Understanding and Mitigating Internal and External Attention Deficits in Adults with ADHD

by

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Dedication

This dissertation is dedicated to the supportive pillars in my life who have encouraged and believed in me every step of the way.

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Abstract

Attention Deficit Hyperactivity Disorder (ADHD) is known to involve symptoms of inattention, hyperactivity, and impulsivity. Though ADHD is most widely associated with children, it occurs in approximately 2.5% of adults and is known to adversely affect their career, social, and academic functioning. In adults with ADHD, one major inattentive symptom is heightened distractibility. This heightened distraction can be attributable to both external sources such as salient, irrelevant distraction (e.g., an emergency siren driving by may cause one to lose a train of thought) and internal sources such as mind-wandering (e.g., thinking about plans to stay in for the weekend may pull attention from the task at hand). In the current dissertation, I unfold three experiments in an attempt to: 1) parse the individual contributions of external and internal distractors to heightened distraction in adults with ADHD and 2) identify a cognitive training intervention to reduce these types of distraction in adult ADHD. In each study I employed the same visual search task with a singleton distractor presented within the circular search display during half of the trials. In this task, participants indicated the direction of a line in the center of the "odd-man-out" target shape (i.e., a circle among nine diamonds or a diamond among nine circles). In Study 1, I found that participants with ADHD initially experienced more distraction due to current and recently presented distractors during this task than control participants. In order to better understand whether these differences in task performance were attributable to external and/or internal distraction, I conducted a second study using a lengthened version of the task with eye-tracking and mind-wandering probes. Study 2 showed that participants with

ADHD experienced poorer target selection which was worst during unintentional mind-wandering when a distractor was presented. Finally, in Study 3 I used the same task as a daily cognitive training intervention in participants with and without ADHD. Compared to a control training task, participants who received attention training improved more at that task; this improvement lasted at a follow-up session. Additionally, limited and still inconclusive evidence suggested that participants who received the attention training task also experienced a higher reduction in distraction on a near-transfer task than those who received the control training task. Future work should further pursue more demanding and ecologically valid versions of this task as a cognitive training intervention to reduce distraction in adult ADHD.

Chapter 1 — Introduction

Adult ADHD and Deficits in Cognitive Functions

Attention deficit hyperactivity disorder (ADHD) is known as a relatively common neurodevelopmental disorder that is diagnosed in 5-11% of children ages 4-17 (Center for Disease Control and Prevention, 2012; Polanczyk, de Lima, Horta, Biederman, & Rohde, 2007). While most research has focused on ADHD in childhood, the disorder can persist into adulthood. In fact, approximately 2.5% of adults have been diagnosed with ADHD (Simon, Czobor, Balint, Meszaros, & Bitter, 2009). Adult ADHD has been found to be related to several negative outcomes including an increased risk of motor vehicle accidents (Fuermaier et al., 2015), worse career outcomes (Gjervan, Torgersen, Nordahl, & Rasmussen, 2012), and lower disposable income (Daley, Jacobsen, Lange, Sørensen, & Walldorf, 2019).

ADHD manifests in the individual as three main types of symptoms that adversely affect functioning: inattentive (e.g., "often easily distracted by extraneous stimuli—for older adolescents and adults, may include unrelated thoughts"), hyperactive (e.g., "often fidgets with or taps hands or feet or squirms in seat"), and impulsive (e.g., "often has difficulty waiting his or her turn"; American Psychiatric Association, 2013). There are three presentations of ADHD combining these three symptom types: predominantly hyperactive-impulsive, predominantly inattentive, and combined hyperactive-impulsive and inattentive.

The Diagnostic and Statistical Manual of Mental Disorders (5th Edition, DSM-5) specifies that in adults with ADHD, inattention and restlessness are common (American

Psychiatric Association, 2013). Typically, the restlessness displayed by adults with ADHD emerges as fidgeting or internal feelings of jitteriness and is quite muted when compared to childhood restlessness, e.g., running or climbing when inappropriate. Still, impulsive symptoms may be present even if hyperactivity is reduced. Adults with ADHD are prone to distraction by both external stimuli in the surrounding environment as well as internal stimuli (i.e., mind-wandering, or self-generated thoughts unrelated to the task at hand; American Psychiatric Association, 2013; Franklin et al., 2017).

This most recent version of the DSM largely appears to direct ADHD clinicians and researchers to more seriously consider cognitive function in the diagnosis and investigation of ADHD, specifically in relation to inattentive behaviors. In fact, the DSM-5 indicates that "cognitive problems on tests of attention, executive function, or memory" are "associated features supporting diagnosis" of ADHD (American Psychiatric Association, 2013).

Additionally, for diagnosis per the DSM-5, development and functioning in various settings (i.e. social, career, and/or academic) must be hindered by ADHD symptoms, but no longer to "clinical significance" (American Psychiatric Association, 2013). This change in language opens the door for more people with milder difficulties regulating their attention to be diagnosed with ADHD. This suggests that research should focus on effects of ADHD on cognition, such as deficits in visual search and visual attention tasks. For the purposes of this dissertation, I will focus primarily on inattentive symptoms in ADHD and, in particular, distraction by irrelevant stimuli, both external and internal.

External Versus Internal Distraction: Is this a Real Distinction?

Are mechanisms that mitigate external versus internal distraction truly separable? A handful of studies have attempted to investigate this distinction and have unearthed some evidence that supports it. Friedman and Miyake (2004) conducted a latent-variable analysis into three proposed functions related to resistance to distraction: "Prepotent Response Inhibition" (the ability to resist automatic responses), "Resistance to Distractor Interference" (the ability to resist external distraction), and "Resistance to Proactive Interference" (the ability to resist internal distraction). They found that prepotent response and external distractor inhibition are distinguishable from resistance to internal distraction. Similarly, past work has supported the claim that resistance to internal distraction may be related to experiencing intrusive memories while prepotent response inhibition is not (Verwoerd, Wessel, & de Jong, 2009). Research investigating susceptibility to mind-wandering and external distraction has found evidence that external distraction, but not mind-wandering, is due to failures in attentional control (Stawarczyk, Majerus, Catale, & D'Argembeau, 2014). Taken together, these findings support the claim that external and internal distraction contribute to task performance differentially.

One line of research investigating the effects of both external and internal distraction has probed how mind-wandering and external distraction are related to performance on perceptual load tasks with distractors (Forster & Lavie, 2009, 2014). During high load (when attentional resources are thought to be exhausted) participants reported lower frequency of mind-wandering and lower levels of distraction than during low load (when there are attentional resources to spare). The authors claim that increasing perceptual load of a task may prevent interference by both internal and external distraction (Forster & Lavie, 2009). Findings also suggest that self-reported susceptibility to mind-wandering is associated with distraction by task-irrelevant perceptual distractors but not by response-competition distractors (Forster & Lavie, 2014). This finding corroborates evidence that people with ADHD experience heightened mind-wandering as well as heightened distraction by perceptual, but not response-competition, distractors.

Another recent study investigating mind-wandering during an attentional capture task found reduced target facilitation and poorer distractor suppression during mind-wandering (Geden, Staicu, & Feng, 2018). The authors argue that this suggests perceptual decoupling during mind-wandering selectively modulates stimuli (in this case, suppressing distractor information) rather than suppressing all stimuli, targets and distractors alike. The authors also point out that most mind-wandering tasks have presented stimuli sequentially, but it may be important to present stimuli in a single display in order to capture this selective distractor suppression related to mind-wandering.

As it stands, my literature search did not unearth any work that has attempted to directly address the interaction of both external and internal distraction related to ADHD symptoms. There is currently a limited number of published studies investigating mind-wandering in ADHD (Lanier, Noyes, & Biederman, 2019). Several studies on the topic have consisted of correlational and regression analyses of mind-wandering and ADHD symptom self-report measures (Biederman et al., 2017; Seli, Smallwood, Cheyne, & Smilek, 2015). The work which has involved behavioral tasks to investigate real-time mind-wandering generally involve dull, repetitive tasks with low cognitive load (e.g. sustained attention tasks; Franklin et al., 2017; Jonkman et al., 2017). These are both important directions that the field should continue pursuing, but this also demonstrates a clear gap in the literature and presents an area rife with possibilities to connect the consequences of internal and external distraction in people prone to attention deficits.

External Distraction in ADHD

Even though distraction by external stimuli irrelevant to the task at hand is a key symptom of ADHD (American Psychiatric Association, 2013), past research has not consistently demonstrated higher levels of distraction during visual search in ADHD, compared to control, participants. For example, many studies employing visual search tasks with response competition distractors – distractors which initiate the same (congruent) or different (incongruent) response as the target – have failed to display differences in distractor interference between ADHD and control participants (Booth, Carlson, & Tucker, 2007; Huang-Pollock, Nigg, & Carr, 2005; Merkt et al., 2013).

Past studies that have successfully pinpointed larger distraction effects during visual attention tasks in people with ADHD have often involved salient visual perceptual distractors irrelevant to performance on the behavioral task (Forster & Lavie, 2016; Forster, Robertson, Jennings, Asherson, & Lavie, 2014; Mason, Humphreys, & Kent, 2005; Tirosh, Perets-Dubrovsky, Davidovitch, & Hocherman, 2006). These perceptual distractors are thought to capture attention from the task at hand during the early perceptual processing stages of visual search rather than create conflict in the participant during the late response selection stage of visual search. Therefore, higher levels of distraction by these stimuli suggest that participants have deficits filtering out irrelevant information to ultimately select the correct stimulus for attention.

Notably, spatial attention does not appear to be affected in ADHD (Roberts, Ashinoff, Castellanos, & Carrasco, 2018; Stevens et al., 2012). Studies employing visual discrimination tasks with spatial cues have found that participants with ADHD perform as well as control participants. Essentially, ADHD participants experience a performance decrement when attending to an incorrectly cued location and a performance boost when attending to a correctly cued location (Roberts et al., 2018). Yet when participants with ADHD are tasked with selecting a target without a spatial cue, they experience higher levels of interference from irrelevant information than controls do (Stevens et al., 2012).

Methods to Measure External Distraction

Behavioral tasks involving some form of distractor are the most common method to study visual distraction in participants. This method is convenient, inexpensive, and allows for efficient data collection, limited only by access to participants and programming experience. As discussed above, visual search tasks employing salient perceptual distractors have proven reasonably successful in indexing distraction in ADHD (Forster & Lavie, 2016; Forster et al., 2014; Mason et al., 2005; Tirosh et al., 2006). Additionally, since ADHD does not seem to be involved with a spatial attention deficit (Roberts et al., 2018; Stevens et al., 2012), tasks in which the distractor is incorporated into the display at the same time as the target may result in larger distractor interference effects.

Eye-tracking is another method that can be used to measure the explicit external allocation of attention via eye movements. For example, this method has been shown to evince robust distraction effects due to task-irrelevant perceptual distractors in a visual search task (Theeuwes, Kramer, Hahn, Irwin, & Zelinsky, 1999). Gaspelin, Leonard, and Luck (2017) replicated this finding and altered the task to discourage capture by the singleton distractor. The researchers found an oculomotor distractor suppression effect such that participants' saccades specifically evaded the distractor under certain conditions. Ultimately, these findings taken together show eye-tracking can be an effective tool to evaluate changes (including attentional capture and distractor suppression) in explicit attention. Similar to eye-tracking and less expensive, tracking cursor location can also be used as an indirect measure of attention allocation during a behavioral task (Tirosh et al., 2006).

Neuroimaging can be a valuable method to index neural regions involved in attention processes. This technique can be quite expensive and time-consuming but provides the researcher with the unique opportunity to probe the brain and behavior link. Functional magnetic resonance imaging (fMRI) produces high spatial resolution of brain structure as well as the neural regions employed during behavioral tasks. As an example, fMRI studies of individuals with ADHD have found evidence that people with ADHD experience reduced deactivation of the default mode network during cognitive tasks (Fassbender et al., 2009; see for a review: Rubia, 2018). Another common and less expensive neuroimaging method, electroencephalograms (EEGs), provide high temporal resolution of neural processes, making it easier to isolate the time course of cognitive functions. For instance, past EEG work in ADHD found lower P3b amplitude to unique nontarget items, meaning people with ADHD were not able to prevent attention allocation to task-irrelevant items (Godefroid & Wiersema, 2017; see for a review: Lau-Zhu, Fritz, & McLoughlin, 2019).

Internal Distraction in ADHD

People with ADHD have been observed to be more prone to mind-wandering detrimental to task performance than controls (Franklin et al., 2017). Mind-wandering has also been found to be more common in people with high inattentive ADHD symptomology (Jonkman et al., 2017), although a separate study found that mind-wandering is positively correlated with all ADHD symptom domains (Arabaci & Parris, 2018). In one study, people who endorsed that they frequently made "careless mistakes" and experienced "trouble following instructions" (both symptoms in ADHD) also endorsed experiencing greater levels of mind-wandering (Biederman et al., 2017).

Additionally, people with ADHD have been shown to experience more unintentional mind-wandering than, but similar levels of intentional mind-wandering to, control participants (Seli et al., 2015). Unintentional mind-wandering is typically detrimental to task performance and could lead to day-to-day functional impairments (Lanier et al., 2019). More broadly, this finding of more unintentional mind-wandering in people with ADHD supports the common interpretation of ADHD as a series of deficits to appropriately allocate task-based attention as opposed to a complete inability to attend to a task.

Methods to Measure Internal Distraction

There are currently four empirical methods to capture mind-wandering during cognitive tasks: self-caught, probe-caught, retrospective, and open-ended (Smallwood & Schooler, 2015). The field has not agreed upon the best method to measure mind-wandering, as each strategy involves advantages and disadvantages. Additionally, researchers differ on how to maximize mind-wandering measures. For example, there is considerable variation throughout the literature of the ratio of mind-wandering probes to task duration, the specific verbiage of mind-wandering retrospective questions, and so on. To illustrate this claim, a recent review of 145 experiments found at least 69 variants of the probe-caught method alone (Weinstein, 2018). In general, experimenters need to consider each method in the context of their specific question and approach. Ideally, researchers would take advantage of at least two separate complementary methods in order to corroborate mind-wandering reports.

Self-caught and probe-caught methods occur during the task (Smallwood & Schooler, 2015). The self-caught method relies on the participant to independently recognize and report when they are mind-wandering during the task. One benefit is that it does not require interrupting the participant during their task. However, as people are historically poor at meta-cognition, this method does not capture the true amount of mind-wandering experienced during a given task (Schooler et al., 2011). The probe-caught method involves experimenter-imposed interruptions throughout the task to inquire whether the participant is on-task or mind-wandering. Typically, participants report mind-wandering on approximately 20% – 60% of probes, depending on task features (Forster & Lavie, 2009; Robison, Miller, & Unsworth, 2019; Weinstein, De Lima, & van der Zee, 2018). This method allows the researcher to ask more nuanced questions regarding mind-wandering, such as whether mind-wandering was unintentional. However, this involves interrupting the participant during the task, which may prevent participants from engaging in mind-wandering at their normal rates.

Retrospective and open-ended methods both occur temporally outside of the task, typically after completion (Smallwood & Schooler, 2015). The retrospective method consists of questionnaires, such as the Short State Stress Questionnaire, which assays the participants' state during the cognitive task using questions such as "while performing the task… I daydreamed about myself" (Helton, 2004). The open-ended method involves participants generating a report of their task experience (Smallwood & Schooler, 2015). These methods on their own remove the need to interrupt participants during the task. However, they have many disadvantages as they provide no time-course information about mind-wandering during the task (which has been shown to increase towards the end of a cognitive task; Thomson, Seli, Besner, & Smilek, 2014). Additionally, these methods depend on participants' willingness and ability to recall their experiences and thoughts during the task, again relying on meta-cognition.

Interventions to Reduce Distraction in ADHD

Effects of both internal and external distraction in adults with ADHD can take a serious toll and are associated with adverse effects in personal, occupational, and educational aspects of these individuals' lives. Stimulant medications such as Ritalin and Adderall are currently the most common and well-recognized treatment to relieve these symptoms (American Psychiatric Association, 2013). Stimulant medications have a fairly high efficacy rate as they are partially effective for 70% of people with ADHD (Shim, Yoon, Bak, Hahn, & Kim, 2016). However, they carry several significant risks as well. Stimulant medications are associated with negative side effects such as sleep disorders, tics, and loss of appetite (American Psychiatric Association, 2013; Groenman, Schweren, Dietrich, & Hoekstra, 2017). Stimulant medications also entail a risk of misuse and addiction in people with and without ADHD; in fact, 11% of ADHD patients taking stimulants endorsed selling their medication to people without ADHD who intended to use them for non-medical performance-enhancing purposes (Clemow & Walker, 2014). Additionally, stimulant medications are unsuccessful in the remaining 30% of patients who experience treatment-refractory ADHD (Shim et al., 2016). There is a critical need to develop non-psychopharmacological interventions (to be used alone or in tandem with stimulant medications) specifically to mitigate the heightened visual distractibility in people with ADHD.

One such potential intervention for individuals with ADHD is cognitive training. This method typically targets a specific cognitive process, most often working memory (Gropper, Gotlieb, Kronitz, & Tannock, 2014; Mawjee, Woltering, & Tannock, 2015). There are also several commercially available computerized cognitive training programs for children with ADHD. These programs target various cognitive processes, such as visuospatial and spatioverbal working memory (Cogmed; RoboMemo) or acoustic, visual, and verbal attention (Locu Tour). Notably, the empirical findings derived from these training paradigms have been mixed and difficult to interpret (Sonuga-Barke, Brandeis, Holtmann, & Cortese, 2014). If the intent is to train resistance to distraction in individuals with ADHD, paradigms should specifically target attention circuits and processes as opposed to those of working memory.

Brain stimulation has the potential to enhance the benefits of cognitive training by strengthening the connections between brain regions recruited during training tasks (Nejati, Salehinejad, Nitsche, Najian, & Javadi, 2017). The most promising stimulation methods will be inexpensive with few side effects so the treatment can be affordable, tolerable, and accessible. For example, transcranial direct current stimulation (tDCS) involves a non-invasive, generally painless low-grade electrical current which penetrates the surface of the brain (Woods et al., 2015). On its own, tDCS stimulation of the left dorso-lateral prefrontal cortex has been found to reduce clinical ADHD symptoms in diagnosed adolescents (Soff, Sotnikova, Christiansen, Becker, & Siniatchkin, 2017). When paired with cognitive training across multiple sessions, tDCS may provide enhancements in cognitive functioning which could persist longer than enhancements from cognitive training alone (Katz et al., 2017).

Cognitive behavioral therapy (CBT), a type of psychosocial therapy typically administered by a clinician, may be another viable non-psychopharmacological intervention to ameliorate cognitive deficits in ADHD (Fabiano et al., 2009; Goode et al., 2018). CBT methods often involve a short-term multipronged curriculum to address several deficits. For example, a CBT approach might incorporate lessons to improve organization, time management, and/or planning skills (Antshel & Olszewski, 2014; Boyer, Geurts, Prins, & Van der Oord, 2015; Solanto et al., 2010). This has been shown to be a promising, albeit time-consuming and expensive, option to reduce clinical inattention in adult ADHD (Solanto et al., 2010).

The Current Research

This dissertation is comprised of three studies. Study 1 establishes a visual attention task appropriate for training that differentiates between perceptual distraction levels in control and ADHD participants. Study 2 employs a combination of eye-tracking and mind-wandering probes to evaluate changes in task performance due to suppression of external and/or internal distraction in control and ADHD participants. Study 3 evaluates the efficacy, durability, and generalizability of the training task over the course of a week for ADHD and control participants. Ultimately, combined, these three studies aim to: 1) understand how people with ADHD deal with various types of distraction and 2) identify a cognitive intervention method to ameliorate the heightened distraction they experience.

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Chapter 2 — Singleton Distractors Disrupt Visual Search in Adults with ADHD

Introduction

Although Attention Deficit Hyperactivity Disorder (ADHD) is typically associated with children, it is also common in adults. In the United States alone, six million adults have been diagnosed with ADHD (Simon, Czobor, Balint, Meszaros, & Bitter, 2009), and annual costs associated with adult ADHD (primarily attributable to loss of productivity and income) are 105 – 194 billion dollars per year (Doshi et al., 2012). Symptoms of ADHD negatively affect the occupational, educational, and social functioning of the individual as well (American Psychiatric Association, 2013; Nadeau, 2005). Given these adverse outcomes, researchers are expending a great deal of effort to advance our understanding of this disorder.

ADHD has multiple subtypes, but the inattentive subtype is the most prevalent among adults (Biederman & Faraone, 2004). Adults with this subtype experience greater distraction from irrelevant external stimuli and internal thoughts than healthy adults (American Psychiatric Association, 2013). Furthermore, this heightened distractibility is associated with real-world difficulties at school, work, and during everyday tasks such as driving (Gjervan, Hjemdal, & Nordahl, 2016; Nadeau, 2005; Randell, Charlton, & Starkey, 2016).

The abnormally high levels of distractibility in ADHD provide a unique opportunity to identify key variables that contribute to problems with suppressing distracting stimuli (Mason, Humphreys, & Kent, 2005). To this end, it is useful to employ a task that yields robust distractor interference in individuals with ADHD and healthy controls. With such a task, one can investigate the precise conditions under which distractor interference effects differ between the two groups.

Differences in Perceptual Distraction Between Healthy Individuals and those with ADHD

While ADHD is associated with heightened distractibility, it has proven difficult, though not impossible, to isolate this symptom. For example, tasks involving response-conflict distractors (distractors that demand a different response than the target stimuli themselves) have not shown differences in distraction between ADHD and control participants (Booth, Carlson, & Tucker, 2007; Merkt et al., 2013). This suggests that processes that resolve interference from stimuli that activate prepotent responses remain intact in individuals with ADHD (Huang-Pollock, Nigg, & Carr, 2005).

On the other hand, people with ADHD often exhibit heightened distractibility in tasks involving irrelevant perceptual singletons (Forster & Lavie, 2016; Forster, Robertson, Jennings, Asherson, & Lavie, 2014; Mason et al., 2005; Tirosh, Perets-Dubrovsky, Davidovitch, & Hocherman, 2006). We therefore discuss research that specifically addresses distraction by irrelevant perceptual singletons. As one example, Forster and colleagues (2014) found that adults with ADHD experienced greater distraction than controls during a visual search task due to irrelevant cartoon characters that appeared infrequently at irrelevant locations in the display.

Interestingly, other work has revealed intact spatial attention in adults with ADHD (Roberts, Ashinoff, Castellanos, & Carrasco, 2018; Stevens et al., 2012). A study employing a visual search task with or without distractors in the display found heightened distraction in adults with ADHD compared to controls due to the presence of the irrelevant distractors (Stevens et al., 2012). Interestingly, spatial cueing did not result in differences between control and ADHD participants, suggesting that participants with ADHD are experiencing perceptual interference rather than a spatial attention deficit. That is to say, it is not that those with ADHD cannot attend if appropriately cued to do so; it is that they do not do so on their own.

Even though children are not our population of interest, studies of children with ADHD provide further evidence that individuals with ADHD experience more distraction from irrelevant perceptual distractors than healthy controls. For example, while searching for targets in a rapid serial visual presentation task, children with ADHD experience greater distraction than controls from irrelevant asterisks that appear occasionally in a task-irrelevant color (Mason et al., 2005). In another study, researchers employed a visuomotor attentional tracking task with irrelevant perceptual distractors (Tirosh et al., 2006). Participants were trained to track a moving green dot with their cursor and then completed test trials during which irrelevant distractors were presented. Children with ADHD displayed significantly poorer performance than controls on several tracking measures, such as larger cursor distance from the target path and more time spent outside of the target.

The distractors in many of these tasks appear in locations and colors that participants know are irrelevant. Knowing this, participants may filter these distractors, thus minimizing group differences in distractor interference. While group differences in perceptual distraction do still appear in these tasks, they are often fairly small (Forster et al., 2014) and can be difficult to isolate (Roberts, Fillmore, & Milich, 2011). Tasks that present perceptual distractors in the colors of potential targets within the search display may engender larger group differences in distraction, since participants cannot so easily filter out the distractors based on color or location.

