence the experience and regulation of brain power.

Elucidating the in-the-moment experience of brain power may have implications in several settings. In education, previous research has shown that task-based factors influence the experience of mental effort, or what we call ‘brain power.’ Indeed, recollection of effortful learning is predicted by the difficulty level at the end of a task (Finn, 2010), and positive recollections of learning can be elicited by starting or ending learning with an easy task (Finn & Miele, 2016). Similar industrial/organizational psychology studies show that employers could decrease the likelihood that employees resign from their jobs by minimizing the number of hard tasks completed in a row or inter-splicing those hard tasks with easy tasks (Kang et al., 2022). Results from the present study demonstrate that individual differences may play an important and interacting role with task-based factors. By including assessments of the experience of brain power when completing tasks in applied settings and understanding how the experience is shaped by individual differences while considering task factors like sequencing, we can better understand how to improve outcomes in diverse domains.

Limitations

The present study had several limitations. First, previous literature exploring the experience of brain power has typically included retrospective (e.g., Mies et al., 2019) and/or anticipated (e.g., Bambrah et al., 2019) measures of the experience. The present study only included in-the-moment measures, which limits the ability to generalize and connect the findings within the larger literature. This choice was deliberate given the context of the present study. Still, future research should include multiple measurements of the experience of brain power before, during, and after a task as they may be differentially impacted by person and task-based factors and as they likely regulate different aspects of behaviour such as willingness to engage in a task as opposed to the willingness to persist with an ongoing task.

Second, the present study failed to confirm the validity of our measure of task-elicited brain power. This is important, given that the SBPQ was used to explore a moderated mediation between hyperactivity/impulsivity and inattention and task performance through the experience of brain power. Thus, a failure to confirm one of the basic hypotheses of the present study had implications for the subsequent analyses, namely, the moderated mediation. The validity of our measure of task-elicited brain power may be further investigated using other task types or other event rate manipulations, as highlighted above.

Third, the in-the-moment measurement of volitionally exerted and task-elicited brain power may be confounded by affect. When examining the wording of the SBPQ (see Appendix 1), the volitionally exerted items may have a negative connotation, while the task-elicited items may have a positive connotation. Including reverse-coded items may help overcome this hurdle by minimizing the response bias inherent to some items. Nevertheless, this approach has drawbacks—specifically, it can lead to unexpected factor structures (Netemeyer et al., 2003). A future study should explore the correlations between SBPQ items and affect ratings during a task to determine if the volitionally exerted brain power factor is indeed conflated with affect.

Fourth, it is essential to note that the present study did not control for time-on-task while including three manipulations in cognitive demands. This is a crucial aspect to consider, as it could influence the observed effects. For instance, all participants completed the same number of trials, but the time spent on the task before rating their experience of brain power varied between conditions. Participants completed their brain power ratings after 2.08, 5.42, and 10.42 minutes for the 1000, 3000, and 6000 ms conditions, respectively. Given that larger effects were observed in the 6000 ms condition, it is possible that what was observed was a time-on-task effect rather than an event rate manipulation effect. Therefore, it is recommended that future research should control time-on-task while manipulating cognitive demands to determine the true nature of the observed effects in the present study.

Conclusions

Engaging in challenging tasks that require brain power is critical for individual and collective flourishing. Yet, essential questions about the mechanisms that give rise to the experience of brain power remain unanswered. The present study sought to answer some of these questions by including measures and manipulations of person- and task-based factors, finding that both seem to influence the experience of brain power. This study reveals that hyperactivity/impulsivity and inattention profoundly influence the experience of both task-elicited and volitionally exerted brain power. Moreover, event rate manipulations in the CPT significantly shape the perceptions of volitionally exerted brain power. The powerful interplay between task- and person-based factors determines the experience of brain power, which, in turn, mediates the relationship between hyperactivity/impulsivity and inattention and commission error rates. Therefore, this evidence underscores that the experience of brain power is a dynamic and critical regulator of cognition, driven by individual differences and task demands.

