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ADHD Reflects Impaired Externally Directed and Enhanced Internally Directed Attention in the Immediate Free-Recall Task

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Previous attempts to understand the neurocognitive mechanisms underlying attention-deficit/hyperactivity disorder (ADHD) may be limited by the tendency to focus exclusively on "externally directed cognition" (EDC) while ignoring "internally directed cognition" (IDC; Dixon, Fox, & Christoff, 2014. There is clear evidence that ADHD reflects deficiencies in EDC because of weaknesses in modulatory, motivational, and cognitive control constructs, but little is currently known about the integrity of IDC in ADHD. In the present study, we used a verbal episodic memory task involving immediate free recall to assess the integrity of EDC and IDC in a sample of 111 adolescents, 50 with study-confirmed diagnoses of ADHD and 61 without. The ADHD group was found to have significantly worse scores on outcomes that depend on EDC during encoding (serial position), and significantly better scores on outcomes that depend on IDC during retrieval (lag-conditional response probabilities). In addition, model parameters estimating the contribution of EDC and IDC processes were fit to these data using the retrieved context model of memory search. The model suggested that, during encoding, the ADHD group had slower mental context drift, indicative of weaker externally directed attention to the list items, as well as deficiencies in their ability to allocate and sustain attention when the study list first appeared. During retrieval, in contrast, the model suggested that the ADHD group had faster mental context drift indicative of stronger internally directed attention to retrieved context. These findings provide novel evidence that ADHD reflects impaired EDC and enhanced IDC, and they reinforce the clinical relevance of distinguishing EDC and IDC in future studies.

General Scientific Summary
Individuals can direct their attention to objects and events in the external world or to thoughts, feelings and memories in their "internal" world. The present study distinguished between these two types of attention and showed that individuals with ADHD performed significantly worse than age-matched controls when the task required them to attend to stimuli in the external world, but these same individuals performed significantly better when the task required them to attend to memories retrieved from their internal world.

Keywords: ADHD, verbal immediate free recall, retrieved context model, externally directed cognition, internally directed cognition

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Attention-deficit/hyperactivity disorder (ADHD) is a prevalent neurodevelopmental disorder in children that is characterized by a constellation of inattentive, hyperactive, and impulsive behaviors (Nigg & Barkley, 2014). Attempts to reveal the deficient neurocognitive mechanisms underlying ADHD (and other forms of psychopathology) have been guided by cognitive taxonomies, such

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as the one proposed by the National Institute of Mental Health's (NIMH) research-domain criteria (RDoC; Clark, Cuthbert, Lewis-Fernandez, Narrow, & Reed, 2017), that seek to show how patterns of maladaptive behavior arise from specific constructs within distinct domains of functioning. Such efforts have been interpreted to suggest that ADHD may not arise from a core deficit in a single construct (Sonuga-Barke, Bitsakou, & Thompson, 2010); rather, ADHD may be a heterogeneous disorder that reflects deficiencies in a variety of different constructs, including Alerting (Sergeant, Oosterlaan, & van der Meere, 1999), Reward Response (Sonuga-Barke, 2005), and Working Memory (WM; Kasper, Alderson, & Hudec, 2012), that are distributed across correspondingly distinct systems of functioning (e.g., arousal/modulatory, positive valence, and cognitive systems, respectively).

The utility of NIMH's RDoC taxonomy for understanding ADHD remains to be determined. However, there is increasing recognition within the contemporary cognitive neuroscience community that traditional taxonomies may be limited by their tendency to focus exclusively on "externally directed cognition" (EDC) while ignoring "internally directed cognition" (IDC).

> EDC involves attention directed externally (i.e., "outside of the head or body") to stimuli present in the external world [whereas] IDC involves attention directed internally (i.e., "inside the head or body") to thoughts and other information that has been previously stored in long-term or working memory (Dixon, Fox, & Christoff, 2014 p. 322).