In light of this issue, we employed a variant of Theeuwes' (1991) color-singleton visual search task (Figure 2.1; Moser, Becker, & Moran, 2012). This task provides a robust paradigm for measuring individual differences in attentional capture by perceptual singletons (e.g., among trait-anxious individuals; Moran & Moser, 2014; Moser, Becker, & Moran, 2012), suggesting that it may be useful to port over to individuals with ADHD. In this task, researchers instruct participants to search for a unique target shape among other shapes, all of which are arranged around the perimeter of a circle (e.g., a diamond embedded among circles), and to ignore other perceptual features that might individuate an item in the search array. Along these lines, a shape that differs in color from the other items (i.e., a color singleton) appears on half the trials. In the version of the task we employ, both the target shape and the color singleton shape can appear in red or in green. Further, each of these shapes can be a circle or a diamond. To ensure participants know they should ignore the color singleton, researchers tell them that the uniquely colored (singleton) shape is never the target shape. Researchers operationalize distractibility as increased reaction time (RT) and/or error rate (ER) on distractor-present trials relative to distractor-absent trials.

In this task, participants cannot filter irrelevant perceptual singletons via their color or location (Theeuwes, 1991). This is because such singletons appear in the same colors and locations as targets in different, randomly intermixed trials. The result is that distractor interference effects are relatively large in this task.

Notably, many studies investigating perceptual singleton distraction effects in participants with ADHD have been with speeded tasks, which typically only allow for a short response time and small distractor interference effects (approximately 25 – 60 ms in studies with ADHD adult participants; Forster & Lavie, 2016; Sali, Anderson, Yantis, Mostofsky, & Rosch, 2018). In contrast, our task is self-paced, which allows for much longer response times as participants complete the visual search task, potentially also resulting in larger distractor interference effects. Consistent with the latter possibility, this task typically produces large distractor interference effects (up to approximately 300ms; Pinto, Olivers, & Theeuwes, 2005; Theeuwes, 1991). Thus, this task allows us to more robustly probe and manipulate distractor interference by perceptual singletons between groups. We therefore reasoned that employing this task might increase our ability to observe group differences related to minimizing distraction.

Theeuwes (1991) assumed that participants would not use a top-down attentional set based on color to find the target, because the target appears unpredictably in either of two colors. Under this assumption, heightened distraction by the color singleton distractor indexes the deployment of a bottom-up attention system – that is, a system that is reflexively drawn to the odd color. However, less interference by the distractor in some conditions than in others would suggest the use of a top-down attention system that enhances the ability to suppress salient distractors known to be irrelevant. Consequently, there has been a lively debate concerning whether this task truly pits top-down attention against bottom-up processing. In the Discussion, we elaborate on this debate and its implications for the present study. Ultimately, we conclude that this task provides a measure of perceptual distraction regardless of the underlying mechanism and, therefore, that this task may reveal important insights into ADHD-related deficits that are related to minimizing distraction.

Group Differences for Sequential Effects Caused by Perceptual Singletons

Distractors may also influence future performance. In Stroop-like tasks, for example, the nature of the distractor on one trial influences performance on the next trial in at least two ways (Botvinick, Braver, Barch, Carter, & Cohen, 2001; Gratton, Coles, & Donchin, 1992; Schmidt & Weissman, 2014; Ullsperger, Bylsma, & Botvinick, 2005; Weissman, Jiang, Egner, & Weissman, 2014). First, Stroop-like distractor interference is reduced after incongruent trials compared to after congruent trials. This *congruency sequence effect* is thought to index, at least partly, control processes that react to distraction after an incongruent trial by increasing attention to the target, inhibiting the distractor, or both. Second, participants respond more slowly after incongruent trials than after congruent trials, which may reflect greater response caution after recently experienced distraction (Ullsperger et al., 2005). Together, these findings suggest that participants form a memory of the distraction they experience on each trial, which influences performance on the next trial (Egner, 2014; Weissman, Hawks, & Egner, 2016).

Researchers have identified two related sequential effects in visual search tasks that include perceptual singleton distractors. First, using a variant of the visual search task that we employ in the present study, Müller, Geyer, Zehetleitner, & Krummenacher (2009) reported that healthy individuals experience less interference from a singleton distractor after distractor-present trials than after distractor-absent trials. Analogous to explanations of the congruency sequence effect, they asserted that this *sequential singleton effect* indexes greater top-down suppression of the distractor after distractor-present trials than after distractor-absent trials. In line with this view, they found that presenting distractors more often, which may increase the recruitment of top-down suppression mechanisms (cf. Bugg, Jacoby, & Toth, 2008) leads to (1) less distractor interference overall and (2) a further reduction of interference after distractor-present trials. Second, Müller et al. (2009) observed faster responses after distractor-present trials than after distractor-absent trials. This result suggests that, unlike in Stroop-like tasks, controls exhibit less response caution after distractor-present trials than after distractor-absent trials. To our knowledge, researchers have yet to investigate this hypothesis in adults with ADHD.

The findings reviewed above suggest that online top-down attention (on the current trial) and memory-dependent sequential modulations of attention (across consecutive trials) play important roles in reducing interference from perceptual singletons. Thus, we hypothesized that the original visual search task in Theeuwes (1991), which is similar to the variant employed by Müller et al. (2009), would allow us to isolate group differences related to three attentional processes. These include (1) employing top-down attention online to minimize distraction in the current trial, (2) using a memory of the previous trial to minimize distraction more effectively after distractor-present trials than after distractor-absent trials, and (3) exercising less response caution after distractor-present trials than after distractor-absent trials.

Time-on-task in ADHD

Task performance can also change with time-on-task due to several possible factors. For example, participants with ADHD generally perform worse towards the end (versus beginning) of dull, repetitive cognitive tasks due to deficits in sustained attention (Bubnik, Hawk, Pelham, Waxmonsky, & Rosch, 2015; Huang-Pollock, Karalunas, Tam, & Moore, 2012; Tucha et al., 2017). Notably, this research has been restricted to sustained attention tasks with very little visual input or cognitive load and no perceptual distractors, making it (and its findings) quite distinct from the task in the present study.

On the other hand, past work in our lab has employed a visual search task involving high and low perceptual load conditions with salient distractors. In this study, participants with ADHD experienced reduced perceptual distraction over the course of the task, such that they eventually performed as well as controls (Abagis & Jonides, 2017). This perceptual load task is very similar to the task in the present study. They both involve two key components: multi-item visual search displays and periodic perceptual distractors. Therefore, in contrast to findings from sustained attention tasks, the findings from our lab's perceptual load study would provide us with stronger insights about the task in this study. We therefore expected group differences in perceptual distraction between ADHD and control participants to become smaller over the course of the task.

The Present Study

We made four predictions concerning the nature of group differences in the Theeuwes (1991) task.[1] First, if participants with ADHD less effectively implement top-down attentional processes than controls, they should exhibit greater distractor interference on the current trial, as indexed by a larger difference in performance between distractor-present trials and distractor-absent trials. Second, if participants with ADHD less effectively modulate top-down attentional processes in a memory-dependent fashion than controls, they should exhibit a smaller sequential singleton effect compared to controls. Third, if participants with ADHD exercise different levels of response caution after distraction than controls, the two groups should exhibit differently speeded responses after distractor-present trials relative to distractor-absent trials. Finally, given recent data from our lab indicating that ADHD-related attentional deficits dissipate following brief exposure to visual search tasks (Abagis & Jonides, 2017), we predicted that, if detected, the group differences above would be smaller after a period of exposure to the task.

Method

Participants

We recruited 87 participants (Table 2.1) from the University of Michigan through the Introductory Psychology Subject Pool and via flyers posted throughout campus.[2] Control

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[1] Of note, these predictions are only for reaction time (RT) as this task typically has very low error rates (ERs) and therefore small distractor interference ER effects (around 0-2%; Müller, Geyer, Zehetleitner, & Krummenacher, 2009; Theeuwes, 1991, 1992). In fact, most participants perform so accurately on this task that robust group differences in ER would not be expected.

[2] One might imagine that participants who respond to flyers and those who complete the study via the Subject Pool perform differently due to different performance incentives. We therefore removed participants recruited via flyers (4 controls, 7 ADHDs) and analyzed the remaining data. The significant main effects and interactions persisted, except for the interaction between current-trial distractor presence and group, which nearly achieved significance ($F(1, 64) = 3.795$, $p = 0.056$; $\eta2 = 0.056$). Most important, the three-way interaction among current-trial distractor presence, group, and block remained significant ($F(1, 64) = 4.344$, $p = 0.041$; $\eta2 = 0.064$).

participants had normal color vision, normal or corrected-to-normal visual acuity, and no current mental disorders. ADHD participants fulfilled the same requirements but had also been diagnosed with ADHD by a healthcare professional in the past, per self-report. Many of the ADHD participants were taking ADHD-related medication (N = 41). Participants recruited through the Subject Pool received 1 hour of credit towards the completion of an Introductory Psychology course. All other participants received $10 per hour. We excluded from the data analyses participants who used incorrect response keys (4 ADHD, 0 control) and participants whose mean RTs fell two standard deviations outside of the group mean (3 ADHD, 1 control). The final sample included 50 participants with ADHD (24 female, 26 male) and 27 controls (12 female, 15 male).

Table 2.1. *Description of groups*

	Control Group	ADHD Group	*p-value*
N	27	50	
Age	19.3 (1.3)	19.4 (2.1)	0.926
% Female	44.4%	48.0%	
CAARS Inattention Score	49.1 (8.2)	58.5 (12.2)	0.001
CAARS Hyperactivity Score	48.7 (8.6)	55.8 (10.5)	0.003
CAARS Impulsivity Score	45.1 (9.5)	50.7 (11.4)	0.033
ASRS Inattention Score	0.5 (0.7)	3.2 (2.6)	< 0.001
ASRS Hyperactivity Score	0.3 (0.7)	1.20 (1.5)	0.003
CFQ Score	38.3 (11.3)	50.6 (17.5)	0.002
Aospan	48.2 (17.6)	47.64 (15.3)	0.907
Visual Arrays	0.84 (0.07)	0.85 (0.07)	0.832

Apparatus, Stimuli, and Procedure

Participants completed the task in a quiet room using a desktop computer equipped with a

19-inch monitor and E-prime presentation software (version 2.0.10.353). We dimmed the room lights to 50% of normal brightness to ensure there was no glare on the computer screen. Viewing distance was approximately 60 cm from the computer screen.

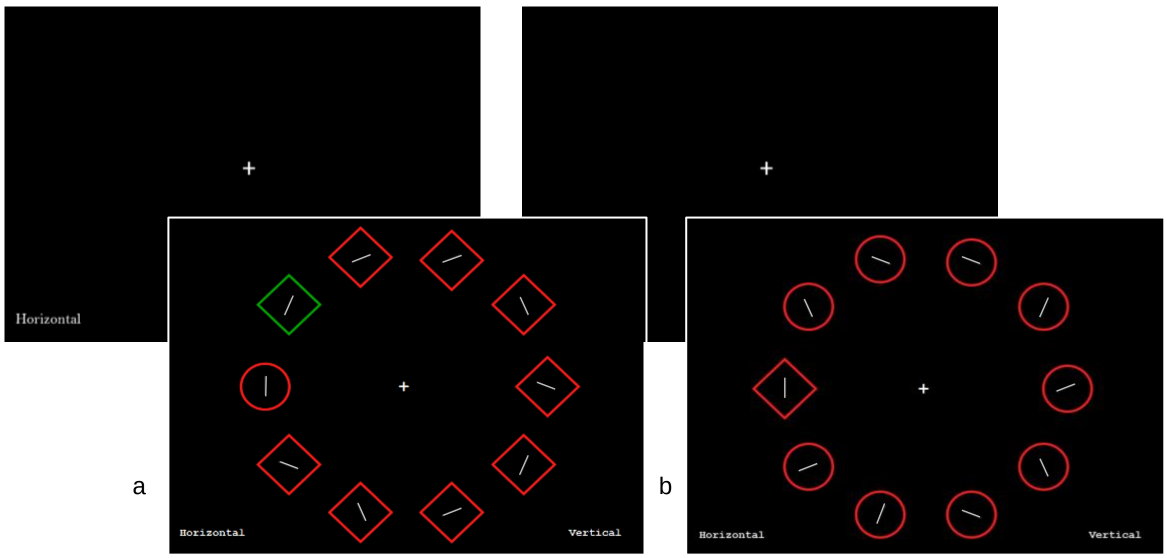


Figure 2.1. A visual search task trial with (a) and without (b) a singleton color distractor.

The stimuli appeared on a black background (Figure 2.1). The fixation cross was followed by the search circle, which remained on the screen until the participant responded. In total, the task consisted of 2 blocks of 160 trials each. The search circle (radius, 11°), which was centered at fixation, consisted of 10 unfilled shapes. For half of the trials, nine diamonds (4.5° X 4.5°) and one circle (1.7° radius) appeared. For the other half of the trials, nine circles and one diamond appeared. Each of the nine similar shapes (i.e., non-targets) contained a grey line (1.5° X 0.2°) that was randomly oriented 22.5° away from either the vertical or horizontal axis. The unique shape (i.e., target) contained a grey line that was randomly oriented either vertically or horizontally. There were two types of trials: (1) distractor-absent trials and (2) distractor-present trials. On distractor-absent trials, all items were the same color (red or green). On distractor-present trials, one of the non-target stimuli, the singleton distractor, appeared in a different color than the other items (i.e., the singleton distractor was red and all the other items were green or vice-versa). Distractor-absent and distractor-present trials appeared equally often (i.e., 50% of the time) and were randomly intermixed within each block.

Participants were instructed to identify the orientation of the line inside the target shape (horizontal or vertical) as quickly and as accurately as possible by pressing the “z” or the “/” key (covered with white stickers) on a standard QWERTY keyboard. The stimulus-response pairings were counterbalanced across participants. After each incorrect response, participants were provided with auditory feedback through headphones (a brief beep from the computer, which was set at 20% volume).

Measures

Participants completed the CAARS (Conners, Erhardt, & Sparrow, 1999), the ASRS (Kessler et al., 2005), and the CFQ (Broadbent, Cooper, FitzGerald, & Parkes, 1982; see Appendix A). Trained research staff conducted a 20-minute formal semi-structured clinical ADHD interview with each participant. The interview served as a check of the current load of ADHD symptomology. Interviewers asked questions about diagnosis and treatment history; DSM ADHD symptomology; personal, educational, and occupational consequences of ADHD symptoms; and family history of ADHD (cf., Gorlin, Dalrymple, Chelminski, & Zimmerman, 2016; see Appendix B).

We excluded participants for several reasons. First, we excluded participants who indicated an ADHD diagnosis but did not endorse high levels of ADHD symptomology in the interview (American Psychiatric Association, 2013). Second, we excluded participants who did not indicate an ADHD diagnosis but endorsed high levels of ADHD symptomology in the interview. Third, we excluded participants who had been diagnosed with any type of mental disorder or had a history of brain trauma, as indicated on a health and demographics form that participants completed. To conserve time and reduce participant fatigue, we did not also include measures of anxiety or depression, which co-occur in a minority of individuals with ADHD and may contribute to attention deficits (American Psychiatric Association, 2013; Kessler et al., 2006). Instead, we excluded people based on self-report of these diagnoses (for similar practices see also: Forster et al., 2014; Grossman, Hoffman, Berger, & Zivotofsky, 2015). Nonetheless, some ADHD participants may have untreated anxiety and/or depression symptoms. We assert that the possible presence of these symptoms would contribute to a more ecologically valid adult ADHD population, conclusions from which may be better generalized.

Of the participants included in analysis, most, but not all, (19 control, 45 ADHD) completed an automated operation span task (Aospan; see Unsworth, Heitz, Schrock, & Engle, 2005) and a visual array change detection task (see Luck & Vogel, 1997; see Appendix A) to assess working memory capacity (some participants could not complete these tasks due to time conflicts). Our research staff also administered Ishihara's Test for Color Deficiency (Ishihara, 2010). The data from participants found to be color-weak or color-blind were excluded from subsequent analyses (0 ADHD, 2 control). Finally, participants completed an exit questionnaire to assess any task strategies they may have developed during their participation.

Statistical Analysis

We used the IBM Statistical Package for the Social Sciences (SPSS) for Windows, version 24 (SPSS Inc, Chicago, IL, USA) to analyze the data.[3] All RT analyses were conducted on correct RTs only. The first three trials of each block were excluded to avoid warm-up effects. We conducted repeated-measures ANOVAs on the mean RT and mean ER data with previous-

[3] I also conducted an ancillary analysis using diffusion modeling methods to better probe psychological processes involved in performing this task (see Appendix C).

trial distractor presence (distractor present, distractor absent), current-trial distractor presence (distractor present, distractor absent) and block (1, 2) as within-participants factors and group (ADHD, healthy control) as a between-participants factor. Finally, we conducted pairwise comparisons to explore the nature of significant interactions.

Results

Mean RT

Table 2.2. *Mean reaction time in milliseconds and percent of errors*

			Control (N = 27)		ADHD (N = 50)	
Previous-trial distractor presence	Current-trial distractor presence	Block	RT (ms)	% errors	RT (ms)	% errors
Present	Present	1	1408 (226)	4.9 (5.6)	1599 (358)	4.6 (5.4)
Absent	Present	1	1458 (201)	6.1 (6.4)	1604 (359)	4.7 (5.2)
Present	Absent	1	1245 (180)	3.3 (3.6)	1344 (285)	2.5 (3.3)
Absent	Absent	1	1227 (160)	4.0 (4.9)	1265 (252)	2.5 (3.4)
Present	Present	2	1162 (221)	4.3 (4.1)	1207 (233)	3.8 (3.5)
Absent	Present	2	1182 (216)	3.7 (5.0)	1234 (249)	3.9 (4.0)
Present	Absent	2	1039 (219)	3.9 (4.0)	1073 (220)	2.8 (3.3)
Absent	Absent	2	1010 (205)	4.0 (5.3)	1047 (191)	3.8 (3.5)

Note: Standard deviations in parentheses.

There were two significant main effects (see Table 2.2 for cell means). First, there was a main effect of current-trial distractor presence in that mean RT was significantly longer on distractor-present trials (1373 ms) than on distractor-absent trials (1164 ms) ($F(1, 75) = 308.90$; $p < 0.001$; $\eta2 = 0.81$). Second, there was a main effect of block in that mean RT was significantly longer in block 1 (1410 ms) than in block 2 (1034 ms) ($F(1, 75) = 127.11$; $p < 0.001$; $\eta2 = 0.63$). There were no main effects of previous-trial distractor presence ($F(1, 75) = 0.53$; $p = 0.47$; $\eta2 = 0.01$) or participant group ($F(1, 75) = 2.49$; $p = 0.12$; $\eta2 = 0.03$). The absence of the latter main effect shows that, on average, ADHDs and controls were well matched on overall performance.

There were two significant interactions across all participants. First, there was an interaction between previous-trial distractor presence and current-trial distractor presence ($F(1, 75) = 14.41$; $p < 0.001$; $\eta2 = 0.16$; Figure 2.2), because there was less distractor interference after distractor-present trials (181 ms) than after distractor-absent trials (237 ms). Second, there was an interaction between block and current-trial distractor presence ($F(1, 75) = 26.13$; $p < 0.001$; $\eta2 = 0.26$): there was less distractor interference in block 2 (157 ms) than in block 1 (261 ms).

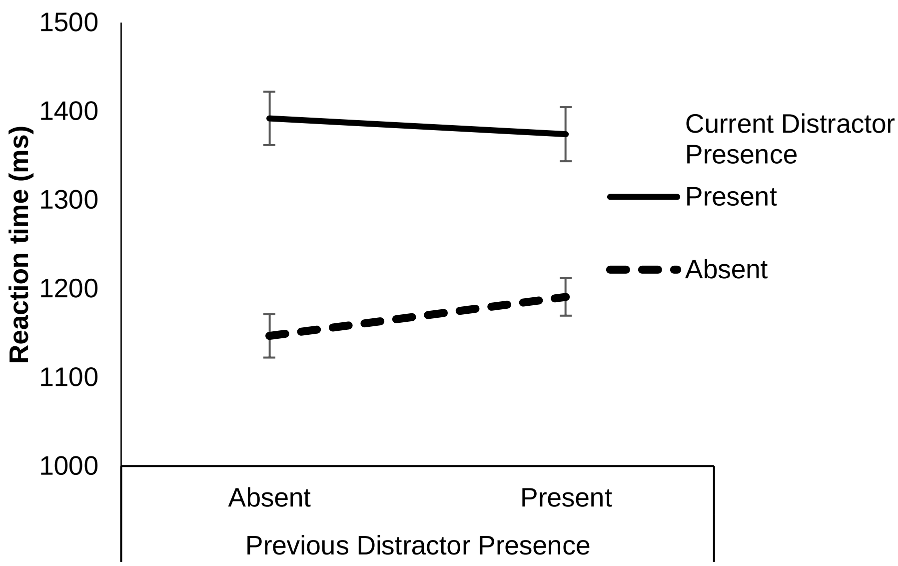
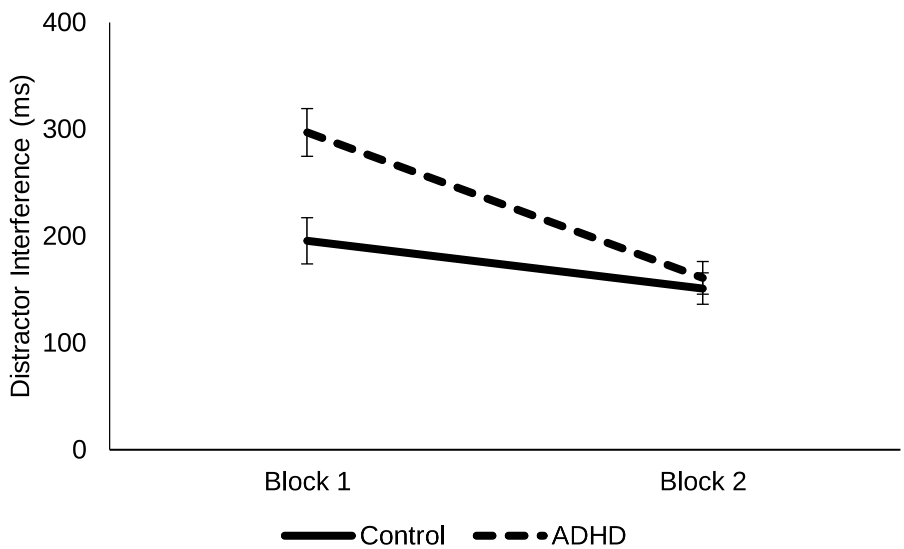


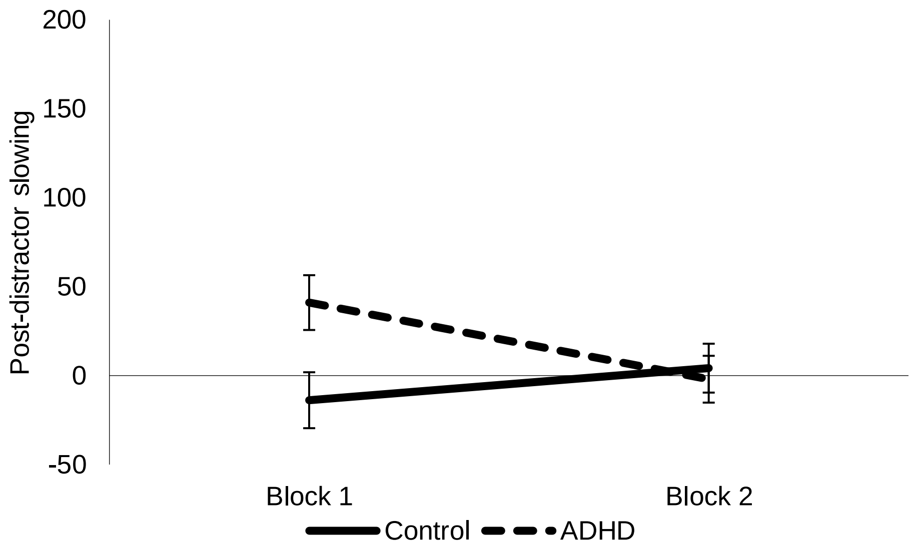
Figure 2.2. Mean RT by current distractor presence and previous distractor presence. Error bars indicate the ±1 standard error of the mean.