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Appendix

State Brain Power Questionnaire

Task-elicited questions:

1. This task was able to engage my brain power:
   Only a little A great deal

2. This task was able to energize my brain power:
   Only a little A great deal

3. This task stimulated my brain power:
   Only a little A great deal

Volitional questions:

4. I had to push myself to use my brain power:
   Only a little A great deal

5. I had to force myself to engage my brain power:
   Only a little A great deal

6. I needed to push myself to activate my brain power:
   Only a little A great deal

Table S1

Hypotheses and Results

Hypothesis	Results
Brain Power Ratings	
Task-Elicited Brain Power	
Higher ratings of task-elicited brain power in the 1000 ms condition than in the 3000 and 6000 ms conditions.	Not confirmed. No difference in task-elicited brain power ratings between any condition.
Higher ratings of task-elicited brain power in the 1000 ms condition than in the 3000 and 6000 ms conditions.	
Volitionally Exerted Brain Power	
Higher ratings of volitionally exerted brain power in the 6000 ms condition than in the 1000 and 3000 ms conditions.	Confirmed. Higher ratings of volitionally exerted brain power in the 6000 ms condition than in the 1000 and 3000 ms conditions.
Higher ratings of volitionally exerted brain power in the 3000 ms condition than in the 1000 condition.	Not confirmed. No difference was observed between the 1000 and 3000 ms conditions.
ADHD Symptoms and Task-Elicited Brain Power	
Higher ratings of ADHD symptomatology will be associated with lower ratings of task-elicited brain power.	Confirmed.
ADHD Symptoms and Volitionally Exerted Brain Power	
Higher ratings of ADHD symptomatology will be associated with higher ratings of volitionally exerted brain power.	Confirmed.
Task Performance Hypotheses	
Commission Errors	
Higher commission error rates on the 1000 ms condition compared to the 3000 ms condition.	Confirmed.
Higher commission error rates on the 1000 ms condition compared to the 6000 ms condition.	Confirmed
Higher commission error rates on the 3000 ms condition compared to the 6000 ms condition.	Not confirmed.
Non-X Latency	

Faster reaction times on the 1000 ms condition than the 3000 and 6000 ms conditions.	Confirmed.
Slower reaction times on the 6000 ms condition than the 1000 and 3000 ms conditions.	Confirmed.
ADHD Symptoms	
ADHD symptoms will predict higher commission errors on all three task conditions.	Not confirmed.
ADHD symptoms will predict faster non-X latency on the 1000 ms condition than on the 3000 ms condition.	Confirmed.
ADHD symptoms will predict slower non-X latency on the 6000 ms condition than on the 3000 ms condition.	Confirmed.
Moderated Mediation Models Hypotheses	
Commission Errors and Task-Elicited Brain Power	
Higher ADHD symptoms predict lower ratings of task-elicited brain power, predicting higher commission errors. Task condition moderates the relationship between ADHD symptoms and task-elicited brain power, with larger effects in the 1000 and 6000 ms conditions.	Not confirmed.
Commission Errors and Volitionally Exerted Brain Power	
Higher ADHD symptoms predict higher ratings of volitionally exerted brain power, predicting higher commission errors. Task condition moderates the relationship between ADHD symptoms and volitionally exerted brain power, with larger effects in the 1000 and 6000 ms conditions.	Confirmed.
Non-X Latency and Task-Elicited Brain Power	
Higher ADHD symptoms predict lower ratings of task-elicited brain power, predicting faster reaction times in the 1000 ms condition and slower reaction times in the 3000 ms condition.	Not confirmed.
Non-X Latency and Volitionally Exerted Brain Power	

	Higher ADHD symptoms predict higher ratings of volitionally exerted brain power, predicting faster reaction times in the 1000 ms condition and slower reaction times in the 3000 ms condition.	Not confirmed.