Within the context of this more inclusive taxonomy, there is clear evidence that ADHD reflects deficiencies in EDC as a result of the previously mentioned weaknesses in modulatory, motivational, and cognitive control constructs, but little is currently known about the extent to which IDC is also impaired in ADHD. In fact, there is some evidence that individuals with ADHD may perform poorly on EDC tasks because they are too focused internally (Van den Driessche et al., 2017), perhaps suggesting that ADHD reflects a tendency for IDC to interfere with EDC (Sonuga-Barke & Castellanos, 2007). However, EDC and IDC need not compete for the same resources in all task contexts; rather, optimal performance on some tasks involves coordination between EDC and IDC processes (Dixon et al., 2014). In the present study, we therefore sought to assess the integrity of EDC and IDC in ADHD under conditions in which both forms of attention had the potential to contribute positively to task performance.

EDC, IDC and the Dynamics of Memory Search

The immediate free-recall (IFR) task is a valid and often used episodic memory task (Rabin, Barr, & Burton, 2005) that may serve as a model for understanding coordination between EDC and IDC. In this task, a list of unrelated words (12 words in the current study) is presented one at a time, after which participants attempt to recall as many of the items as possible. In general, attention is directed externally to the words during the initial encoding phase of the IFR task, whereas, it is directed internally to searching memory during the ensuing retrieval phase. The influence of these factors can be determined by examining outcome measures that reflect which items are successfully encoded and recalled (EDC), and the order in which they come to mind (IDC).

The extent to which study-list items are encoded and recalled is reflected in the "serial position curve" (SPC) which indicates the proportion of items correctly recalled as a function of study-list position. The SPC for IFR typically shows a strong recency effect and a weaker primacy effect (Murdock, 1962). That is, accuracy is typically found to be highest for the last few items in the list and slightly lower for the first few items in the list, but lowest of all for the middle portion of the curve. As is discussed below, the relative magnitude of the primacy effect can be interpreted as a marker of EDC, as it reflects the extent to which participants attend to externally presented stimuli (Howard & Kahana, 1999; Sederberg, Howard, & Kahana, 2008).

Another measure of which items are successfully encoded and recalled is the "probability of first recall" (PFR). This outcome is similar to the SPC except that it reflects only the *first* recall response on each trial. Because this outcome focuses on the first recall response, it also reflects the order in which items come to mind, thus providing potential information about how participants direct attention inward to search memory. However, as is discussed below, the probability of first recall is not a straightforward measure of IDC because the first recall response is influenced by the encoding of context, which is interpreted to reflect EDC, at least in part. Furthermore, although most individuals naturally tend to begin recall from the end of the study list (Healey & Kahana, 2014), many studies (including those reported in this article) have selected or explicitly instructed participants on the basis of a particular "recall initiation strategy" to ensure that individuals were using the same recall strategy (see, e.g., Craik & Birtwistle, 1971).

A purer measure of how individuals direct attention inward is provided by the "lag-conditional response probability" (lag-CRP) function (Kahana, 1996), which indicates the probability of recalling an item as a function of its study-list position (or lag) relative to the just-recalled item. The typical lag-CRP function shows two important effects: a contiguity effect and a forward temporal asymmetry effect. The contiguity effect reflects a higher probability of recalling an item whose study-list position was adjacent to the just-recalled item, whereas the forward temporal asymmetry effect reflects a higher probability of recalling an adjacent item whose study-list position occurred after the just-recalled item. As is discussed below, the relative magnitude of the forward temporal asymmetry effect can be interpreted as a marker of IDC because it reflects the extent to which participants successfully reinstate the internal mental context of the study period.

The PFR, SPC, and lag-CRP have all been important for understanding the nature of group differences in episodic memory for verbal material across a number of grouping dimensions, including Age (Kahana, Howard, Zaromb, & Wingfield, 2002; Wahlheim & Huff, 2015), WM Capacity (Spillers & Unsworth, 2011), Trait Anxiety (Pajkossy, Keresztes, & Racsmány, 2017), and Psychosis Status (Murty, McKinney, DuBrow, Jalbrzikowski, Haas, & Luna, 2018; Polyn, McCluey, Morton, Woolard, Luksik, & Heckers, 2015). In these studies, the older Age, lower WM-Capacity, higher Trait-Anxiety, and Psychosis-present groups all showed a reduction in recall accuracy across the SPC that was matched by a reduction in the lag-CRP effects. Hence, these previous studies have suggested that impaired EDC tends to coexist with impaired IDC in verbal IFR tasks.