There were also three significant interactions involving group (i.e., ADHD vs control). First, there was an interaction between group and current trial distractor presence ($F(1, 75) = 6.12$; $p = 0.016$; $\eta2 = 0.08$) because participants with ADHD exhibited greater distractor interference (228 ms) than controls (172 ms). Second, this interaction was qualified by a significant interaction among group, current-trial distractor presence, and block ($F(1, 75) = 5.89$; $p = 0.018$; $\eta2 = 0.07$). In block 1, the ADHD group displayed greater distractor interference (297 ms) than the control group (196 ms; $F(1, 75) = 8.73$; $p=0.004$; $\eta_2 = 0.10$; Figure 2.3a). In block 2, however, the two groups did not exhibit significantly different levels of distractor interference

(ADHD = 161 ms; control = 151 ms; $F(1, 75) = 0.18$; $p = 0.67$; $\eta_2 = 0.002$; Figure 2.3a). Third, there was a significant interaction among group, previous-trial distractor presence, and block ($F(1, 75) = 5.60$; $p = 0.021$; $\eta 2 = 0.07$; Figure 2.3b). In block 1, the presence (versus absence) of a distractor on the previous trial lengthened current-trial RT more in the ADHD group (37 ms) than in the control group (-14 ms; $F(1, 75) = 4.60$; $p=0.035$; $\eta_2 = 0.06$). In block 2, however, there was no group difference in such "post-distractor slowing" (ADHD = -4 ms; control = 4 ms; $F(1, 75) = 0.14$; $p = 0.71$; $\eta_2 = 0.002$).



(a)



(b)

Figure 2.3. Distractor interference (a) and post-distractor slowing (b).
(a) Distractor interference (distractor-present RT minus distractor absent RT) and (b) post-distractor slowing, both plotted as a function of group (ADHD, control) and block (1, 2). Error bars indicate the ±1 standard error of the mean.

We conducted a supplementary ANOVA with identical within-subjects factors as above and a single between-subjects factor – medication status of each ADHD participant (medicated, not medicated). There were no significant differences between medicated and unmedicated ADHD participants. We note that this analysis was severely underpowered, as only 9 of the ADHD participants were not medicated. No other effects were significant.

Mean ER

We observed one significant main effect and one significant interaction, both of which also appeared in the mean RT data (see Table 2.2 for cell means). First, there was a main effect of current-trial distractor presence, because mean ER was significantly higher on distractor-present trials (4.5%) than on distractor-absent trials (3.2%) ($F(1, 75) = 14.06$; $p < 0.001$; $\eta 2 = 0.16$). Second, there was a significant interaction between current-trial distractor presence and block ($F(1, 75) = 10.25$; $p = 0.002$; $\eta 2 = 0.12$). Across all participants, distractor interference was significantly smaller in block 2 (0.4%) than in block 1 (2.2%). There were no other significant effects, including those involving group, indicating again that the two groups were well matched on overall performance.

Exploratory Analysis

In the overall analysis above, we observed less distractor interference after distractor-present trials than after distractor-absent trials. In an exploratory analysis, we investigated the generality of this reduction in distractibility. One possibility is that participants learn to minimize distraction from the particular distractor color that they encounter on each trial (e.g., a red shape among green shapes). According to this view, the sequential singleton effect is color-specific and changes from trial to trial. Another possibility is that participants learn a more general strategy, which involves minimizing distraction from any “odd-colored” distractor, regardless of whether this distractor is a green shape among red ones or a red shape among green ones.

We distinguished between these two possibilities by determining whether performance on consecutive distractor-present trials varied with whether the distractor’s color changed (e.g. a red distractor trial followed by green distractor trial) or remained the same (e.g. a red distractor trial followed by a red distractor trial). Specifically, we performed an exploratory repeated-measures ANOVA on RT with block (1,2) and distractor color repetition (same, different) as within-participants factors and group (ADHD, control) as a between-participants factor. Distractor color repetition was not associated with a significant main effect ($F(1, 75) = 1.00$; $p = 0.318$; $\eta 2 = 0.01$) or any significant interactions. This suggests that participants learn to minimize distraction from an odd-colored distractor in distractor-present trials, rather than a distractor of a specific color.

Discussion

The present study yielded five principal results. First, relative to controls, individuals with ADHD exhibited heightened interference from perceptual singletons in the color-singleton visual search task. Second, the presence of a distractor on the previous trial lengthened mean RT on the current trial more in participants with ADHD than in controls. Third, these group differences vanished after a single block. Fourth, the sequential singleton effect did not differ between participants with ADHD and controls. Fifth, an exploratory analysis indicated that the strategy deployed by ADHD and healthy participants to overcome distraction was a general one aimed at filtering any odd-colored distractor rather than a distractor of a particular color. These findings indicate that the Theeuwes (1991) visual search task is sensitive to heightened perceptual distractibility in ADHD, that participants with ADHD are impaired only on certain attentional measures in this task, and that these impairments diminish with exposure to the task.

ADHD is Associated with Greater Distraction from Singletons during Visual Search

Participants with ADHD exhibited greater interference from irrelevant perceptual singletons than controls in the present visual search task. More specifically, the presence (versus absence) of a singleton distractor led to a larger increase of RT in the ADHD group than in the control group. Of importance, performance in the two groups did not significantly differ on trials that lacked a perceptual singleton distractor.[4] Therefore, the visual search task of Theeuwes (1991) appears to provide a specific measure of heightened distractibility in adults with ADHD.

This heightened distractibility may reflect impaired attentional control, a symptom often noted in the diagnosis of ADHD. Other groups have observed associations between heightened distraction from perceptual singletons and ADHD diagnosis (Forster et al., 2014; Mason et al., 2005; Tirosh et al., 2006) although, interestingly, not from distractors that engender response conflict (Huang-Pollock et al., 2005). As we describe next, our findings go further by revealing effects of both (1) previous-trial distractor presence and (2) prior exposure to the visual search task on perceptual distraction in individuals with ADHD.

The Effects of Irrelevant Perceptual Singletons on Visual Search

Irrelevant perceptual singletons influenced overall visual search task performance in two ways. First, they interfered with visual search on the current trial as indexed by longer mean RTs and higher mean ERs in distractor-present trials than in distractor-absent trials. Second, they facilitated the ability to minimize distraction on the next trial, as indexed by less distractor interference after distractor-present trials than after distractor-absent trials (i.e., a sequential

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[4] An independent-sample t-test of distractor-absent trial RTs between ADHD and control groups showed there were no difference between control (1129 ms) and ADHD groups (1183 ms; $t(75) = -1.17$, $p = 0.24$)

singleton effect; Figure 2.2). An exploratory analysis further revealed that whether the distractor's color repeated or changed on consecutive distractor-present trials did not influence performance. This outcome suggests that participants learn to ignore an item whose color differs from those around it, rather than the specific color in which the distractor appeared in the previous trial. This general strategy would be more efficient once devised, because it would not need to be adjusted or swapped out on a trial by trial basis. However, additional research on this topic will be necessary before researchers can draw a firm conclusion.

What is the source of the sequential singleton effect? One possibility is that singleton distractors trigger a top-down control process that transiently monitors for distractors, which then reduces distractor interference (e.g., via distractor suppression) on the next trial (Müller et al., 2009). A second possibility is that the sequential singleton effect indexes bottom-up associative processes, such as inter-trial priming related to the distractor and/or target (Pinto et al., 2005). In that whether the distractor's color repeated or changed on consecutive distractor-present trials did not influence performance, our findings would appear more consistent with a top-down control process than with a bottom-up priming mechanism. However, as this claim is based only on an exploratory analysis, this issue warrants further study.

If the sequential singleton effect indexes a top-down distractor monitoring process, then its existence is consistent with the view that working memory (WM) and visual attention are closely linked. Indeed, such a link could allow the memory of a recent distractor to influence attentional processes that underlie distractor suppression on the next trial. This potential connection between visual attention and WM is consistent with two prior findings: (1) WM is important for suppressing saccades to perceptual distractors (Van Der Stigchel, 2010) and (2) as WM load increases, attentional processes that suppress the influence of irrelevant distractors on performance operate less effectively (Lavie & De Fockert, 2005). Further, converging evidence from neuroimaging shows that visual attention and WM recruit several overlapping neural regions, most notably those involved in a "task-related" fronto-parietal network (Fedorenko, Duncan, & Kanwisher, 2013; Petersen & Posner, 2012). In the present study, the sequential singleton effect did not differ between participants with ADHD and controls. Additionally, there were no significant differences in WM capacity (as measured by the change detection and Aospan tasks) between the ADHD and control participants (Table 2.1). Our participants with ADHD may be "high-functioning" as they do not experience lower WM capacity, and therefore are still able to use recent experience to influence visual attention.

Exposure to the Task Closes the Distraction Gap between ADHD and Control Groups

Group differences in distractor interference were larger in block 1 than in block 2. In block 1, the ADHD group showed significantly greater distractor interference than the control group. Additionally, the ADHD group showed significantly greater slowing of mean RT following distractor-present trials as compared to following distractor-absent trials. In block 2, however, participants with ADHD and controls performed no differently from each other.

The fact that in block 1 participants with ADHD, but not controls, exhibited post-distractor slowing (i.e., slower performance after distractor-present trials than after distractor-absent trials) shows that individuals with ADHD exhibit a larger carry-over effect of distraction from the previous trial. This ADHD-specific effect may index more cautious responding following distractor-present trials in order to maintain high levels of accuracy (cf. Ullsperger et al., 2005). Since the opposite effect appeared in controls (see also, Müller et al., 2009), however, the ADHD-related effect may alternatively index a deficit in reactive control, wherein ADHD participants have difficulty refocusing attention following distractor-present trials (c.f. Notebaert et al., 2009). Therefore, future studies will be needed to distinguish between these possibilities.

We offer three potential explanations for why increased exposure to a task enables people with ADHD to perform as well as controls: practice, self-timed breaks, and feedback. With regard to practice, participants with ADHD may eventually learn to suppress the color singleton distractors. This view suggests that visual-attention training might decrease distractibility in ADHD. Future research involving more task blocks or multiple task sessions could provide a clearer view of the time course of performance changes including the critical reduction in distraction. With regard to self-timed breaks, research on mind wandering has revealed that participants with ADHD benefit more from a self-timed break than controls (Hall-Ruiz, 2016). In fact, experimenter-imposed breaks may actually impair performance in participants with ADHD (Hall-Ruiz, 2016). In that we permitted participants to take a self-timed break between blocks 1 and 2 in the present study, it is possible that the performance improvements exhibited by the ADHD group in block 2 resulted from this self-timed break. Future work comparing experimenter-imposed and self-timed breaks could probe the value of self-timed breaks. Finally, with regard to feedback, ADHD is associated with difficulties in monitoring task performance (Shiels & Hawk, 2010). Further, in various domains such as sustained attention (Bubnik et al., 2015) and response inhibition (Rosch et al., 2016), ADHD task performance improves with reinforcement. Thus, the auditory feedback we provided after incorrect responses may have enabled the participants with ADHD to better monitor their performance and eventually perform as well as controls. Future work investigating different methods of feedback may elucidate whether auditory feedback in this task helps ADHD participants to improve their performance.

Does Distraction from Color Singletons Index Bottom-up or Top-down Mechanisms?

There is an ongoing debate over whether distraction from perceptual singletons reflects “bottom-up” or “top-down” processes. While our findings are agnostic regarding this debate, we find it useful to address some relevant issues here. One issue is that, in the task we employed, the target could change from trial to trial (Theeuwes, 1991). For this reason, some claim that attentional capture in this task is not due to a bottom-up mechanism, but to changes in top-down attentional set (Bacon & Egeth, 1994). For example, if the target is green, participants activate a “target = green” set. If this trial is followed by one in which the distractor is green, the “target = green” set may enhance the processing of the distractor, leading to increased capture.

To address this possibility, researchers have held the target (and its color) constant throughout each block (e.g. a green diamond; Theeuwes, 1992). Here, participants can employ the same top-down attentional set throughout each block (e.g., “search for the green diamond”) and singleton distractors never appear in the target color. Still, RTs are longer on distractor-present trials than on distractor-absent trials, suggesting that the distractor captures attention in a bottom-up manner to some extent. Notably, however, distractor interference is reduced to 20 ms (Theeuwes, 1992), which is far lower than in the task we used (i.e., 150 ms; Theeuwes, 1991).

One possible explanation for increased distractor interference when the target varies from trial to trial is that participants strategically alter their top-down attentional set when the target varies. Bacon and Egeth (1994) reasoned that, with target uncertainty, participants would not tune their attentional sets solely to a circle or a diamond. Instead, they would adapt to the task and allow the target to be an odd form and color, depending on the surrounding task stimuli. Thus, Bacon and Egeth (1994) argued that susceptibility to distraction would increase.

In contrast, Pinto and colleagues (2005) suggested that increased distractor interference when the target varies from trial to trial reflects bottom-up inter-trial priming. Their model hinges on bottom-up activation of features associated with the target and inhibition of features associated with the distractor. With heightened target uncertainty, the target (e.g. a green diamond) can possess features of the distractor on the previous trial (e.g. green and/or diamond). Thus, the current-trial target may receive a carry-over of inhibition related to the color and/or form of the distractor in the previous trial. This could make the target more difficult to identify and, hence, increase the period during which the distractor can engender interference.

In a study aimed at distinguishing between the top-down and bottom-up views, Pinto and colleagues (2005) asked participants to perform a task in which the target either 1) changed across trials as in our study (mixed condition), or 2) remained the same shape (pure condition). They further investigated trial sequences in which targets and non-targets stayed the same (same trials; mixed and pure conditions) and trial sequences in which targets and non-targets switched features (switch trials; mixed condition only). The top-down account predicts larger interference effects in the mixed condition same-trials than in the pure condition same-trials, because attentional sets should be less restrictive in the former condition than in the latter one. In contrast, the bottom-up account predicts equivalent interference effects in these conditions. Pinto and colleagues' (2005) results supported the bottom-up view. Hence, they concluded that larger interference effects observed with heightened target uncertainty likely index bottom-up effects.

As we mentioned earlier, this debate over top-down and bottom-up mechanisms of distraction is likely to continue for some time. Critically, however, both views suggest that the task we employed provides a robust measure of distraction by perceptual singletons. Thus, regardless of the outcome of this debate, the present findings reveal novel information about how distraction from perceptual singletons differs between individuals with and without ADHD.

Limitations of the Selected Sample

There are several limitations to the current study methods, which we acknowledge below and have done our best to address throughout this paper. These include ADHD medication status and ADHD symptom severity.

First, participants did not undergo a washout period for stimulant medications. This is a valuable facet of any investigation of individuals with ADHD as medications to treat ADHD are quite effective in symptom management (Faraone, 2009). We note, however, that participants taking medications for ADHD performed no differently than those who were not taking medications for ADHD.

Second, we relied on participant self-report of previous ADHD diagnosis by a clinician, which may not always be accurate. To serve as a check of current ADHD symptom load, participants completed a semi-structured interview (see supplementary online material). Even though most participants with ADHD were taking medications to mitigate their symptoms and the adult ADHD population tends to underestimate their own executive function deficits in self-report scales (Kooij et al., 2008), the ADHD group still had significantly higher levels of ADHD symptomology than the control group (table 1; as measured by CAARS, ASRS, and CFQ). This further substantiates the elevation in current ADHD symptom load in our ADHD group.

Conclusion

ADHD is a condition that affects tens of millions of adults and is often associated with increased susceptibility to distraction, which can adversely affect home and work life. This study shows greater distraction due to salient color distractors in people with, compared to those without, ADHD. Yet, with exposure to the task, this difference in distraction disappears, suggesting that some challenges associated with ADHD can be ameliorated. Future studies could be aimed at investigating more precisely the attentional processes underlying these group differences, why these group differences dissipate following greater exposure to the task, and whether these group differences can be reduced by some form of cognitive (i.e., attention) training (i.e., in participants with ADHD).

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Appendix A: Supplementary Methods for Questionnaires and Tasks in Chapter Two

The CAARS (Conners et al., 1999) is intended to probe symptoms of ADHD in adults, namely inattention, hyperactivity, and impulsivity. Participants completed the long self-report version, which is made up of 66 items, each of which target a symptom of ADHD with a distinct subscale (e.g. "Things I hear or see distract me from what I'm doing."). Participants can respond to each item with four possible frequency responses (*Not at all, never*; *Just a little, once in a while*; *Pretty much, often*; and *Very much, very frequently*). Responses to each subscale are summed and final subscale T-scores are calculated through a formula considering both gender and age. The total score is an average of all subscale T-scores. A score of 60 or above indicates a clinical level of ADHD symptomology.

The ASRS (Kessler et al., 2005) provides another measurement of adult ADHD symptomology. The scale is made up of 18 questions to index symptoms of ADHD in adults in the past six months (e.g. "How often do you have difficulty concentrating on what people say to you, even when they are speaking to you directly?"). Participants respond to each item with one of five possible frequency responses (*Never, Rarely, Sometimes, Often*, and *Very Often*). The score is a count of inattentive and hyperactive-impulsive symptoms.

The CFQ (Broadbent et al., 1982) probes errors in the cognitive functions of memory, perception, and motor function and is correlated with cognitive deficits. Factor analysis has shown that the items load onto three factors: forgetfulness, distractibility, and false triggering (Rast, Zimprich, Van Boxtel, & Jolles, 2009). The scale consists of 25 questions about cognitive failures in the last six months (e.g. “Do you fail to notice signposts on the road?”). Participants respond to each question with one of five possible frequency responses (*Very often*; *Quite often*; *Occasionally*; *Very rarely*; and *Never*). The score is the sum of all responses.

The Aospan task (Unsworth et al., 2005) is an adapted version of an operation span task that automatically produces measurements of working memory (WM) capacity. During the task, participants were shown simple mathematical calculations followed by a display with a single number on the screen above “true” and “false.” Participants selected whether the number was the answer to the mathematical calculation. For example, if the calculation was *(3 * 2) + 1* and the following number was the solution (*7*), the participant would select “true.” If the following number was not the solution (e.g. *6*), the participant would select “false.” Participants then saw a letter, which they were told to remember. At the end of each block, which consisted of three to seven calculation and letter trials, participants viewed a screen with 12 letters and selected each letter they saw in the order in which they saw them. Participants completed four practice letter trials, 15 practice calculation trials, three practice blocks with both, and 15 experimental blocks. The task produced an “absolute” score: the sum of all items remembered in the correct order. For example, if a participant recalled all items from a block of 3 and a block of 5 in the correct order and just two items from a block of 3 in the correct order, then would receive a score of 8: 3 + 5 + 0.

The visual arrays change detection task (Luck & Vogel, 1997) produces another measure of WM capacity. Participants were shown a display of four, six, or eight randomly arranged colored blocks on a screen, followed by a blank display, and finally a screen with the same arrangement of blocks with one block circled. Participants indicated whether the circled block was the same (no change) or different (change) color as the one that was originally presented.

Fifty percent of the trials were change trials and the other fifty percent were no change trials. Participants completed six practice trials and 60 experimental trials. Percent correct responses were calculated.

Appendix B: Semi-structured clinical interview of ADHD history and symptomology

ADHD History
Previous Diagnosis and Treatments:

Current Treatments: Have you taken any medication in the past 24 hours? In the past 72 hours? If yes, when and what (medication name and dosage)?

Inattention
- Inability to focus/sustain attention
- Distractibility by external stimuli
- Distractibility by extraneous thoughts
- Difficulty multitasking
- Difficulty shifting attention from one task to another
- Indecision, difficulty recalling and organizing details required for a task
- Poor time management, losing track of time
- Avoiding tasks or jobs that require sustained attention
- Procrastination
- Difficulty initiating tasks
- Difficulty completing and following through on tasks

Hyperactivity
- Restless/ Full of energy
- Fidgets/ Can't sit still
- Chooses highly active, stimulating jobs
- Avoids situations with low physical activity or sedentary work
- May choose to work long hours or two jobs
- Seeks constant activity
- Easily bored

Impulsivity
- Impatient (e.g., wants people to get to the point, often speeds while driving, cuts into traffic to go faster than others).
- Intolerant to frustration, easily irritated
- Impulsive, snap decisions and irresponsible behaviors
- Loses temper easily, angers quickly
- Often acts without thinking of consequences
- Often rushes through activities or tasks, is fast paced (e.g., averse to doing things carefully and systematically).

- Often has difficulty resisting immediate temptations or appealing opportunities, while disregarding negative consequences (commits to a relationship after brief acquaintance, takes job or enters into business arrangement without doing due diligence).

Family History of ADHD

Educational History

Special Education

- LD class
- Behavioral/emotional class
- Resource room
- Speech and language therapy

Stage	Grades/Performance	Behaviors
Preschool/ Kindergarten		
Grades 1-3		
Grades 4-6		
Diagnosis of ADHD before age 7?		
Middle school		
High School		
College		
Post-College		
Work		

Occupational history

- History of employment/Reasons for termination
- Current employment, perceptions of co-workers, managers, worries about termination

Interpersonal history

- Childhood relationships with/perceptions of siblings and friends.
- Current relationships with/perceptions of significant other/immediate family
- Current relationships with/perceptions of friends

Appendix C: Supplementary diffusion modeling analysis

In the interest of better understanding the underlying mechanisms which differentiate between control and ADHD participants' performance on the visual search task, I ran an ancillary diffusion modeling analysis using the EZ-diffusion method (Figure 2.4; (Murata, Hamada, Shimokawa, Tanifuji, & Yanagida, 2014; Wagenmakers, Van Der Maas, & Grasman, 2007). This method produces three parameters from a model that describes participant behavioral performance. Drift rate (*v*) is the slope at which each participant accumulates information to make their final decision. The boundary separation (*a*) is the difference between the correct and incorrect decision thresholds. Non-decision time (*Ter*) is some amount of the RT not devoted to the decision process and can be allotted before (e.g. stimulus encoding) or after (e.g. response execution) the decision.

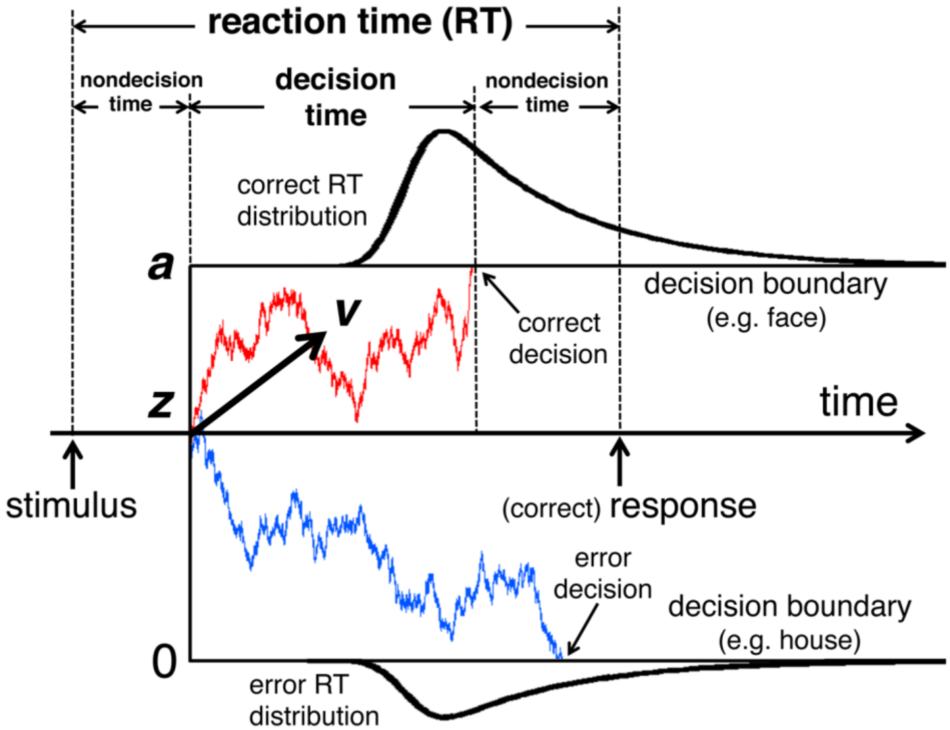

Figure 2.4. A graphical representation of diffusion model parameters. These include drift rate (v), boundary separation (a), and non-decision time. The x-axis represents time from when the stimulus is presented (first dotted vertical line) to when the response is reached (last dotted vertical line), which fully encompasses RT. RT involves some time for decision processes sandwiched by non-decision processes. The red and blue lines represent drift rate for correct and incorrect responses, respectively. The difference between the top and bottom vertical lines represents the boundary separation between information required for a correct and incorrect response. The correct and error RT distributions represent the probability density of each RT distribution that is predicted by the model. From Murata et al., 2014.

I applied the EZ-diffusion method using functions in the R language (Wagenmakers et al., 2007) because this method has proven to be effective for tasks with low numbers of trials (Lerche, Voss, & Nagler, 2017). The EZ-diffusion method requires the input of three dependent variables (mean RT of correct responses, RT variance of correct responses, mean accuracy) for each participant (Wagenmakers et al., 2007). This method calculates both drift rate and boundary separation using just accuracy and RT variance. An increase in RT variance and/or a decrease in accuracy suggests a decrease in drift rate, meaning the participant gathers information more slowly, leading to high variance around the mean RT and lower accuracy. A decrease in RT variance and/or a decrease in accuracy suggests a decrease in boundary separation, meaning the participant requires less information to reach a response with low variance around the RT and lower accuracy. Finally, EZ-diffusion calculates non-decision time with mean RT and RT variance. A decrease in mean RT and an increase in RT variance suggests a decrease in non-decision time, meaning the participant uses less time for non-decision processes.

First, I calculated the dependent variables (mean RT, RT variance, and accuracy) for distractor-present and distractor-absent trials separately, resulting in 154 separate sets of parameters (each of the 77 participants represented twice by distractor-present and distractor-absent parameters). Second, using EZ-diffusion I estimated the drift rate, boundary separation, and non-decision time (Table 2.3). Third, I conducted repeated-measures ANOVAs for each of the three dependent variables with a between-subjects factor of diagnosis (ADHD, control) and a within-subjects factor of condition (distractor-present, distractor-absent).

Table 2.3. *Mean EZ Diffusion parameters calculated in R.*

	Distractor Present		**Distractor Absent**	
	Control Group	**ADHD Group**	**Control Group**	**ADHD Group**
Drift rate (V)	1.38 (0.24)	1.34 (0.25)	1.60 (0.31)	1.61 (0.30)
Boundary separation (A)	2.43 (0.53)	2.54 (0.45)	2.26 (0.47)	2.44 (0.51)
Non-decision time in ms (Ter)	478 (152)	492 (164)	452 (100)	429 (123)

Note: Standard deviations in parentheses.

With these analyses, I found two significant main effects, one near-significant main effect, and no interactions. First, there was a main effect on drift rate by condition such that drift rate is larger for the distractor-absent (1.61) as opposed to the distractor-present (1.35) condition ($F(1, 150) = 32.63$; $p < 0.001$; $\eta 2 = 0.18$). This suggests that participants take more time to accumulate information necessary to make a response during distractor-present trials. Second, there was a main effect on non-decision time by condition showing non-decision time is larger for the distractor-present (487 ms) versus distractor-absent (437 ms) condition ($F(1, 150) = 4.94$; $p = 0.03$; $\eta 2 = 0.03$). This suggests that distractor-present trials require more non-decision time, likely due to the additional non-decision component of attentional capture by the distractor. Third, there was a near-significant main effect on boundary separation such that it is larger in participants with ADHD (2.49) than control participants (2.35; $F(1,150) = 2.95$; $p = 0.09$; $\eta 2 = 0.02$). This suggests that ADHD participants have a higher (more conservative) threshold for the amount of information needed to make a response.

Additionally, I conducted a parameter simulation-recovery study to determine whether the diffusion model is an appropriate method given features of this task and data set (e.g., accuracy, trial number). There are a few reasons to conduct such a study: the task employed has fewer trials per condition than typically recommended for diffusion modeling and can result in RTs longer than those typically analyzed with the model (can be over 1500 ms), as well as low error rates (typically 0-10% error rate per condition). Using the 154 previously estimated sets of EZ-diffusion parameters (those from two conditions for all 77 participants) and number of trials per condition (160), I simulated data with the “rtdists” package’s “rdiffusion” command in R. This command simulates RTs and responses predicted by a given set of diffusion model parameters (“upper” and “lower,” corresponding to “correct” and “incorrect,” respectively). I next removed incorrect responses; calculated mean RT, mean ER, and RT variance; and calculated (or “recovered”) the three EZ-diffusion parameters drift rate, boundary separation, and non-decision time. Finally, I calculated the correlations between the three real and recovered EZ-diffusion parameters, which are all considered evidence of "strong" parameter recovery (Figure 2.5; cf. White, Servant, & Logan, 2018), suggesting the diffusion model is indeed an appropriate method to investigate behavioral performance on this task.

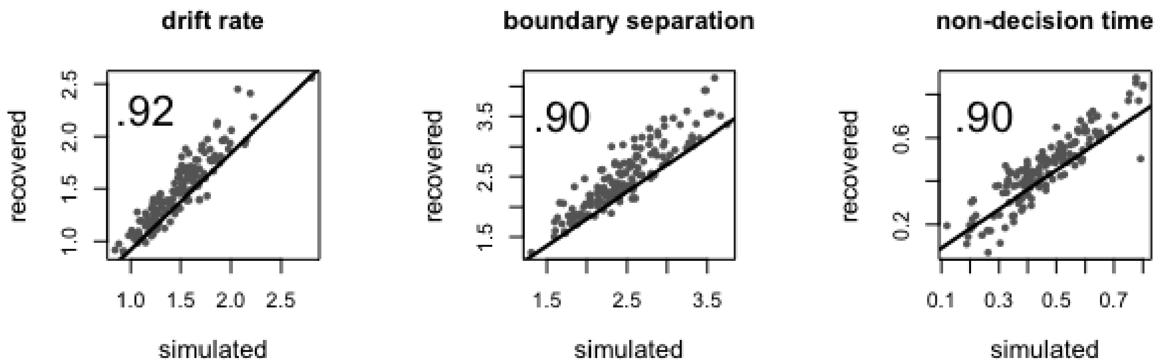

Figure 2.5. Correlations between the simulated and recovered parameter values for drift rate, boundary separation, and non-decision time.

Ultimately, the simulation-recovery study suggests that the diffusion model is an appropriate ancillary method[5] to probe a bit deeper into participant performance in this situation. The EZ-diffusion analysis I employed points to a few interesting implications both about the task and the participant groups (ADHD, control). First of all, the smaller drift rate (i.e., slower information accumulation) for distractor present trials supports the claim that presence (versus absence) of a distractor slows task performance. Additionally, the longer non-decision time for distractor present trials suggests that the presence (versus absence) of a distractor consumes a larger amount of time, likely attributable to attentional capture. Finally, the near-significant main

[5] Of note, it would not be appropriate as a primary analysis method because there are too few trials to separate the data according to all between-subjects factors (i.e., parceling the data into current-trial distractor presence, previous-trial distractor presence, and block results in eight different condition with just 40 trials each and very low error rates: not sufficient for a strong diffusion analysis).

effect of ADHD on boundary separation suggests that ADHD participants actually adopted a more conservative approach to the task as compared to the control participants. Though this effect is sub-significance threshold in this study and has not been consistently found in the literature, past work has found similar evidence that ADHD participants have a higher boundary separation than controls, suggesting it may be a strategy to compensate for deficient attention (Merkt et al., 2013). Future work could better investigate these diffusion model processes between ADHD and control participants by incorporating more trials (at least double) and making the task more difficult to avoid ceiling effects.

Chapter 3 — Eye Movements Indicate Target Selection Deficits in Adults with ADHD: An Investigation of Internal and External Attention Allocation

Introduction

ADHD is generally understood as an attention regulation disorder. This is supported by findings that adults with ADHD struggle to redirect their attention, as demonstrated by studies finding they experience poorer attention-switching ability (White & Shah, 2006) and higher levels of hyperfocus (Hupfeld, Abagis, & Shah, 2018) as compared to adults without ADHD. Additionally, individuals with ADHD experience poorer resistance to internal task-irrelevant distraction, or mind-wandering (Franklin et al., 2017; Jonkman, Markus, Franklin, & Van Dalfsen, 2017), as well as to external task-irrelevant distraction (Forster & Lavie, 2016; Tirosh, Perets-Dubrovsky, Davidovitch, & Hocherman, 2006).

In the literature, researchers typically parse internal thoughts by two axes: task-relatedness and initiation (i.e., self-generated or perceptually guided; Smallwood & Schooler, 2015). Task-related, perceptually guided thoughts indicate a state of *task focus*, meaning the participant is appropriately attending to the task and is not distracted by unrelated thoughts. This type of thought is often referred to as “on-task” and reflects proper attention regulation. Task-related, self-generated thoughts (*performance-based thoughts*) occur when the participant is thinking about the task but may not be completely attending to it. For example, these thoughts may be about how they are performing on the task (e.g., “Oops I got that one wrong!”) rather than focused on the task itself. Task-unrelated, perceptually guided thoughts indicate a state of *distraction*, meaning thoughts have been somehow captured by the external world, such as the participant's phone ringing elsewhere. Finally, task-unrelated, self-generated thoughts are commonly defined as *mind-wandering,* or *task-unrelated thoughts (*e.g., "I wonder what I'll have for dinner tonight…"*)*. Mind-wandering can be further broken up by intentionality: whether or not the participant meant to begin mind-wandering.

Of note, while this is widely how internal thoughts have been defined, any thoughts that are not pure on-task focus have the potential to be distracting and could result in poorer task performance. For example, performance-based thoughts could reflect negative affect (e.g., "This task is so frustrating and long, I'm sick of it!"), which has been found to worsen performance on many tasks including attentional control (Crocker et al., 2012; Hur et al., 2014) and multitasking (Morgan & D'Mello, 2016) tasks. Additionally, even when mind-wandering is intentional, it is associated with reductions in efficient task performance (Seli, Cheyne, Xu, Purdon, & Smilek, 2015). Thus, it is important to capture both axes (task-relatedness and initiation) to more neatly distinguish between the four types of internal thoughts during task performance.

Studies of mind-wandering in ADHD have also found that participants with ADHD are more prone to mind-wandering than control participants (Arabaci & Parris, 2018). In particular, adults with ADHD may be more prone to unintentional (but not intentional) mind-wandering (Seli, Risko, & Smilek, 2016). This mind-wandering in ADHD appears to adversely affect behavioral task performance as well (Franklin et al., 2017; Hall-Ruiz, 2016). Investigating the contexts in which adults with ADHD experience mind-wandering may allow the field to better isolate methods to reduce distracting internal thoughts in this clinical group.

Past work investigating eye movements during a visual search task with salient distractors has found a clear oculomotor capture effect in which participants tend to look at the distractor, when present, before looking at other items in the search display (Gaspelin, Leonard, & Luck, 2017). Additionally, there was a target selection effect of distractor presence; participants looked at the target before other items more often when there was no distractor as opposed to when a distractor was present. Employing a similar approach will allow me to probe whether ADHD is associated with an oculomotor capture effect and/or a target selection effect detrimental to task performance.

Further, a handful of studies have combined both eye-tracking and mind-wandering measures during behavioral tasks to evaluate the effects of both internal and external attention allocation. For example, one study of reading behavior in participants found that eye fixations during “mindless reading,” which is similar to mind-wandering, were longer than during normal reading (Reichle, Reineberg, & Schooler, 2010). In another study, participants completed anagram and sentence-generating tasks which were manipulated to be either internally or externally directed (Benedek, Stoiser, Walcher, & Körner, 2017). Internally directed cognition during the tasks was found to be associated with several eye-tracking variables, such as fewer and longer fixations. To my knowledge, no study has been conducted to investigate internal and external attention allocation during a visual attention task with perceptual distraction in healthy participants, let alone in a clinical ADHD sample.

In Study 1, I established a task that displays performance differences due to current and previous distraction in adults with and without ADHD. In the second study of this dissertation, I investigate how external (task-irrelevant perceptual distractors) and internal distraction (mind-wandering) affect task performance in people with and without ADHD. A multi-faceted approach of using both eye-tracking and mind-wandering measurements provides a more comprehensive look into task-based distraction regulation in ADHD.

I made three predictions for the present study. First, I expected that participants would be distracted by the color singleton (as demonstrated by slower RTs, higher ERs, and higher proportion of first fixation on the distractor). I expected this distraction would be largest in the first block and reduce throughout the task as participants gained task exposure. Second, I expected that participants with ADHD would display higher levels of distraction than participants without ADHD, as shown in both behavioral task performance and eye movements. Third, I expected that participants with ADHD versus those without ADHD would experience higher levels of mind-wandering throughout the task which would be detrimental to performance.

Method

Participants

I recruited 48 participants through the University of Michigan Introductory Psychology Subject Pool and flyers. Participants included in the analysis satisfied the same inclusion criteria as described in *Study 1 Participants* and also had normal vision without correction. I excluded from the data analyses participants with under 70% accuracy (1 ADHD). The final sample includes 14 participants with ADHD and 26 control participants (Table 3.1).

Table 3.1. *Description of groups.*

	Control Group	ADHD Group	*p-value*
N	26	14	
Age	19.1 (1.1)	20.1 (3.13)	0.272
% Female	46.2%	40.0%	
CAARS Inattention Score	48.5 (6.4)	60.0 (11.1)	0.002
CAARS Hyperactivity Score	50.0 (9.5)	60.2 (7.1)	< 0.001
CAARS Impulsivity Score	44.4 (8.4)	50.2 (9.5)	0.032
SSSQ Distress Score	1.9 (0.6)	2.1 (0.8)	0.271
SSSQ Engagement Score	3.2 (0.5)	3.3 (0.6)	0.531

SSSQ Worry Score	2.4 (0.6)	2.3 (0.5)	0.761

Note: Standard deviations in parentheses.

Task

The task employed in this study was roughly the same as the one described above in *Study 1 Task*. There were a handful of minor changes in order to accommodate the best data collection for both eye-tracking and mind-wandering measurement methods, described in more depth below.

Eye-tracking Methods. In order to measure external distraction during the visual search task, I employed eye-tracking using an EyeLink 1000 Plus device (SR Research Eyelink). The task was administered via OpenSesame (version 3.2.8 *Kafkaesque Koffka*) using a desktop computer equipped with a 19-inch monitor. Viewing distance was approximately 80 cm from the computer screen. To be certain that participants were attending to the task during each trial they were required to fixate at the fixation cross for one second before the next trial could begin. Calibration was performed at the beginning of between each block and after trials when fixation-triggering time exceeded 10 seconds. In order to optimize eye-tracking data collection, we reduced the size of the search circle (radius, 9.2°), search items (diamonds (3.6° X 3.6°) and circles (1.5° radius)) in the search display, and the lines (0.6 X 0.1°) inside of the search items (Figure 3.1).

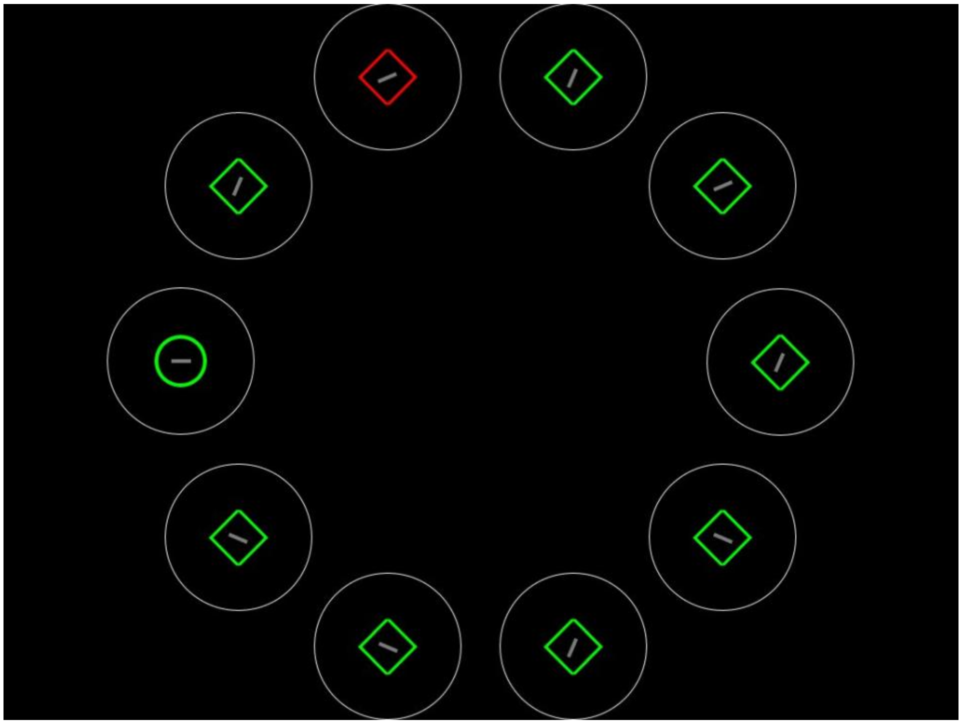

Figure 3.1. Visual search task display for Study 2.
The trial above includes a red singleton distractor (top left) and a circle target (center left) showing defined areas of interest (AOIs; in white circles; circles were not present in the actual displays).

Mind-wandering Methods. To best measure internal distraction during the task, I employed two complementary mind-wandering methods: in-task probe-caught and retrospective (see *Short Stress State Questionnaire* below). Prior to the task, researchers described mind-wandering to the participants and informed them that it is okay to mind-wander during the task. Researchers reminded participants to honestly report mind-wandering when it occurs before the presented probes. To increase the likelihood of mind-wandering, the task was extended from two blocks of 160 trials each to five blocks of 160 trials each. Increasing the number of trials is expected to fatigue participants and cause them to mind wander more over the course of the task.

Mind-wandering probes were presented after a pseudo-random 10% of trials, balanced across block and trial distractor presence, such that eight probes were shown for each combination of block and distractor presence. The probe displayed the question *"Were your thoughts on-task or off-task?"* If the participant responded "Yes" to the mind-wandering probe, the computer displayed the question: *"Were your off-task thoughts intentional or unintentional?"* If the participant responded "No" to the mind-wandering probe, the computer displayed the question: *"Were your thoughts about the task or your performance?"* This procedure separated possible mind-wandering probe responses into four distinct groups: on-task thoughts, performance-based thoughts, unintentional mind-wandering, and intentional mind-wandering.

Questionnaires

Participants completed the CAARS (see *Study 1 Questionniares*), a formal unstructured clinical ADHD interview conducted by trained research staff, the Short Stress State Questionnaire (SSSQ; Helton, 2012), and an exit questionnaire to assess task strategies.

The SSSQ assays each participant's distress, engagement, and worry states during the task. Responses to this questionnaire make up retrospective measurements of mind-wandering. The first ten items probe participants' mood during the task (e.g. depressed or impatient). The remaining 14 items ask about participants' thoughts during the task, such as: "while performing the task… I daydreamed about myself." Participants respond to each item with one of five Likert-scale items to describe how much each item applied to their task mood and thoughts (*Not at all*, *A little bit*, *Somewhat*, *Very much*, and *Extremely*). Average scores are calculated for each subscale (distress, engagement, and worry)**.**

Analysis

I performed statistical analyses in R version 1.1.463. All RT analyses were conducted on correct RTs only. The first three trials of each block were excluded to avoid warm-up effects.

Fixation data consisted of fixation durations between 80 – 2000 ms. The dependent variables included behavioral measures (mean RT, mean ER), eye-tracking measures (proportions of first and second fixation locations), and the mind-wandering measure (probe response).

Results

Behavioral Task Results

I conducted the same analyses for behavioral variables as in Study 1: repeated measures ANOVAs including previous-trial distractor presence (distractor present, distractor absent), current-trial distractor presence (distractor present, distractor absent) and block (1, 2, 3, 4, 5) as within-participants factors and group (ADHD, healthy control) as a between-subjects factor.[6]

Mean RT. There were two significant main effects of mean RT. First, there was a main effect of current-trial distractor presence in that mean RT was significantly longer on distractor-present trials (M = 1245 ms, SD = 245 ms) than on distractor-absent trials (M = 1102 ms, SD = 209 ms; $F(1, 39) = 64.90$; $p < 0.001$; $\eta 2 = 0.08$). Second, there was a main effect of block in that mean RT significantly decreased throughout the experiment from the first (M = 1431 ms, SD = 278 ms) to last block (M = 1049 ms, SD = 202 ms; $F(4, 36) = 60.02$; $p < 0.001$; $\eta 2 = 0.24$; Figure 3.2).

[6] An ancillary diffusion modeling analysis identical to that in Study 1 (Appendix C) found a main effect of distractor on drift time such that there was a larger drift rate for distractor-absent versus distractor-present trials ($F(1, 75) = 4.99$; $p = 0.03$; $\eta 2 = 0.06$) and a main effect of distractor on non-decision time such that there was more non-decision time during distractor-present than distractor-absent trials ($F(1, 75) = 12.49$; $p < 0.001$; $\eta 2 = 0.14$). There were no significant effects on boundary separation. There were no main effects of ADHD. Of note, this analysis demands more ADHD participants to be properly powered and interpreted, particularly to capture differences between ADHD and control participants.

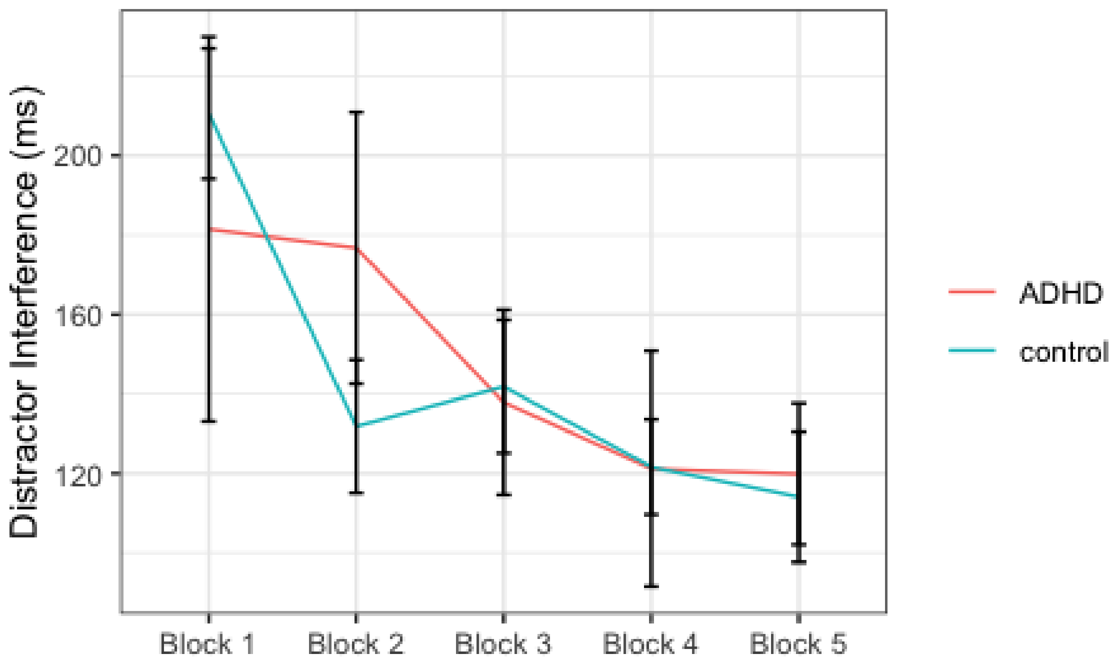

Figure 3.2. Distractor interference decreases over the course of the task for all participants. Error bars show standard errors.

Since we found a "sequential singleton" effect of previous distractor presence in Study 1, I pursued this effect in the current study by employing the same analysis. I used distractor interference (distractor-present trial RT minus distractor-absent trial RT) as the dependent variable with block and previous distractor presence as within-subjects factors and ADHD group as a between-subjects factor. I found two significant main effects, replicating Study 1 findings. First, there was a main effect of block such that distractor interference decreased from the first (M = 200 ms, SD = 147 ms) to the last block (M = 116 ms, SD = 105 ms; $F(4, 36) = 6.52$; $p < 0.001$; $\eta 2 = 0.06$). Second, there was a main effect of previous distractor presence such that distractor interference was smaller following a distractor-present (M = 125 ms, SD = 106 ms) versus a distractor-absent trial (M = 165 ms, SD = 131 ms) ($F(1, 39) = 12.06$; $p < 0.001$; $\eta 2 = 0.03$; Figure 3.3). There were no significant interactions with group.

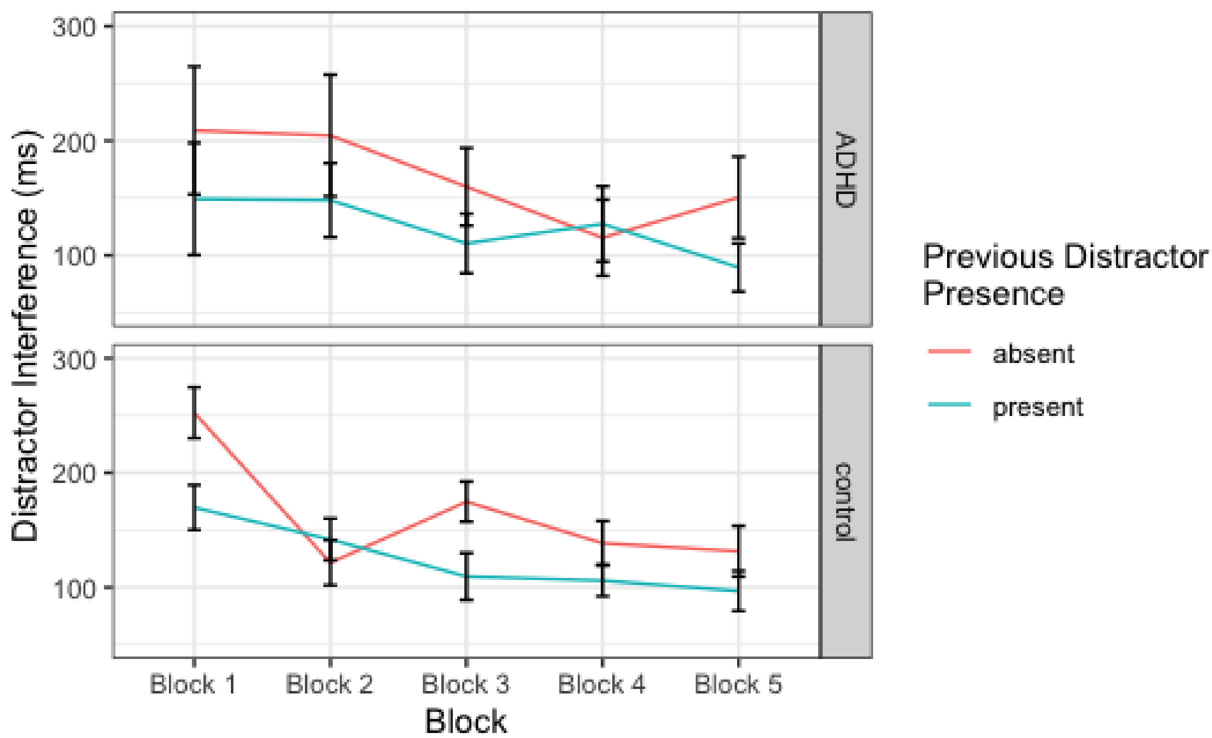

Figure 3.3. Sequential singleton effect as a function of block and ADHD group.

Mean ER. There was one significant main effect, one near-significant main effect, and one significant interaction. First, there was a main effect of block such that ER reduced from the first block (M = 4.5%, SD = 0.7%) to the last block (M = 3.2%, SD = 0.3%; F(4, 36) = 2.97; p = 0.011; η2 = 0.02). Second, there was a near-significant main effect of distractor such that participants had higher ER on distractor-present trials (M = 3.7%, SD = 0.5%) than distractor-absent trials (M = 3.2%, SD = 0.3%; F(1, 39) = 2.97; p = 0.085; η2 = 0.02). Third, there was a significant interaction of distractor by block such that ER distractor interference decreased from the first (M = 2.5%, SD = 8.3%) to the last block (M = 0.4%, SD = 0.4%; F(4, 36) = 2.84; p = 0.023; η2 = 0.02).

Eye-tracking Results

First Fixation Location Analysis. Since only distractor-present trials have distractor fixations, an analysis including distractor presence will be inherently unbalanced. Thus, I instead employed two separate ANOVAS (cf. Gaspelin, Ruthruff, & Jung, 2014). The first evaluated the "oculomotor capture effect", or whether the singleton distractor captured attention more than the other nontarget distractors, and the second evaluated whether the presence of the singleton distractor affected attention allocation to the target (Figure 3.4).

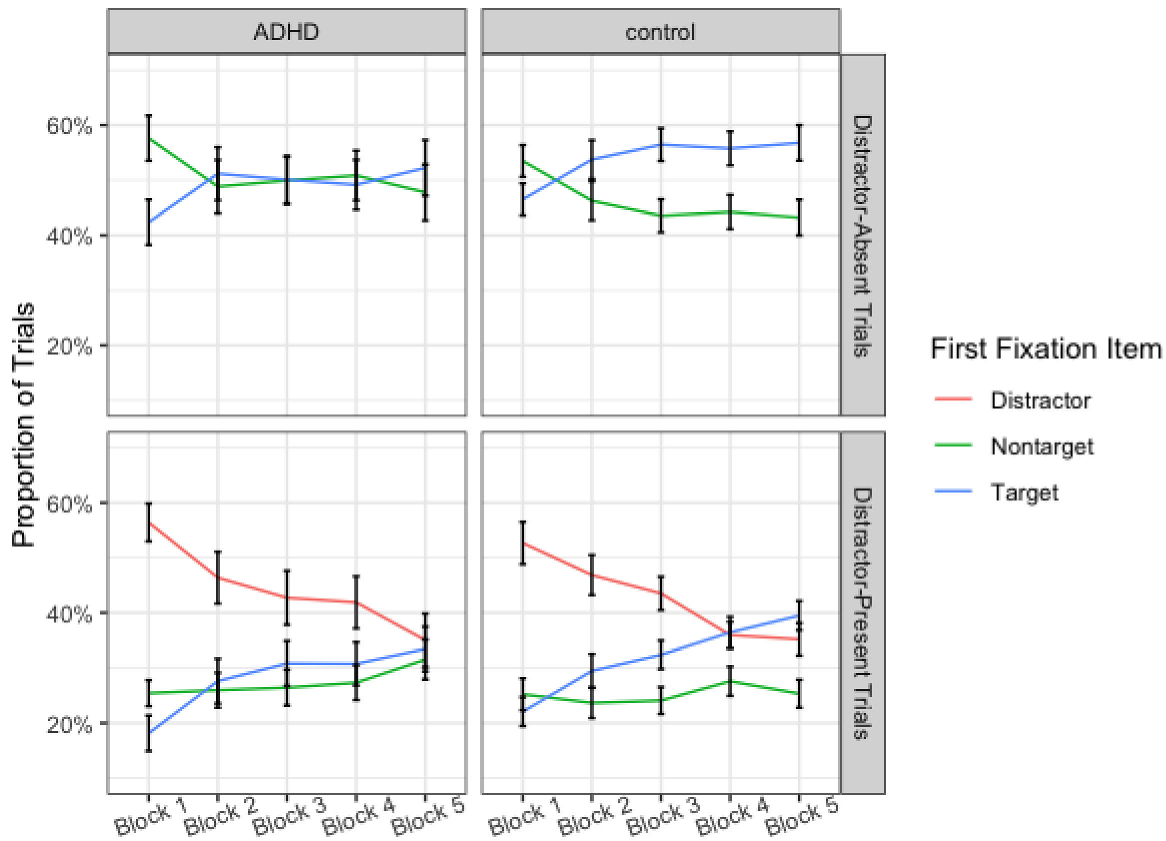

Figure 3.4. The proportion of first fixations on each item type over the course of the task by ADHD and distractor presence.
The target selection effect is the difference between the blue target lines in the distractor-absent and distractor-present trials. Both groups display the oculomotor capture effect and the poorer target selection of distractor presence, though both are more severe for ADHD participants and participants overcome the effects with exposure to the task.

To determine whether there was an oculomotor capture effect in the eye movement data, I first conducted a repeated-measures ANOVA of the first fixation on the distractor or the average nontarget item when the distractor was presented (cf. Gaspelin, Ruthruff, & Jung, 2014). I included within-subjects factors of block and item type and a between-subjects factor of ADHD. There was a main effect of first fixation item type; overall, participants looked first at the distractor more frequently ($M = 43\%$, $SD = 17\%$) than at any other nontarget item ($M = 25\%$, $SD = 13\%$; $F(1, 39) = 146.12$, $p < 0.001$; $\eta 2 = 0.28$). There was a second main effect of block such that participants had higher fixation rates on the distractor or nontarget in the first block ($M = 39\%$, $SD = 21\%$) compared to the last block ($M = 31\%$, $SD = 15\%$; $F(4, 37) = 3.74$, $p = 0.005$; $\eta 2 = 0.04$). Finally, there was an interaction of first fixation item type and block ($F(4, 37) = 6.75$, $p < 0.001$; $\eta 2 = 0.07$) such that first fixation on the distractor decreased from the first ($M = 54\%$, $SD = 17\%$) to the last block ($M = 35\%$, $SD = 16\%$) while first fixation on any other nontarget item did not change. I had expected to find a difference in first fixation on the distractor between groups such that ADHD participants fixated first on the distractor more than controls. Given the small number of ADHD participants, the above analysis may not be able to capture such a specific effect if it occurred only early on in the task. To probe this prediction, I conducted pairwise comparisons of first fixation on the distractor item for each block between ADHD and control groups. There were no significant differences in first fixation on the distractor between groups (p's > 0.2).

Additionally, to determine if the distractor captures attention from the target, I conducted a repeated-measures ANOVA of the first fixation on the target and non-target items in distractor-present and distractor-absent trials (cf. Gaspelin, Ruthruff, & Jung, 2014). There were two significant and one near-significant main effects as well as one significant and two near-significant interactions. Overall, there was a main effect of item type showing participants first fixated on the target (M = 42%, SD = 19%) more than on any nontarget (M = 36%, SD = 19%) item ($F(1, 39) = 28.01$; $p < 0.001$; $\eta 2 = 0.04$). There was also a near-significant main effect of block such that participants had smaller first fixation rates on the target or nontarget items in the first block (M = 37%, SD = 20%) compared to the last block (M = 41%, SD = 19%; $F(4, 36) = 2.36$; $p = 0.052$.; $\eta 2 = 0.01$). A significant interaction of item by block ($F(4, 36) = 8.51$; $p < 0.001$; $\eta 2 = 0.04$) showed target fixation increased from the first (M = 33%, SD = 18%) to the last (M = 47%, SD = 18%) block while nontarget fixation remained roughly the same. Additionally, a near-significant interaction of item type by ADHD showed that participants with ADHD had a smaller difference in initial fixation on the target item versus the nontarget items (M = 2%, SD = 25%) than control participants (M = 7%, SD = 23%; $F(4, 36) = 3.59$; $p = 0.059$; $\eta 2 = 0.01$).[7]

Second Fixation Location Analysis. To evaluate how participants recovered from the first fixation, I conducted the same analyses as the above first fixation location on the second fixation locations (Figure 3.5).

I first conducted the repeated-measures ANOVA of proportion of second fixations on the singleton distractor and the nontarget items. There were two significant main effects. The main effect of second fixation location found a reverse oculomotor capture effect; there were larger second fixation rates on the nontarget items (M = 20%, SD = 12%) than on the singleton distractor (M = 15%, SD = 11%; $F(1, 39) = 27.11$; $p < 0.001$; $\eta 2 = 0.07$). The main effect of block found that participants had higher second fixation rates on the distractor or nontarget in the

[7] If ADHD participants were more impulsive in their eye movements during this task, one would expect that the latency to their first fixation would be significantly shorter than that of the control participants. To investigate this possibility, I conducted the same repeated-measures ANOVAs with first fixation latency. There were no significant group effects, suggesting ADHD participants were not necessarily more impulsive in their eye movements.

first block ($M = 24\%$, $SD = 12\%$) compared to the last block ($M = 14\%$, $SD = 9\%$; $F(4, 37) = 11.67$, $p < 0.001$; $\eta2 = 0.11$). I again conducted a follow-up pairwise comparison of second fixation proportion on the distractor between ADHD and control groups for each block, finding no differences in distractor fixation (p's > 0.2).

The repeated-measures ANOVA of the second fixation on the target in distractor-present and distractor-absent trials revealed a significant main effect of item type as well as a near-significant interaction of ADHD by item type. Here, participants fixated second on the target ($M = 48\%$, $SD = 14\%$) more than on a nontarget ($M = 21\%$, $SD = 12\%$; $F(1, 39) = 11.67$; $p < 0.001$; $\eta2 = 0.02$). A near-significant interaction showed that participants with ADHD had a smaller difference in initial fixation on the target item versus the nontarget items ($M = 35\%$, $SD = 19\%$) than control participants ($M = 40\%$, $SD = 20\%$) ($F(4, 36) = 3.27$; $p = 0.071$; $\eta2 = 0.004$).

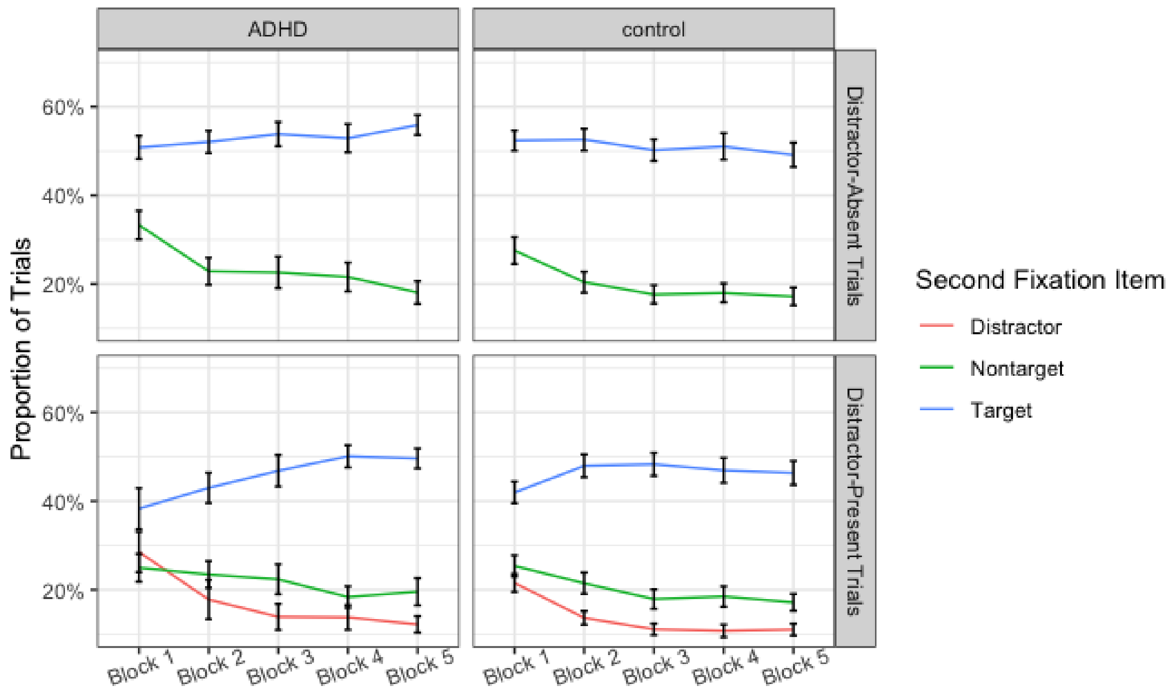

Figure 3.5. The proportion of second fixations on each item type over the course of the task by ADHD and distractor presence.

The oculomotor capture effect is the difference between the red distractor line and green nontarget line in the distractor-present trials. The target selection effect is the difference between the blue target lines in the distractor-absent and distractor-present trials. Both groups display a reverse oculomotor capture effect and similar target selection effects of distractor presence. Error bars show standard errors.

Mind-wandering Results

Participants experienced significantly different rates of each thought type: there were the most reports of on-task thoughts (M = 48%, SD = 21%), followed by unintentional mind-wandering (M = 29%, SD = 19%), performance-based thoughts (M = 17%, SD = 15%), then intentional mind-wandering (M = 6%, SD = 8%; $F(3, 37) = 52.37$; $p < 0.001$; $\eta 2 = 0.50$; Figure 3.6). Pairwise comparisons showed that ADHD participants endorsed near significantly higher rates of performance-based thoughts (M = 23%, SD = 17%) than control participants (M = 14%, SD = 12%; $t(39) = 1.80$; $p = 0.09$). No other thought types differed between group.

Because the occurrence of performance-based thoughts and intentional mind-wandering was fairly low and provided insufficient power, I conducted the subsequent analyses in only on-task thoughts and unintentional mind-wandering. Additionally, on-task thoughts and unintentional mind-wandering are the "purest" indicators of on-task focus or capture by internal distraction, respectively.

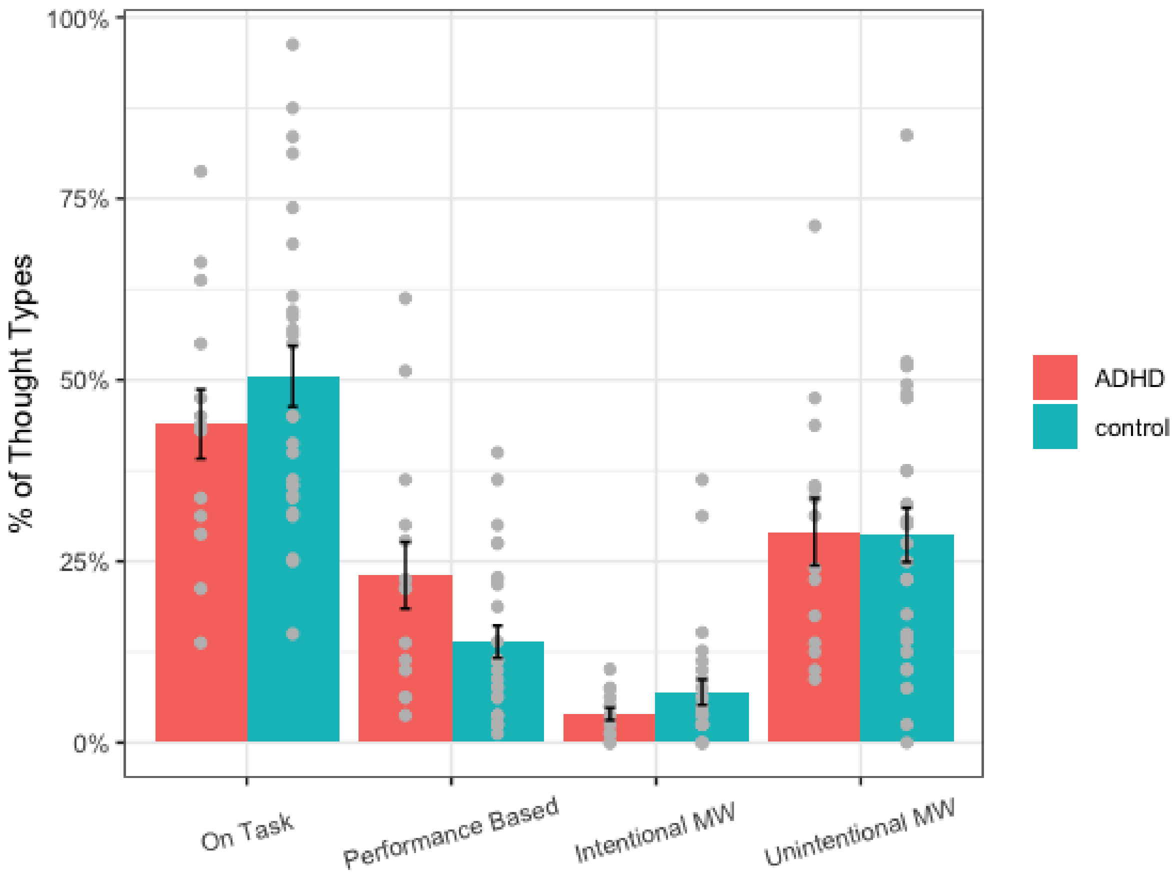

Figure 3.6. Thought type by ADHD diagnosis.
The ADHD group experienced higher rates of performance-based thoughts than controls. No other thought type rates were different between groups.

Analysis of pre-probe accuracy found an interaction of mind-wandering type by accuracy ($F(3, 37) = 12.90$; $p < 0.001$; $\eta 2 = 0.08$). Pairwise comparisons showed that correct responses (as compared to incorrect responses) were associated with lower rates of unintentional mind-wandering (correct M = 28%, SD = 18%; incorrect M = 44%, SD = 38%; $t(45) = 2.20$, p =

0.033) and higher rates of on-task thoughts (correct M = 49%, SD = 20%; incorrect M = 30%, SD = 36%; t(45) = -2.68, p = 0.01; Figure 3.7). This interaction was no different for control and ADHD participants.

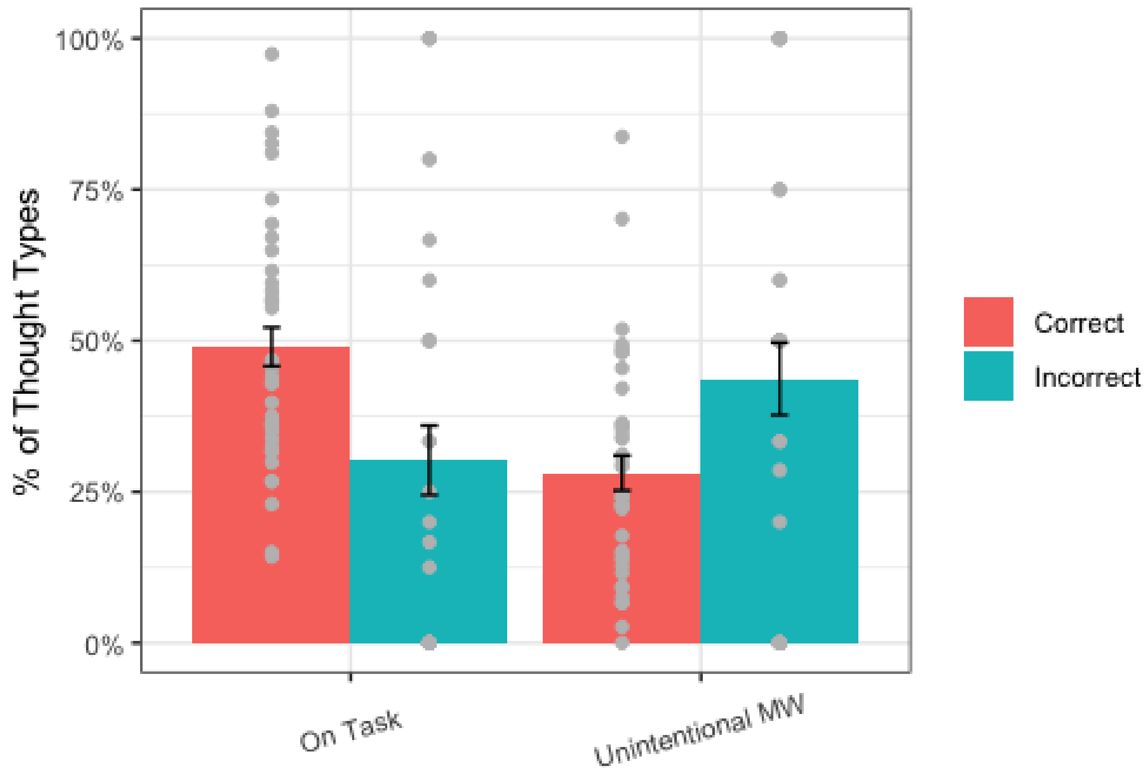

Figure 3.7. Thought type by pre-probe trial accuracy.
Correct responses were more often followed by on-task thoughts and incorrect responses were more often followed by unintentional mind-wandering (MW).

Mind-wandering and Eye-tracking

To investigate the relationship between mind-wandering and target selection, I conducted an analysis of the first fixation location on the target during unintentional mind-wandering. Though not significant, there was a fairly large effect such that, during unintentional mind-wandering, ADHD participants displayed a larger initial target fixation effect of distractor presence (initial target fixation for distractor-absent minus distractor-present trials; M = 28%, SD = 13%) than control participants (M = 13%, SD = 33%; F(1, 39) = 2.11; p = 0.15; η2 = 0.03;

Figure 3.8). A follow-up pairwise comparison between ADHD and control groups of the initial target fixation effect of distractor presence found a nearly significant difference ($t(39) = 2.02$; $p = 0.051$).

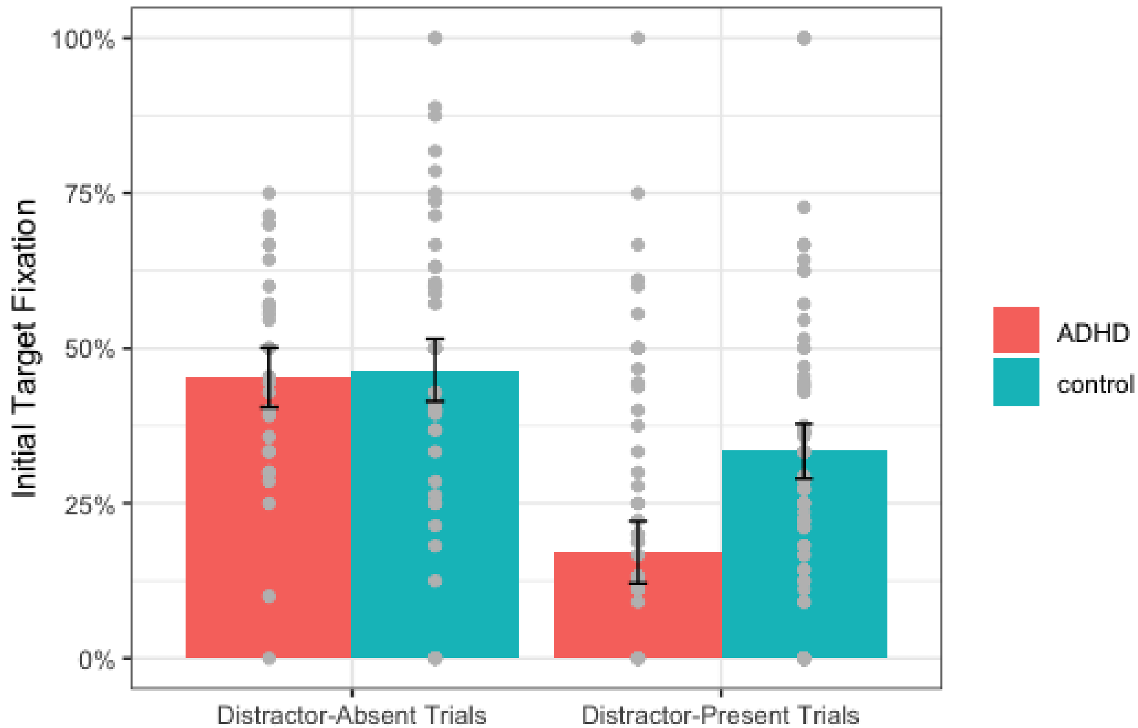

Figure 3.8. Proportion of first fixations on the target while participants were experiencing unintentional mind-wandering by ADHD group and distractor presence. Compared to controls, ADHD participants showed a larger worsening in target selection during distractor-present from distractor-absent trials.

To investigate whether unintentional mind-wandering affects distractor suppression differently in ADHD and control participants, I conducted an analysis of first fixation location of distractor-present trials during unintentional mind-wandering. A significant interaction of ADHD by first fixation location showed that, when mind-wandering, ADHD participants first fixated more on a nontarget item ($M = 33\%$, $SD = 20\%$) and less on the target item ($M = 17\%$, $SD = 19\%$) than control participants did (nontarget $M = 21\%$, $SD = 18\%$; target $M = 33\%$, $SD = 22\%$; $F(1, 39) = 3.91$; $p = 0.023$; $\eta 2 = 0.07$; Figure 3.9). This again suggests that participants with

ADHD struggle more with target selection while mind-wandering than controls do. This did not occur during on-task or performance-based thoughts (Figure 3.9) during distractor-present trials.

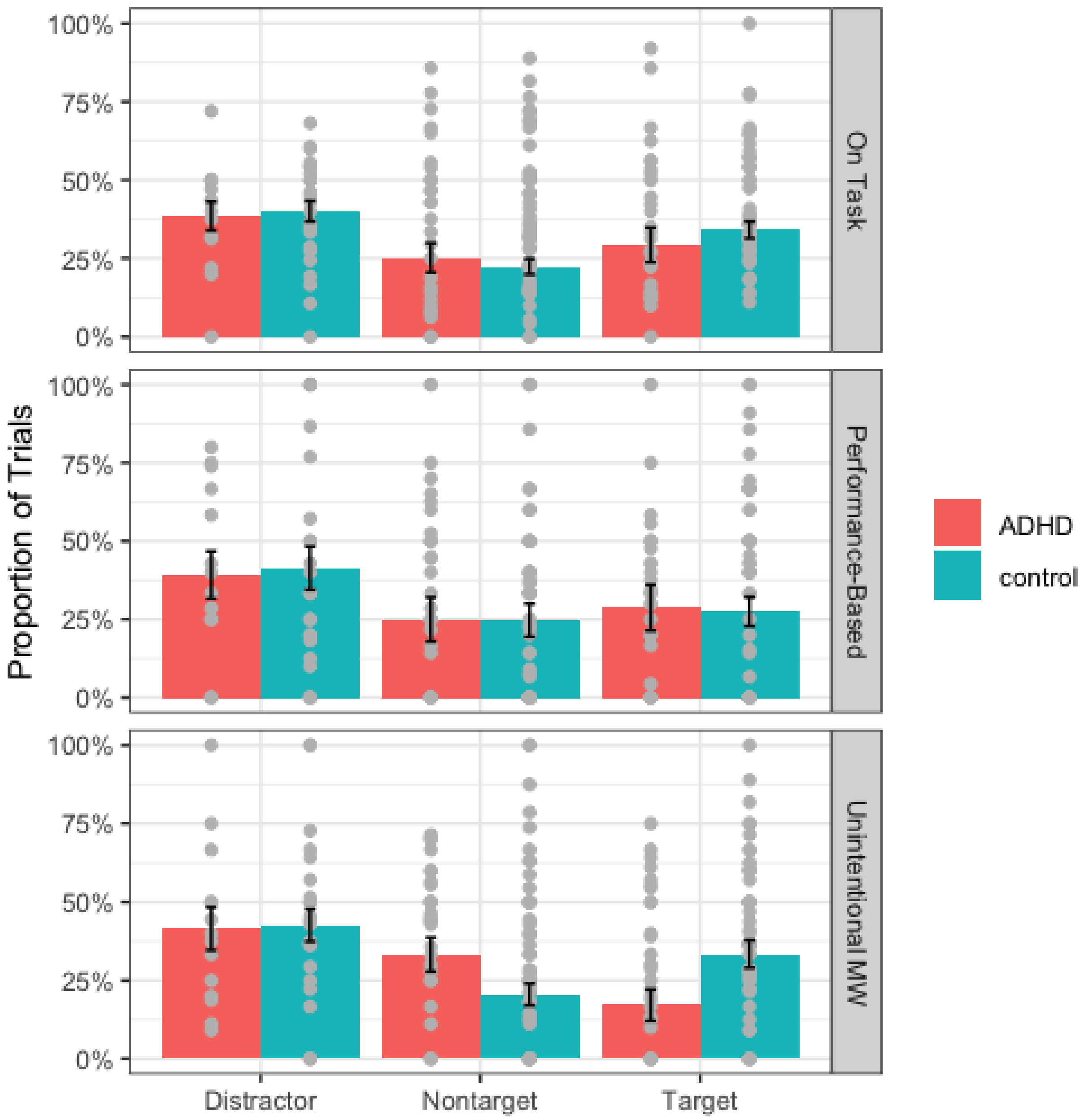

Figure 3.9. Proportion of first fixations during distractor-present trials while participants were experiencing on task thoughts, performance-based thoughts, or unintentional mind-wandering by ADHD group and item type.
ADHD participants showed worse target selection than control participants.

Discussion

Taken together, the findings revealed four effects of interest. First, participants displayed an oculomotor capture effect in the first fixation and a reversed effect in the second fixation. Second, several results point to a deficit in target selection, but not distractor suppression, in ADHD participants, which was worsened during unintentional mind-wandering. Third, incorrect responses were associated with higher rates of unintentional mind-wandering, while correct responses were associated with higher rates of on-task thoughts. Fourth, ADHD participants experienced higher rates of performance-based thoughts than control participants.

Oculomotor Capture Effect Reversed after First Fixation

The current study replicated the oculomotor capture effect found by Gaspelin and colleagues (2017), though our capture effect is considerably larger in magnitude. Notably, Gaspelin and colleagues (2017) employed a task almost identical to the visual search task in the current study, though their search display consisted of six items while ours consisted of ten items. In order to optimize the eye-tracking results and defined areas of interest, search display items need more space between them than the original version of this task (Moser, Becker, & Moran, 2012) allowed. Rather than reduce the number of items in the display, I chose to reduce the item size. The distractor captured initial fixations at much higher rates than if we were to reduce the number of items. This capture effect reduced with exposure to the task.

Additionally, there was a “reverse” oculomotor capture effect in the second fixation analysis: participants fixated second more often on any nontarget item rather than on the salient distractor. This effect suggests that participants are initially captured by the distractor but quickly recover for the second fixation and are able to focus their attention away from the distractor.

One might expect that ADHD participants would experience a more severe oculomotor capture effect because ADHD is thought to be associated with heightened distraction by irrelevant stimuli (American Psychiatric Association, 2013). Yet this was not indicated by the eye-tracking data in the current study: ADHD participants did not display a heightened explicit attention capture by the distractor. This contributes to a limited amount of eye-tracking work in individuals with ADHD. One visual search study of boys with ADHD and their non-affected brothers also failed to find heightened capture by a distractor in the ADHD group (Van der Stigchel et al., 2011). This study did find that the ADHD group displayed more intrusive saccades directed towards neither the target nor distractor than controls, corroborated by our finding that ADHD participants initially fixated on the nontarget items more than control participants did.

ADHD Findings Suggest Target Selection Deficits

Participants with ADHD appeared to have difficulties fixating on the target item initially. Initial target fixation was fairly high in control participants and continued to increase with exposure to the task. However, participants with ADHD first fixated on the nontarget items more than on the target item. Notably, control participants experienced this initial target selection error in the first block but were able to overcome it by the second block (Figure 3.4). Yet, throughout the task, participants with ADHD were not able to fixate first on the target more than any nontarget. Rather, after the first block, participants with ADHD first fixated on the target at the same rate as any other nontarget.

To add to this, when mind-wandering, participants with ADHD had worse target selection when a distractor was presented than control participants. Further, when mind-wandering, first fixation on the target was significantly lower and first fixation on the nontarget items was significantly higher for ADHD as opposed to control participants. First fixation on the distractor was no different between ADHD and control participants. This suggests that, in this task, participants with ADHD struggled more than controls to correctly select the target but did not experience changes in distractor capture when mind-wandering.

Combined, these results suggest that participants with ADHD experienced a deficit in effective target selection, but their gaze was not necessarily directed towards the distractor more than controls. The finding that ADHD participants tended to fixate on the nontarget initially points to inaccuracies in selecting the correct item and thus allocating their focus correctly. However, this does not support the theory that people with ADHD are distracted by salient, task-irrelevant items. It, rather, suggests they are able to overcome the attention-grabbing temptation of these singleton distractors but are not adept at rapidly isolating the target among other items.

Past studies have suggested that individuals with ADHD (compared to controls) experience inefficient information processing as they are slower to collect task-relevant information (Huang-Pollock et al., 2017; Metin et al., 2013; Weigard, Huang-Pollock, Brown, & Heathcote, 2018). Metin and colleagues (2013) posited that if participants with ADHD experienced *inefficient* information processing, they would have smaller drift rates than controls, as they are collecting information from the search display slower than controls. If participants with ADHD experienced *impulsive* information processing, they would have smaller boundary separations than controls, as they would be making their decision more impulsively than controls. They found that participants with ADHD were indeed exhibiting slower drift rates than controls and similar boundary separations. Thus, participants with ADHD were inefficiently collecting information during the task, potentially by devoting more attention to nontarget items, as in the current study. Further, an eye-tracking study of boys with ADHD found that this group experienced more “intrusive saccades,” that is, saccades toward items that were neither the target nor the distractor (Van der Stigchel et. al., 2011). This finding is very similar to the target selection deficit found in the current study, which showed that participants with ADHD were more likely than controls to first look at a nontarget item, thus collecting more information at slower rates. Notably, my drift diffusion analysis did not isolate a difference in drift rate between ADHD and control participants as in past work. However, given the ADHD group is made up of a rather small sample, this analysis will need to be repeated once the full dataset is collected.

Mind-wandering Related to Higher Error Rates

Of the four thought types, participants endorsed mostly experiencing on-task thoughts (48%) and unintentional mind-wandering (29%). Participants did also endorse experiencing performance-based thoughts (17%) and intentional mind-wandering (6%), but at much smaller rates. These findings are consistent with past research showing that participants endorse mind-wandering around thirty to forty percent of the time (Robison, Miller, & Unsworth, 2019; Thomson, Besner, & Smilek, 2013; Unsworth & Mcmillan, 2014).

Unintentional mind-wandering was associated with a higher rate of incorrect (vs. correct) responses while on-task thoughts were associated with a higher rate of correct (vs. incorrect) responses. This adds to past work that has found that mind-wandering is associated with task performance deficits and that on-task thoughts are associated with improved performance (Hall-Ruiz, 2016; Stawarczyk, Majerus, Catale, & D’Argembeau, 2014; Thomson, Seli, Besner, & Smilek, 2014). Naturally, people are inclined to perform better on a task when attention is fully devoted to performance and are likely to perform worse when attention is being shared between the task and internal distraction.

More Performance-based Thoughts in ADHD Participants

The finding that ADHD participants only had different rates of performance-based thoughts is a bit surprising, as I had expected they would experience more mind-wandering and fewer on-task thoughts than controls (Jonkman et al., 2017; Lanier, Noyes, & Biederman, 2019). This result is interesting, though, as it does contribute to some similar findings. For example, adults with ADHD experience higher rates of intrusive thoughts (Abramovitch & Schweiger, 2009) and hyperfocus (Hupfeld et al., 2018). These phenomena (and the higher rate of performance-based thoughts) all appear to relate to a difficulty in maintaining appropriate focus on the task at hand and thus a deficit in disengaging focus from perseverative thoughts. This finding further supports the widely accepted theory that ADHD largely consists of deficits in properly regulating attention. Importantly, many mind-wandering studies neglect to address these performance-based thoughts and they instead contribute to the rate of on-task thoughts. Including this thought type appears to be valuable in understanding individual differences in internal thoughts during cognitive tasks.

How Does Attention Shift between External and Internal Loci?

There are several leading views attempting to describe the interaction between internal and external attention allocation, particularly how and why attention shifts from an external locus (e.g., a behavioral task such as that employed in Study 1 and in the current study) to an internal locus (e.g., mind-wandering, as investigated in the current study). Notably, as they are all describing separate aspects of mind-wandering, these theories are not necessarily mutually exclusive. First, the *control failure theory* focuses on how attention is shifted from the external to the internal world: essentially, how mind-wandering is initiated. Here, mind-wandering is driven by poor regulation of attention, or failures in executive control processes (McVay & Kane, 2010;

Watkins, 2008). McVay & Kane adapted the control failure theory to also incorporate aspects of an earlier hypothesis of mind-wandering, the *current concerns theory*, which states that attention is directed towards the stimulus or goal (internal or external) with the highest salience (McVay & Kane, 2010). Thus, McVay and Kane (2010) argue that mind-wandering occurs due to a failure of executive control to maintain attention on the task goals which results in the prioritization of other, more salient stimuli (e.g., internal thoughts of evening plans).

Another of these hypotheses — the *perceptual decoupling theory* — focuses on the continued maintenance of mind-wandering (Smallwood, 2013). According to this view, external and internal attention share domain-general resources such that spare attentional resources can be allocated either towards stimuli in the external world (e.g., perceptual distractors) or the internal world (e.g., mind-wandering; Smallwood & Schooler, 2015). Mind-wandering occurs, then, when attentional resources are "perceptually decoupled" from the external world towards internal thoughts. The theory asserts that continued mind-wandering is maintained by cognitive control processes (Smallwood, 2013). Thus, task performance suffers with increased mind-wandering because cognitive control resources are being consumed by internal thoughts. In contrast to the control failure theory, which claims that mind-wandering *occurs due to failures* in cognitive control, the perceptual decoupling theory argues that mind-wandering *requires* cognitive control resources.

A third theory aimed at describing this interaction of internal and external attention, the *meta-awareness theory*, attempts to address both the occurrence and the regulation of mind-wandering. The theory proposes that mind-wandering occurs and persists when thoughts are regulated infrequently (Smallwood, 2013). According to this hypothesis, mind-wandering occurs more often in people who have poor meta-awareness and/or are not regulating their thoughts.

Mind-wandering is inappropriately maintained (i.e., at the expense of task performance), then, in people with worse meta-awareness and/or in people who are not working to regulate their thoughts towards the task.

Employing both mind-wandering measurement methods and eye-tracking to evaluate internal and external attention, respectively, are unlikely to isolate these hypotheses. Firstly, these theories are not necessarily distinct and may co-occur. For example, an episode of mind-wandering may occur due to a failure in executive control that results in some executive control resources being decoupled from the task at hand and towards mind-wandering. Secondly, the current mind-wandering methodologies do not allow researchers to distinguish inceptions or conclusions of unintentional internal thoughts. As it stands, current methods force us to rely on self-report and good meta-awareness (which, according to the meta-awareness theory, is worse when people are prone to mind-wandering). However, this study could not provide more nuances for these theories, though it does allow us to better theorize how attention deficits relate to the control of internal and external attention.

Limitations of the Present Study

There are a couple of notable limitations worth discussing. First, though I investigated behavioral performance and eye-tracking measurements across blocks, I was not able to do this with the mind-wandering probes. In order to minimize interruptions, there were only 16 probes per block, not sufficient to capture the nuances of thought type change throughout the task. Future studies might combine blocks and/or increase the proportion of probes to better evaluate how mind-wandering changes throughout the task. Second, the ADHD group data collection is not completed and thus, results may change as we achieve our sample size goal. While I found some interesting effects suggesting ADHD participants performed differently than control participants, not all of the group differences from Study 1 were replicated, as this analysis was underpowered. Once possible, data collection will continue and I will analyze the complete dataset.

Conclusion

Overall, this study found that adults with ADHD displayed eye movement indications of a target selection deficit during the visual search task, but not a distractor suppression deficit. Both eye movement and mind-wandering results contributed to this interpretation. Additionally, participants with ADHD were more likely to experience performance-based thoughts, focusing on their performance on the task at hand when they were meant to focus on the task itself. These findings have the potential to inform methods to treat attention deficits in adults with ADHD by aiding them in improving target selection in the presence of distracting information or educating them on how to keep their internal thoughts on performing the task rather than perseverating on their task performance.

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Chapter 4 — Little Evidence of Transfer from a Visual Attention Training Task

Introduction

Stimulant medications prove at least partially effective for about 70% of people with ADHD, yet they are still associated with negative side effects (e.g. sleep problems, headaches, and tics; American Psychiatric Association, 2013), have a risk of misuse and addiction (Clemow & Walker, 2014), and are unsuccessful in the remaining patients with treatment refractory ADHD (Shim, Yoon, Bak, Hahn, & Kim, 2016). There is now a critical need to develop non-pharmacological interventions for individuals with ADHD.

There are several potentially promising non-psychopharmacological interventions to reduce symptomology in ADHD, including cognitive training (Sonuga-Barke, Brandeis, Holtmann, & Cortese, 2014), brain stimulation (Soff, Sotnikova, Christiansen, Becker, & Siniatchkin, 2017), and cognitive behavioral therapy (Antshel & Olszewski, 2014). Of these, cognitive training is the least expensive, least invasive, and most accessible option to people around the world.

While there has been interest in cognitive training for well beyond the past century (Aiken, 1895; Katz, 2017), the field of cognitive training has expanded rapidly in the last decade. The targeted cognitive domain varies among studies, with a majority of groups training working memory (Chooi & Thompson, 2012; Jaeggi, Buschkuehl, Jonides, & Perrig, 2008; Rudebeck, Bor, Ormond, O'Reilly, & Lee, 2012) and others training response inhibition (Zhao, Chen, & Maes, 2018), motor skills for surgery (Wallace et al., 2017), and more. Research may involve vastly different populations such as neurotypical participants (Jaeggi et al., 2008), older adults (Lampit, Hallock, & Valenzuela, 2014), even infants with a family history of ADHD (Goodwin et al., 2016), and so on.

In adults with ADHD, symptoms of inattention are the most common (American Psychiatric Association, 2013) and may be the most detrimental. Higher inattentive symptomology has been linked to higher risk of motor vehicle accidents, endangering the individuals with ADHD and others on the road around them (Fuermaier et al., 2015). Inattention has been positively correlated with mind-wandering (Jonkman, Markus, Franklin, & Van Dalfsen, 2017), which can adversely affect cognitive functioning such as reading comprehension (Feng, D'Mello, & Graesser, 2013) and suppression of task irrelevant external distraction (Forster & Lavie, 2014). In the interest of addressing these risk factors, I chose a behavioral task that has achieved a reduction in perceptual distraction in individuals with ADHD to eventually perform as well as control participants. This intervention may have the potential to generalize to other distracting situations in day-to-day life.

As the cognitive training literature continues to expand, research groups are beginning to investigate this method to ameliorate cognitive deficits in clinical populations, including individuals — most often children — with ADHD (Karch, Albers, Renner, Lichtenauer, & Von Kries, 2013; Sonuga-Barke et al., 2014). The majority of training paradigms in ADHD have focused on working memory enhancement (e.g., the commercial training product CogMed; Dentz, Guay, Parent, & Romo, 2017; Gropper, Gotlieb, Kronitz, & Tannock, 2014; Mawjee, Woltering, & Tannock, 2015). Working memory and attention are thought to be closely linked and do indeed involve several overlapping brain regions (Fedorenko, Duncan, & Kanwisher, 2013; Petersen & Posner, 2012), potentially justifying this working memory-oriented approach to cognitive training in ADHD. However, working memory training research has also found little transfer outside of working memory in adults with ADHD (Dentz et al., 2017; Mawjee et al., 2015). Thus, in order to directly address adverse effects due to heightened distractibility by irrelevant stimuli in ADHD, I chose to instead implement a cognitive training paradigm targeting visual attention.

While a successful cognitive training paradigm should result in improved performance in the specific task at hand, it should also generalize — or transfer — to other, similar tasks. Near-transfer effects, or transfer to tasks closely related in the same domain as the training task, are most common in cognitive training research. For example, an adaptive visuospatial n-back task has been found to transfer to a visual n-back task (Au et al., 2016). Far-transfer effects, or transfer to tasks distinct from the training task, are much less common and consistent in the literature. For example, research groups have found transfer from a demanding dual n-back task to a measure of fluid intelligence (Jaeggi et al., 2008, 2010; Rudebeck et al., 2012), while others have failed to replicate this finding (Chooi & Thompson, 2012; Thompson et al., 2013). Without successful near- or far-transfer effects, a training paradigm provides little to no real-world applications.

Study 1 showed that the Theeuwes (1991) visual attention task is an effective method to isolate heightened distraction in individuals with ADHD. Additionally, over the course of the task, participants showed decreased distraction by irrelevant perceptual items in the search display; thus, it also serves as a useful model of distraction reduction. Study 2 found that participants with ADHD displayed difficulty finding the target item quickly. When a perceptual distractor was present and participants were unintentionally mind-wandering, this target selection deficit was further worsened in participants with ADHD as compared to control participants. Past research has investigated various cognitive training paradigms to improve ADHD symptoms, but no study to date has investigated a task specific to mitigating visual perceptual distraction.

I hypothesized that training visual attention with this task would mitigate distraction from irrelevant visual stimulation and would also lessen distraction in closely related transfer tasks. I also hypothesized that ADHD participants would begin the training with higher levels of distraction but would display a reduction in distraction over the course of the task. Finally, I expected that participants who completed the experimental training task would show a lasting effect of training at the one-month follow-up session. A key comparison of interest to determine whether participants who received the attention training received lasting benefits over and above those who received the control knowledge training task (Knowledge Builder; KB; Buschkuehl, Hernandez-Garcia, Jaeggi, Bernard, & Jonides, 2014) will be the interaction between training group (attention vs KB) and time (including the follow-up session). Due to unforeseen circumstances,[8] just three KB participants have returned for a follow-up session thus far. Therefore, it will not be possible to make solid generalizations regarding lasting transfer effects with such a small sample size. In order to best evaluate the data available, these follow-up data are still included in the analyses but are discussed with reservations and each control training follow-up data point is represented individually in each figure below to best visualize the full range in this small group.

To investigate my hypotheses, I conducted a five-day training study with three groups of participants: 1) ADHD participants assigned to an experimental visual attention training task, 2) control participants assigned to an experimental visual attention training task, and 3) control

[8] Due to current public health concerns (cf. Center for Disease Control and Prevention, 2020), all human subject studies at the university were paused. Just three participants in the KB group had returned for a follow-up session before this announcement.

participants assigned to a control knowledge training task. First, to investigate changes over the course of the training task, I measured performance and training gains from the first to last session in distractor interference. Second, to evaluate transfer effects, I recorded performance on five distinct near- and far-transfer tasks. Third, to determine durability of training and transfer performance gains, participants completed questionnaires, transfer tasks, and the training task one month after training completion.

Method

Design

Each participant first completed a pre-training session consisting of a series of ADHD symptom questionnaires, a clinical interview to confirm ADHD status, and a series of visual attention transfer tasks. The following week, participants completed five daily sessions of their assigned training task (attention training or KB). The fifth training session was immediately followed by a post-training session, consisting of the visual attention transfer tasks. Participants completed a follow-up (during which they completed the training task, transfer tasks, and questionnaires; Figure 4.1).

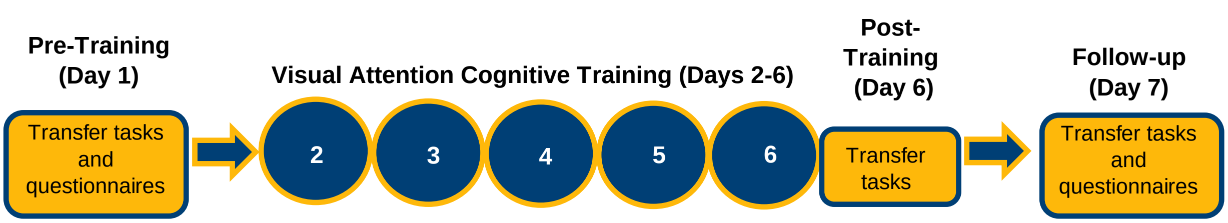

Figure 4.1. Study 3 Timeline.

Participants

One hundred and ten participants (38 ADHD, 72 controls) completed the pre-training session. Of the participants who completed the pre-training session, 23 ADHD and 51 control participants were eligible and participated in the training portion of the study (Table 4.1). Control participants had normal color vision, normal or corrected-to-normal visual acuity, no current mental disorders, and had low inattention as determined by CAARS T-scores (below 60 on the inattention subscale). ADHD participants fulfilled the same requirements but were also diagnosed with ADHD by a healthcare professional and had high inattention CAARS T-scores (above 60 on the inattention subscale). This method resulted in primarily inattentive (rather than hyperactive/impulsive) ADHD participants: an appropriate target for this research into improving inattention. Many of the ADHD participants were taking medication to treat ADHD symptoms (N = 16).

Thus far, 10 ADHD, 3 KB control, and 11 attention training control participants have returned for the 1-month follow-up session (Table 4.2). All 23 ADHD participants received the visual-attention training, 28 control participants received the visual-attention training, and 23 control participants received a daily trivia “control training” task (Knowledge Builder; KB; Buschkuehl, Hernandez-Garcia, Jaeggi, Bernard, & Jonides, 2014). Participants received $10 per hour of participation as well as a bonus $5 for completing all five training sessions. I excluded from the data analyses reaction times three standard deviations outside of the group mean and accuracy below 70. Final data analyses included 23 ADHD participants, 28 control attention training participants, and 23 control KB training participants.

Table 4.1. *Description of groups at pre-training session.*

	Control KB Training Group	Control Attention Training Group	ADHD Attention Training Group	*p-value* *(ADHD vs. control)*
N	23	28	23	
Age	22.0 (3.14)	23.0 (4.82)	22.1 (3.54)	
% Female	78.3%	78.6%	73.9%	
CAARS Inattention Score	45.2 (4.1)	47.5 (11.8)	74.6 (7.9)	< 0.001
ASRS Inattention Score	0.3 (0.7)	0.7 (1.9)	4.7 (2.3)	< 0.001
ASRS Hyperactivity Score	0.4 (0.9)	0.3 (0.7)	3.1 (2.4)	< 0.001
CFQ Score	25.6 (8.5)	31.3 (12.7)	66.1 (15.4)	< 0.001
DDFS Score	27.7 (5.7)	31.6 (11.6)	44.7 (9.5)	< 0.001
HF Disposition Score	27.3 (15.7)	37.1 (24.3)	52.1 (20.3)	< 0.001
HF Screen Time Score	13.3 (10.6)	20.8 (13.9)	43.6 (10.7)	< 0.001

Note: Standard deviations are in parentheses. P-value is a t-test of ADHD vs control participants. There were no significant differences between control attention training and KB training groups at the pre-training session (p > 0.01).

Table 4.2. *Description of groups at 1-month follow-up session.*

	Control KB Training Group	Control Attention Training Group	ADHD Attention Training Group	*p-value* *(ADHD vs. control)*
N	3	11	10	
Age	21.3 (3.21)	23.4 (4.27)	23.6 (3.98)	
% Female	66.7%	76.9%	63.6%	
CAARS Inattention Score	45.2 (4.1)	47.5 (11.8)	74.6 (7.9)	< 0.001
ASRS Inattention Score	0.3 (0.6)	0.5 (0.8)	3.8 (1.8)	< 0.001
ASRS Hyperactivity Score	0.7 (1.2)	0.2 (0.4)	2.1 (2.6)	< 0.001
CFQ Score	33.3 (10.3)	23.2 (11.5)	58.7 (17.2)	< 0.001
DDFS Score	29.3 (12.9)	27.9 (13.4)	47.7 (10.0)	< 0.001
HF Disposition Score	20.0 (7.0)	21.6 (16.2)	45.5 (8.8)	< 0.001
HF Screen Time Score	23.0 (16.5)	16.4 (12.0)	44.8 (13.4)	< 0.001

Note: Standard deviations are in parentheses. P-value is a t-test of ADHD vs control participants. There were no significant differences between control attention training and KB training groups at the follow-up session (p > 0.01).

Training task

The training task is identical to the task described in *Study 1 Task*.

Transfer tasks

Participants completed transfer tasks before and after training to assess the extent to which heightened distraction suppression influences performance on near- and far-transfer measures. All tasks were administered using a desktop computer equipped with a 19-inch monitor and E-prime presentation software (version 2.0.10.353). We dimmed the room lights to 50% of normal brightness to ensure that there was no glare on the computer screen. Viewing distance was approximately 60 cm from the computer screen. Transfer tasks included an arrow flanker task (Kopp, Mattler, & Rist, 1994); a useful-field of view task (UFOV; Wood & Owsley, 2014); a response competition (Lavie, 1995) and a perceptual distraction perceptual load task (S Forster & Lavie, 2008); and a sustained attention to response task (SART; Robertson, Manly, Andrade, Baddeley, & Yiend, 1997). All of these tasks, described below, are widely used and validated to index visual attention performance.

Arrow Flanker Task. The *arrow flanker task* (Kopp et al., 1994) indexes effects of response-competition distraction. A black fixation cross was presented on a white background for 1000ms, followed by presentation of a search array consisting of five items (“=”, “<”, and “>”) arranged horizontally. The next trial began after 2500ms or participant response. The central item (the target) was always an arrow (“<” or “>”) and the four surrounding items were either all an arrow in the same direction (congruent), all an arrow in the opposite direction (incongruent), or all an equal sign (neutral). Participants indicated the direction of the target. Participants completed ten practice trials and three blocks of 60 trials.

UFOV Task. The *UFOV task* (Wood & Owsley, 2014) measures the processing speed of items in the visual periphery. This task has been found to show individual differences between older and younger adults and has proven to be a strong predictor of outcome measures related to driving, such as crash risk. In order to keep participants' eyes fixated at the center, they typically complete a central letter identification task while the peripheral target is presented. Since participants were likely to be high-functioning, healthy adults at a major research university, the stimuli were presented fairly quickly. Each trial began with a gray screen with the word "Ready?" printed in white. Participants clicked any key to begin the stimulus presentation, which consisted of a 67ms presentation of a letter at the center of the screen (E, H, L, or F) surrounded by 24 circles (degrees stuff), one of which contained a solid white stimulus (the target). This screen was followed by a 1250ms mask with checkerboard circles over each stimulus location and then a response screen which contained empty circles over each stimulus location. During stimulus presentation, participants verbalized the letter at the center of the screen into a microphone as quickly as possible. During the trial response screen, participants used the cursor to click on the target circle. Once they responded, the cursor reset to the center of the screen and disappeared from view until the subsequent response screen. Participants completed four practice trials of verbalizing the central letter, four practice trials of the combined task, and 48 experimental trials of the combined task.

Perceptual Load Response-Competition Distractor Task. The *perceptual load response-competition distractor task* is intended to assay distraction during the response selection phase (Lavie, Hirst, de Fockert, & Viding, 2004). First, at the center of the screen, a fixation cross was presented for 500ms, followed by a 100ms presentation of the search circle (1.6° radius) and then a 1900ms presentation of a blank screen during which participants responded. Distractors were presented 1.4° to the left or the right of the search circle. Target letters were 'X' or 'N' with responses made by depressing '0' or '2,' respectively, on the number pad. Distractor letters were equally likely to be either 'X' or 'N.' This distractor could be congruent with the target (e.g. 'X' when the target is 'X'), incongruent (e.g. 'X' when the target is 'N'), or neutral (e.g. 'H' when the target is 'X'). Participants were told to ignore any stimuli presented outside of the circle. The low perceptual load circle consisted of one target letter and 5 small 'o's. The high perceptual load circle consisted of 6 stimuli in the circle: one target letter and 5 angular letters (H, K, Z, M, and/or W; Forster & Lavie, 2007). Participants completed three slowed-down practice trials, 12 at-speed practice trials, and two experimental blocks of 60 trials each of high and low perceptual load.

Perceptual Load Singleton Distractor Task. The *perceptual load singleton distractor task* is intended to index attentional capture due to perceptual distraction during encoding of a target. This task is virtually the same as the perceptual load response-competition distractor task, however, the distractor is a cartoon singleton presented above or below the search circle during 10% of all trials. Participants completed 12 practice trials and two experimental blocks of 60 trials of high and low perceptual load.

SART. The *SART* (Robertson et al., 1997) measures ability to sustain attention during a dull cognitive task. Each trial began with a black screen for 900ms followed by a white number (ranging from "0" to "9") presented at the center of the screen for 250ms. Participants were instructed to press the computer's space bar only when they saw a "3" on the screen, which occurred on ten percent of trials. Participants completed one block of 500 trials.

Questionnaires

Participants completed questionnaires at pre-training and both follow-up sessions to assess ADHD symptomology. These questionnaires include those described above in *Study 1 Questionnaires* — the Conners' Adult ADHD Rating Scales (CAARS; Conners, Erhardt, & Sparrow, 1999), the Adult ADHD Self-Report Scale (ASRS; Kessler et al., 2005), and the Cognitive Failures Questionnaire (CFQ; Broadbent, Cooper, FitzGerald, & Parkes, 1982) — as well as the Day Dreaming Frequency Scale (DDFS; Giambra, 1980), the disposition and scenario scales of the Adult Hyperfocus Questionnaire (AHQ; Hupfeld, Abagis, & Shah, 2018), and a comprehensive ADHD treatment history form.

DDFS. The *DDFS* is a 12-item subscale of the Imaginal Processes Inventory (Giambra, 1980) which indexes frequency of task-unrelated thoughts through items such as "I recall or think over my daydreams:" *infrequently*, *once a week*, *once a day*, *a few times during the day*, or *many different times during the day*. The DDFS is scored by totaling the values of each response (0 – 4).

AHQ. The *AHQ* is intended to probe hyperfocus, the experience of being so closely focused on one task that other tasks or commitments (such as dinner or homework) are often ignored or forgotten (Hupfeld et al., 2018). Hyperfocus occurs more often in people with ADHD and may be linked to difficulties regulating attention. To reduce participants' fatigue, participants completed only the disposition and scenario scales. The disposition scale contains 12 items to assay hyperfocus trait levels in the past year (e.g. "When I am busy doing something I enjoy or something that I am very focused on, I tend to completely lose track of the time"). The scenario scale contains 18 items which are real-world hyperfocus experiences obtained through interviews during survey creation (e.g. "When I am doing something that I really enjoy doing like pleasure reading, I can ‘zone out’ completely. You can shout my name or wave your hands in my face, and I wouldn’t notice.”). Participants are told to think about each scenario in the context of their most common hyperfocus experiences. Participants respond to each item with one of six possible frequency responses: *Never*, *1-2 times every 6 months*, *1-2 times per month*, *Once a week*, *2-3 times a week*, and *Daily*. Scores are calculated by summing response values.

ADHD Treatment History Form. The *ADHD treatment history form* contains a list of medications intended to treat ADHD symptoms broken up into four groups: methylphenidate derivatives (Long acting/extended release), methylphenidate derivatives (Short acting/immediate release), amphetamine derivatives (short acting/immediate release), amphetamine derivatives (long acting/extended release), and non-stimulants. Research staff read through the list with participants and recorded the dose, frequency, and dates prescribed for each medication.

Daily Training Session Questionnaires. After each training session, participants completed a state version of the CAARS inattention scale and a medication question to determine which (if any) medications they took in the last 24 hours. The state version of the CAARS inattention scale consisted of the CAARS inattention questions; each question has been rewritten to probe the participants’ experiences with inattention *in the past 24 hours*.

Analysis

To evaluate changes in task-based distraction over training, I conducted a multi-level model analysis on distractor interference (as a proportion of overall RT) with sessions nested within subjects. I included fixed effects of training day, contrasts of each diagnosis and training group (control attention training, control KB training, ADHD attention training), training day medication status (within last 24 hours) and CAARS trait inattention subscale (group mean centered).[9] The model was improved with the addition of a random intercept ($\chi^2 = 25.22$; $p <$ 0.001), which allows participants to vary on baseline performance. The addition of a random slope conditioned on training day did not significantly improve the model ($\chi^2 = 0.08$; $p = 0.96$) and thus was not included. To assess transfer effects, I calculated participants' performance on dependent measures of each transfer task and questionnaire scores. For consistency, I employed the same multi-level model for transfer effects with session nested within subjects, random intercept effect, and fixed effects of training day, group, medication, and inattention score. Using this model, I evaluated effects of daily visual attention training and ADHD diagnosis on transfer effects for each task. I analyzed the questionnaires using this model without the CAARS inattention subscale and medication status as fixed effects. I employed a *Bonferroni*-corrected adjustment for the eight transfer task analyses (*p-value* = 0.00625) and five questionnaire analyses (*p-value* = 0.01) to determine significance. Results from the multi-level models are reported with coefficient beta values, standard error values, t-values, degrees of freedom, p values, and 95% confidence intervals (CI; Bates, Machler, Bolker, & Walker, 2015).

Results

Training Task

There were two significant effects of training task distractor interference. First, there was a significant main effect of time ($b = -0.020$, se = 0.002, $t(229.8) = -12.83$, $p < 0.001$, 95% CI [-0.03, -0.02]) such that, on average, distraction for all participants reduced over the course of the

[9] Medication was included as a fixed effect in the task analyses because past research has shown that ADHD medication intake generally improves task performance (Baal, Abagis, & Jonides, n.d.; Weyandt, Oster, Gudmundsdottir, DuPaul, & Anastopoulos, 2017). CAARS inattention score was included as a fixed effect in the task analyses in an attempt to control for the varying effect daily changes in inattention scores may have on performance of the visual attention training task.

study. Second, there was an interaction of time by training group (*b* = -0.005, se = 0.002, t(226.4) = -2.46, *p* = 0.014, 95% CI [-0.01, -0.001]) such that participants who completed the attention training had a larger reduction in RT distraction from pre-training to post-training than participants who completed the control KB training (Figure 4.2). No other effects or interactions were significant.

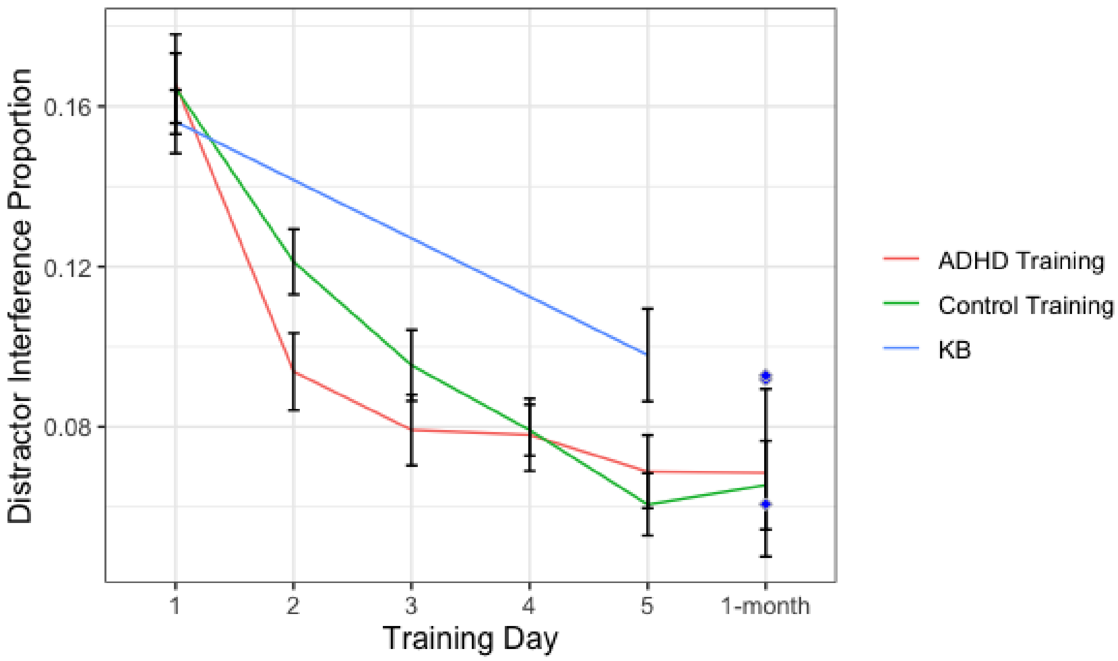

Figure 4.2. Changes in training task distractor interference RT.

Transfer Tasks

Arrow Flanker Task. The dependent measure for the arrow flanker task was the congruency effect: incongruent distractor RT minus congruent distractor RT. There was one near-significant effect: a main effect of ADHD (b = -3.68, se = 1.66, t(67.2) = -2.21, p = 0.030, 95% CI [-6.88, -0.53]) such that the ADHD group had overall smaller congruency effects than the control groups (Figure 4.3). No other effects or interactions were significant.

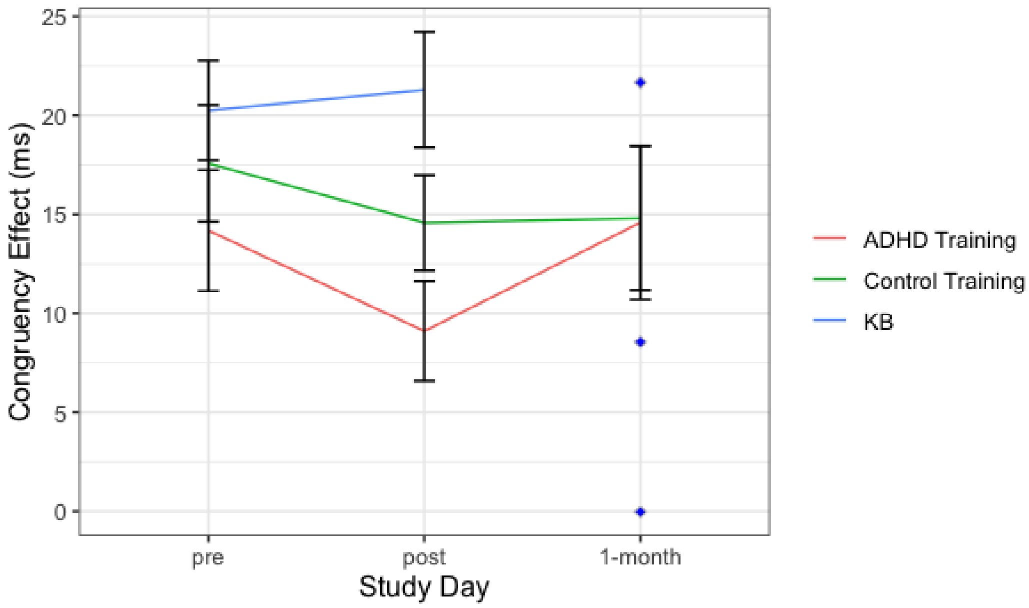

Figure 4.3. Changes in arrow flanker task congruency effect (RT).

UFOV Task. The dependent measure for the UFOV task was the error rate of the peripheral response when the center response was correct. Essentially, this ensures that the peripheral response was truly peripheral as the participant had to be fixation on the center item to correctly identify it. This task proved to be quite difficult for participants; there were 42 sessions in which a participant had an error rate higher than 25%. I removed these data points in order to capture sessions in which the participant was able to completely follow the task.

There was one significant effect: a main effect of training condition (b = 0.027, se = 0.008, t(75.1) = -0.97, p = 0.001, 95% CI [0.012, 0.043]) such that participants who received the attention training had a higher average error rate (Figure 4.4). Apparently, the control participants who received the attention training had the highest error rate out of the three groups. No other effects or interactions were significant.

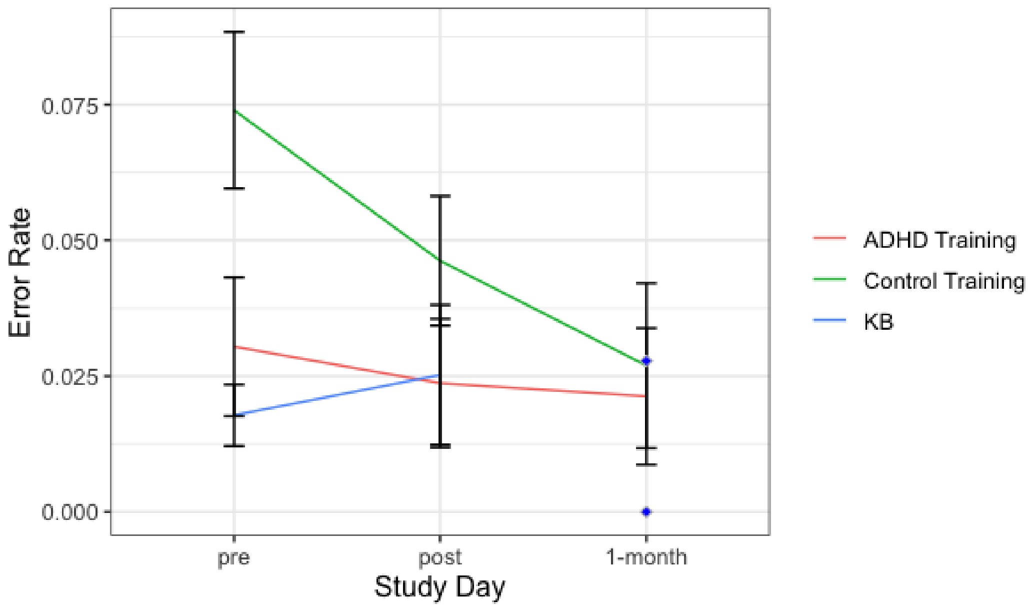

Figure 4.4. Changes in UFOV task error rate.

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Response Competition Perceptual Load Task. The dependent measure for the response competition perceptual load task was the congruency effect: incongruent distractor RT minus congruent distractor RT. The model included the same effects as the training model as well as an additional fixed effect of perceptual load (high, low).

There was one significant effect of perceptual load (b = -15.58, se = 1.98, t(344.2) = -7.85, p < 0.001, 95% CI [-19.43, -11.74]) such that distractor interference was higher for low, as opposed to high, perceptual load (consistent with the perceptual load literature; cf. Lavie, 1995; Lavie & Tsal, 1994). No other effects or interactions were significant (Figure 4.5).

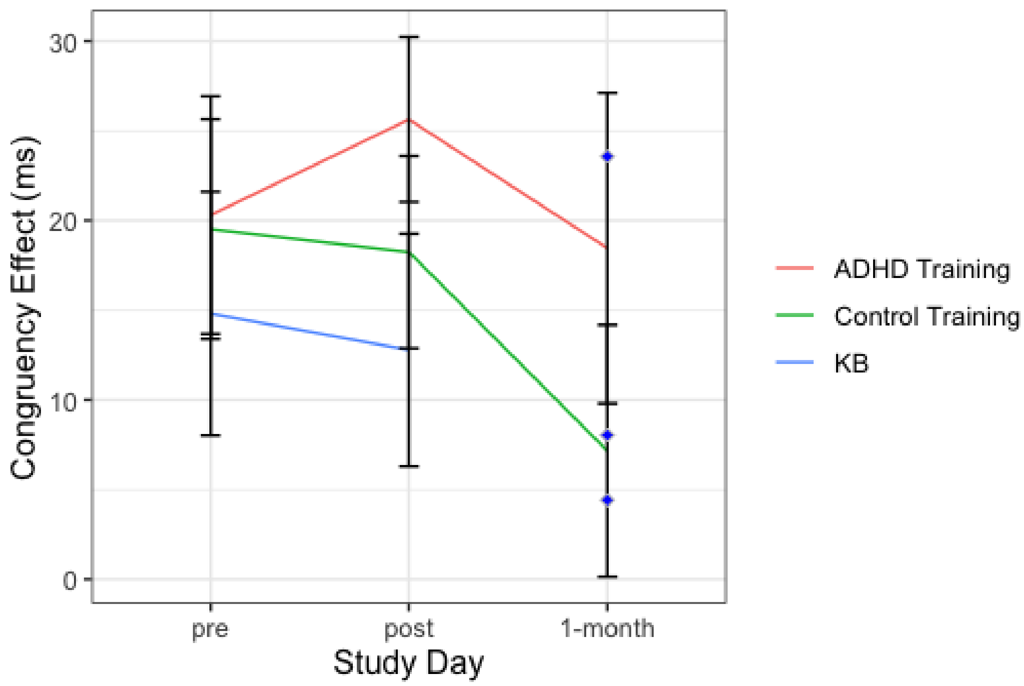

Figure 4.5. Changes in response-competition perceptual load task congruency effect (RT).

Perceptual Distraction Perceptual Load Task. The dependent measure for the perceptual distraction perceptual load task was distractor interference: distractor present RT minus distractor absent RT. The model was the same as that of the response competition perceptual load task.

There was one near-significant effect. First, there was a near-significant effect of time such that all participants reduced their distraction with time (*b* = -18.90, se = 7.85, t(170.8) = -2.41, *p* = 0.01, 95% CI [-33.81, -4.03]; Figure 4.6). No other effects or interactions were significant.

Though not significant (*b* = 10.62, se = 9.85, t(171.42) = 1.74, *p* = 0.28, 95% CI[-8.08, 29.28]), there visually appears to be a small interaction of time by training group between the first two study days as predicted: both attention training groups (ADHD = 58 ms; control M = 36 ms) reduced distractor interference from pre- to post-training at rates larger than the control KB group (M = 17 ms). Considering this is also the most likely "near-transfer" task, I pursued this further by conducting independent sample t-tests on reduction in distractor interference (pre-training minus post-training) between each pair. The ADHD group had a higher reduction in distraction as compared to the KB group (t(40.7) = 2.40, p = 0.02), but not as compared to the control attention training group (t(37.7) = 1.43, p = 0.16). The KB group and control attention training groups were not significantly different (t(40.5) = 1.28, p = 0.21).

As a further check of the relationship between these two measures of distraction, I investigated whether training and transfer distractor interference levels were correlated. Surprisingly, there was no significant correlation between training task distractor interference and distractor interference during this transfer task (r(143) = 0.047, p = 0.58).

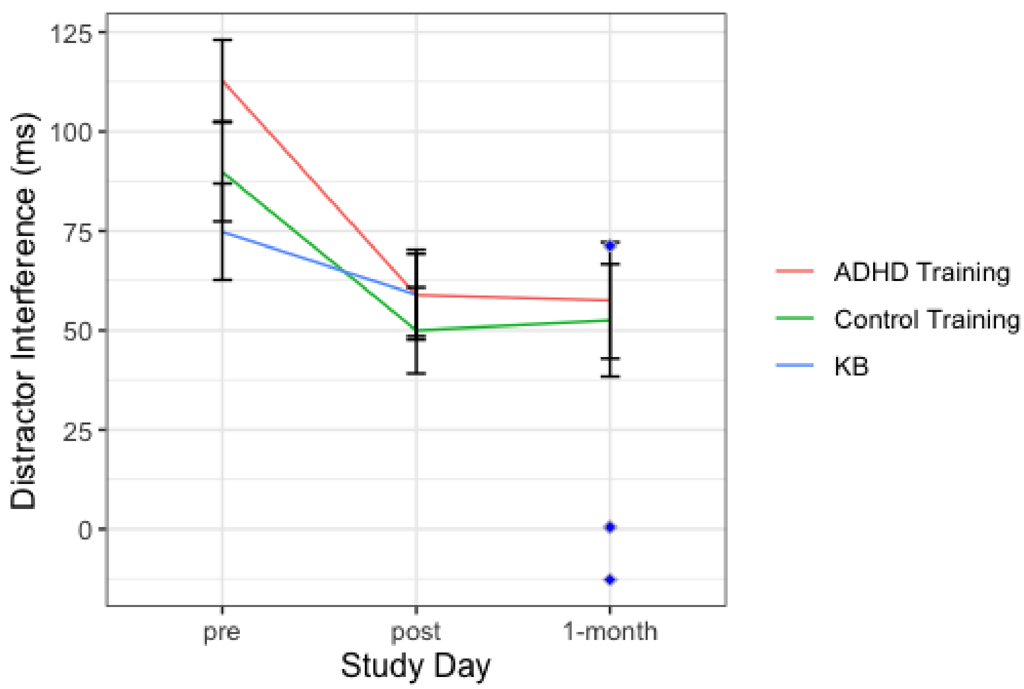

Figure 4.6. Changes in perceptual load task perceptual distractor interference (RT).

SART. I analyzed four dependent measures for the SART: non-target RT, commission ER, omission ER, and post-commission error RT. There were no significant effects of non-target RT or post-commission error RT (p > 0.05).

There was one significant effect of omission ER: a main effect of training condition (b = -0.006, se = 0.002, t(59.8) = 3.13, p = 0.002, 95% CI [0.002, 0.009]) such that the attention training group had a larger overall omission ER than the KB group (Figure 4.7). There was one near-significant effect of commission ER: an interaction of time by ADHD group (b = -0.0042, se = 0.0022, t(22.7) = -2.71, p = 0.007, 95% CI [-0.006, -0.001]) such that ADHD participants displayed a larger reduction in commission ER over time than control participants (Figure 4.8). No other effects or interactions were significant.

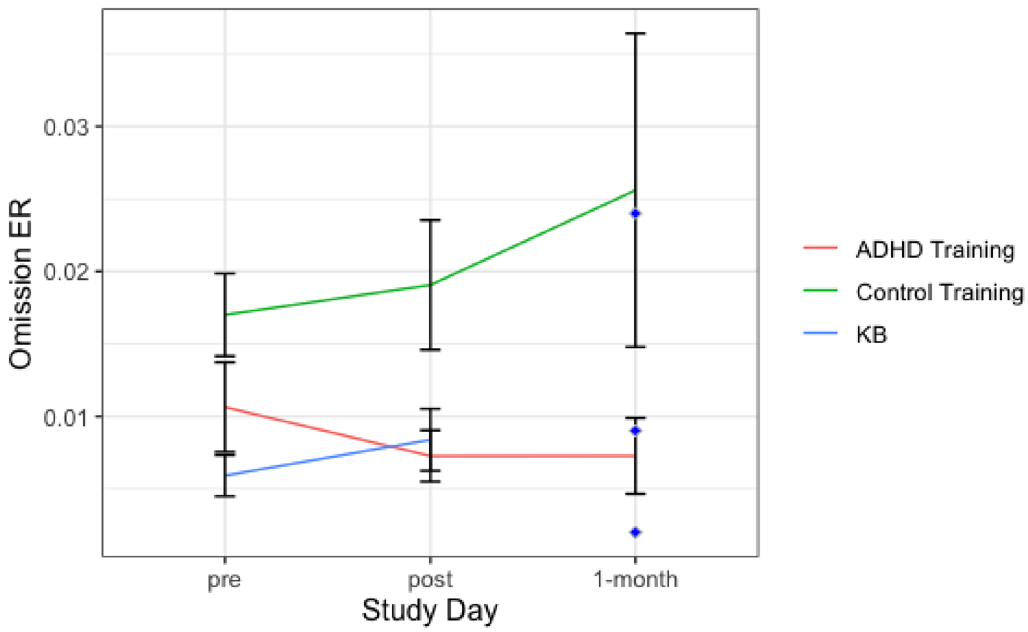

Figure 4.7. Changes in SART omission ER.

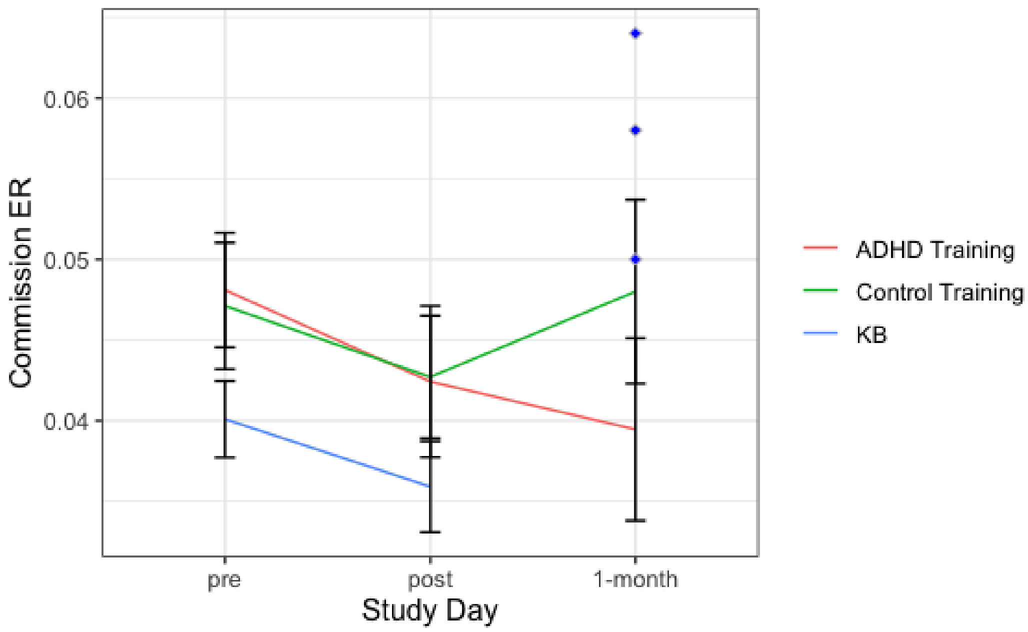

Figure 4.8. Changes in SART commission ER.

Questionnaires

All questionnaire analyses showed a significant main effect of ADHD such that participants with ADHD had significantly higher ADHD symptomology (*p*s < 0.001). The AHQ showed a main effect of time on HF disposition such that all participants experienced a reduction in dispositional HF from the pre-training to follow-up session (*b* = -9.19, se = 3.09, t(21.9) = -2.97, *p* = 0.003, 95% CI [-15.12, -3.27]). The CFQ showed: 1) an interaction of time by ADHD such that ADHD participants had a larger reduction in CFQ score than controls (*b* = -2.60, se = 0.98, t(27.3) = -2.65, *p* = 0.008, 95% CI [-4.48, -0.72]) and 2) an interaction of time by training group such that the attention training participants had a larger reduction in CFQ score than the KB control training group (*b* = -7.27, se = 2.13, t(27.9) = -3.41, *p* < 0.001, 95% CI [-11.36, -3.19]; Figure 4.10). Though potentially informative, the critical KB group has just three participants at the follow-up time point and the average score counterintuitively *increases* at the follow-up; this finding is likely to change with data collection.[10]

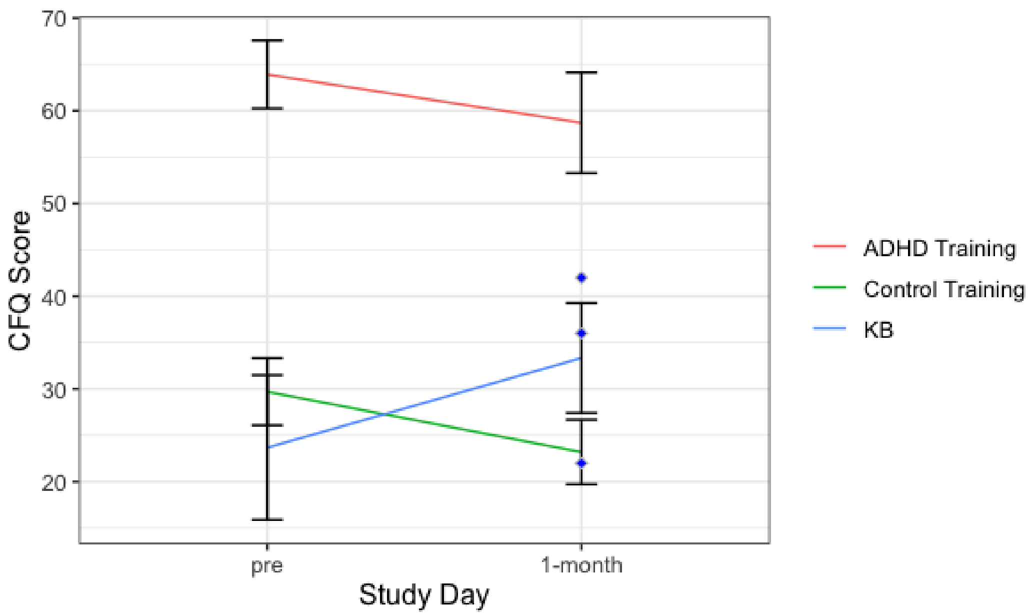

Figure 4.9. Changes in CFQ score.

Discussion

The present study revealed two key results. First, all participants experienced reduced task distraction with increased exposure to the task, though participants who received the training showed a reduction in distraction above that of the control KB training group. Reduced distraction persisted until the 1-month follow-up for all groups. Second, there was one near-transfer effect to a similar visual search task involving perceptual distraction which may be attributable to the attention training intervention.

[10] If data collection shows that KB participants' CFQ scores reduce as much as the attention training participants' scores, then there will be no transfer to this questionnaire. Though, if the collection of KB follow-ups shows that their CFQ score stays roughly the same while the attention training follow-ups show improved CFQ scores, this may mean that cognitive training to address ADHD symptoms could improve self-reported real-world experiences of cognitive failures. Given the good test-retest reliability of the CFQ, this seems possible (Broadbent et al., 1982). Notably, there have been other training studies in the past that have found improvement in cognitive failure reporting in young adults with ADHD (Gropper et al., 2014) concurrent with the completion of a cognitive training task. Though these transfer findings are inconsistent (Cortese et al., 2015; Egeland, Aarlien, & Saunes, 2013).

Task Exposure Reduces Distraction in All Participants

The groups that received the attention training task improved on that task above and beyond the group that received the KB control training task. Interestingly, the control training participants still improved on the attention training task when they took it on day five versus day one of their participation (Figure 4.2). In fact, they improved roughly as much as the attention training groups improved between days one and two, suggesting the interval between training days can vary and participants will still receive comparable benefits from repeating the task. This improvement lasted into the one-month follow-up session for the control training group.

The ADHD attention training participants performed at roughly the same level as the control attention training participants. This is contrary to our findings in Study 1, which showed that participants with ADHD experienced slower RTs than control participants when a distractor was present, but not when a distractor was absent. In order to control for differences in overall RT in this study, I investigated the distraction proportion of overall RT, still finding no difference between the groups.

There are a couple of potential reasons why control and ADHD participants in this study performed so similarly. It is possible that ADHD participants were more motivated in their training task engagement because they experience negative consequences from the heightened distractibility often intertwined with ADHD. Past research has found that motivation can have a significant effect on cognitive training task performance (Katz et al., 2017), potentially explaining the similar baseline performance between the ADHD and control groups. The battery of ADHD symptomology questionnaires before the training week also may have inadvertently primed ADHD participants to work harder to reduce task distraction. Additionally, all participants were collected from the University of Michigan area and were largely made up of undergraduate and graduate students, who are likely to be higher performing and may have higher baseline distractor suppression abilities than the general population, leading again to this similarity between ADHD and control groups.

Limited (and Inconclusive) Evidence of Near Transfer

Though there were no significant transfer effects, pairwise comparisons showed that ADHD participants who received the attention training may have experienced transfer to a similar attention task over and above the KB training group. This transfer task, a singleton distractor visual search task, requires participants to search for a target item while ignoring an infrequently presented irrelevant distractor (Forster & Lavie, 2008). One might wonder why the control participants who received the attention training did not improve more than the control participants who received KB training. This may be due to the fact that the control attention training and KB groups had similar — already fairly low — levels of distractor interference at the first session. The control participants who received the attention training, then, did not have as much room for improvement as the ADHD participants. Because the ADHD participants displayed the most distractor interference at the pre-training session, they then appeared to benefit from the training task more than the other control groups. Therefore, it may be the case that participants with attention deficits are more likely to experience transfer from the training task because they begin with more interference. However, it is important to note that there was no significant correlation between the distractor interference during the training task and during the perceptual distractor transfer task. If there is a strong relationship between performance on these two tasks, we would expect to see a positive correlation. This, then, calls the legitimacy of this transfer effect into question. There were no other likely transfer task effects.

These results contribute findings from the growing collection of studies which have found null transfer effects of training (Chooi & Thompson, 2012; Redick et al., 2013; Thompson et al., 2013) and counter the similarly developing collection of studies which have found transfer effects of cognitive training to closely related processes and even to far-transfer processes such as fluid intelligence (Jaeggi et al., 2008; Jaeggi, Buschkuehl, Shah, & Jonides, 2014). To determine that there is genuine transfer from the attention training task to other similar tasks, I expected that participants who received the attention training task would improve their task performance between sessions as compared to participants who received the control KB training task (in other words, an interaction of training group by time). This particular finding did not occur with any of the other transfer tasks.

There are a few potential methodological explanations as to why this task failed to display significant near- or far-transfer task effects. First, it is possible that the attention training task was too simple for participants to develop a strong performance strategy which might transfer to similar tasks. Studies employing adaptive working memory training tasks have had marginal success in finding transfer, so this training may benefit from incremental increases in difficulty throughout the task period (Katz et al., 2017; Zhao et al., 2018). Second, the task may need to be conducted over more than five consecutive days to display durable transfer effects. For example, some studies have employed up to 20 daily sessions of cognitive training (Jaeggi et al., 2008; Rudebeck et al., 2012). Third, it is possible that this attention training task does not have proper ecological validity to generalize to other tasks. Studies investigating more ecologically valid versions of this task or different tasks for cognitive training of perceptual distraction may be more successful in finding transfer effects.

Limitations of the Study

There are several limitations to this study. First, due to practical scheduling reasons, I did not recruit a group of ADHD participants who received the control training task each day of participation. This would have provided me with a baseline expected improvement for the ADHD group. It may be sufficient to indirectly draw conclusions from the three groups in the current study. Essentially, if there were 1) no differences in transfer task improvement between the control participant attention and control training groups and 2) no differences between the attention training control and ADHD participant groups, I would expect that there would be no differences between ADHD attention and control training groups. However, it is possible that there are ADHD-specific transfer effects missed such that ADHD participants who receive the control training may not improve as much on the transfer tasks relative to the ADHD participants who receive the attention training. Second, there has been a fairly high attrition rate with approximately 40% of participants returning for the one-month follow-up session after the full week of training. This impedes analyses to assess durability of the effect as it severely reduces power and thus increases the likelihood of a false negative effect. Any conclusions derived from the follow-up questionnaires and transfer tasks need to be interpreted with this in mind.

Conclusion

Ultimately, this study failed to find any conclusive evidence that the color singleton task (Theeuwes, 1991) would be an appropriate method to reduce the heightened perceptual distraction so often associated with adult ADHD. There was significant improvement over the course of training for all groups, suggesting that the chosen task may be an appropriate method to investigate cognitive mechanisms underlying changes in distractor suppression over time or differences in distraction between groups (as supported by Studies 1 and 2). Additionally, the groups that received the attention training improved more on that task than the group that received the control training. However, there was just one potential transfer effect: a near-transfer effect to a similar task with visual distraction. These findings are limited by the small number of follow-up sessions with those who received the control training. Thus, this task is unlikely to be a strong enough method to actually improve visual distractibility in the real world, though I will continue to pursue data collection to complete this dataset. Future work might benefit from a few extensions such as increasing the task difficulty adaptively throughout training, changing some components of the task to make it more ecologically valid, or lengthening the amount of task exposure participants receive.

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Chapter 5 — General Discussion and Conclusions

Summary of Findings

This dissertation addressed two main aims: 1) to investigate effects of both external and internal distractions on visual attention task performance in adults with ADHD and 2) to evaluate the potential cognitive training application of the same visual attention task to reduce the negative performance effects attributable to heightened distraction in adults with ADHD. The first two studies presented here addressed aim one. Taken together, they found ADHD (vs control) participants experienced: 1) poorer task performance due to external perceptual distraction; 2) a target selection deficit which worsened when unintentionally mind-wandering; and 3) higher in-task rates of performance-based thoughts.

Study 1 established a task (Theeuwes, 1991) that successfully captured differences in task performance due to an irrelevant distractor in current and recent trials between ADHD and control participants. Though this seems simple, some groups have not been able to successfully find task-based deficits in distraction in adults with ADHD (Huang-Pollock, Nigg, & Carr, 2005). Additionally, the finding that participants with ADHD initially performed worse than control participants and were able to reduce their task-based distraction with task exposure suggests that participants with ADHD require additional exposure to a task in order to optimize performance. Future studies will likely benefit from also considering both time and previous-trial distractor presence as factors to investigate how ADHD participants adapt to distraction during a cognitive task.

Study 2 employed virtually the same task as Study 1 with concurrent eye-tracking and mind-wandering probes to isolate external and internal attention allocation in adults with and without ADHD. Interestingly, eye-tracking data suggest that participants with ADHD experienced a target selection deficit during the task and that they were *not* experiencing poorer distractor suppression, as one might expect. When unintentionally mind-wandering, target selection in participants with ADHD was affected negatively by the presence of a distractor. Rather than displaying increased capture by the distractor, these participants displayed higher rates of initial fixation on nontarget items; meaning they further struggled with effective target selection. This finding is in line with the theory that ADHD involves poor regulation and explicit control of attention. It also suggests that worsened visual search performance may not be specifically related to deficits suppressing distractor information. It may, instead, be that individuals with ADHD cannot allocate attention as easily and accurately to the vital target, potentially due to the presence of (but not necessarily capture attributable to) distracting information.

Study 2 also found that participants with ADHD had higher rates of performance-based thoughts than control participants. This may be related to the findings that adults with ADHD have high comorbidity with anxiety and depression (Kessler et al., 2006), and score higher on hyperfocus scales (Hupfeld, Abagis, & Shah, 2018; Ozel-Kizil et al., 2016), all of which are associated with obsessive and perseverative thoughts. Future studies investigating mind-wandering in ADHD should employ scales to address these types of thoughts and to evaluate whether higher rates of obsessive and/or perseverative thinking are associated with more performance-based thoughts.

Study 3 addressed aim two and found that completion of the attention training task did result in improved training task performance in both control and ADHD participants above and beyond that in a control training group. Given that the training task involves the incorporation of a salient, irrelevant distractor during visual search, I had expected to find transfer to a similar task popular in the perceptual load literature (Forster & Lavie, 2008). Though transfer was not statistically significant in my model, a pairwise comparison showed that the participants who received the attention training may have reduced their distraction more than the participants who received the control training. Thus, it is not yet clear whether there are significant transfer effects or that this is a strong intervention option for adults with ADHD, but it remains a possibility and will be pursued as data collection is completed.

Limitations

The study samples for the three reported studies pose a limitation to the generalizability of results. Participants were mostly undergraduate and graduate students at the University of Michigan, and therefore are likely to have a high socio-economic status and be well-educated. These traits may mean that our participants (particularly the ADHD participants) start at a fairly high-performance baseline compared to the general public. In order to be successful in this environment, it is likely that our ADHD participants have developed methods to compensate for the adverse effects of ADHD symptomology, setting them further apart from the average adult ADHD population. Therefore, recruiting a more representative sample would provide findings which may be more generalizable.

Future Directions

Future work should be pursued to build on the findings of heightened visual distraction in adults with ADHD. Several past studies have produced mixed results in pinpointing this task-based distractibility in ADHD (Huang-Pollock et al., 2005); the task employed in this dissertation could be used to better isolate it. It might be worthwhile to administer this task in a more representative sample of adults with ADHD. Since the participants who completed the present studies were all likely high-functioning, young adults, it is possible that they do not display attention deficits as severe as the general population of adults with ADHD. Thus, work with a more representative sample may find larger effects of ADHD on task performance.

Preliminary work from our lab has also found that ADHD participants who were taking medications performed better at this task than ADHD participants off of medications (Baal, Abagis, & Jonides, n.d.). Likely because there were so few participants with ADHD who were not taking stimulant medications, this was not found in the present dissertation. Stimulant medication will be an important variable to manipulate in future studies, ideally by employing a crossover design with stimulant medication wash-out periods of approximately 48 hours.

Finally, future work should further pursue the value of the task as a cognitive training paradigm. More demanding and/or ecologically valid versions of the task may prove to be more effective at encouraging transfer effects to other attention tasks and ADHD symptomology questionnaires. A strong cognitive intervention for ADHD will prove useful as a non-psychopharmacological method to address adverse effects of ADHD in these individuals' everyday lives.

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