Previous studies that have compared individuals with and without ADHD on a verbal IFR task have shown that the ADHD group achieved a lower proportion of correct scores across most serial positions, though this group difference was largest across the primacy items (Gibson, Gondoli, Flies, Dobrzenski, & Unsworth, 2010; Gibson, Gondoli, Ralph, & Sztybel, 2018). In addition, the two groups were either selected or explicitly instructed to use the same recall-initiation strategy, and thus they did not differ significantly on the PFR. The substantially lower proportion of correct scores observed across the first few items of the SPC can be interpreted to reflect weaker EDC. However, the lag-CRP was not assessed in these previous studies, and thus, the integrity of IDC in ADHD has not yet been determined. There is some reason to expect that the lag-CRP functions may be intact in ADHD, as a recent meta-analysis has concluded that individuals with ADHD may reflect a larger encoding than retrieval deficit, based on a pattern of findings showing a similar magnitude of impairment across recall (i.e., encoding plus retrieval) and recognition (i.e., encoding only) tasks (Skodzik, Holling, & Pedersen, 2017).

These three outcome measures, the SPC, the PFR, and the lag-CRP, reflect the influence of both EDC and IDC, as well as a variety of memory-specific processes. Although they are useful by themselves, they are even more useful when combined with a computational model of the encoding and retrieval processes. Fitting such models to free recall performance has allowed researchers to disentangle these processes and separately estimate the influence of each (Healey & Kahana, 2016). Here we used a retrieved-context model (RCM) of memory search.

RCM

RCMs are a family of models that assume that new events become associated with the current state of a continually drifting mental context representation, and that when an event is recalled, it retrieves, or reinstates, its associated mental context (Healey & Kahana, 2016; Howard & Kahana, 2002; Lohnas, Polyn, & Kahana, 2015; Polyn, Norman, & Kahana, 2009; Sederberg et al., 2008). Like many theories of episodic memory (Bower, 1967; Estes, 1955; Tulving, 1972), RCMs assume that successfully searching memory for a particular item depends on the similarity between the mental context at the time of memory search and the mental context that prevailed at the time of its encoding. Critically, under RCMs, changes in the state of mental context are not random, but are driven by both external events (e.g., stimuli presentation) and internal events (e.g., recalling an item; Howard & Kahana, 2002). We will illustrate how the model operates by walking through a free-recall trial.

Studying the first word of a list, “apple,” may elicit a variety of mental associations such as fruit, trips to the grocery store, or favorite varieties that constitute an apple in mental context. Critically, this apple context lingers when the next item, “dog” is presented, allowing a new episodic association to form between “dog” and the apple context. Therefore, apple can now serve as a retrieval cue for dog. Moreover, the apple context remains active even as dog activates its own mental context, such that the overall mental context is a blend of apple and dog. This blended context then becomes associated with the third list item. In this way, each new list item becomes associated with a recency-weighted representation of previous items’ mental contexts. These new item–context associations are important because context is used to cue the retrieval of items during recall. Successfully recalling apple will reinstate its context, which can then serve as a cue for any list items that had become associated with that context.

The model includes eight free parameters that can be divided into four parameter sets, which we called EDC, IDC, learning, and stopping (see the online supplemental materials for a formal description of the model).

Under the model, the EDC parameter set influences the rate at which mental context drifts during the encoding phase, as well as the extent to which new episodic associations are formed between items and mental context. The β_{enc} parameter controls how rapidly mental context drifts during study, which in our example, was the extent to which the apple context would persist along with the dog context elicited by the subsequent word dog. Lower values of β_{enc} reflect slower drift and longer persistence of prior context, whereas higher values reflect faster drift. If EDC is strong and participants are intently focusing on the externally presented stimuli and not devoting attention to the internal representations of previous items, context will drift rapidly. If EDC is weaker, and external stimuli are processed less extensively, internal representations of past list items will remain active for longer. Hence, although we have interpreted the value of β_{enc} as primarily reflecting the strength of EDC, it may actually reflect a more complex interaction between EDC to the study list items and IDC to the corresponding activated representations stored in memory. Indeed, existing evidence suggests that successful encoding and recall are often associated with neural markers of reduced internal attention to stored memories during encoding (Cabeza, 2008). Regardless, the mental context active at the end of the encoding period serves to cue the first recall; consequently, the drift rate during encoding (β_{enc}) is critical to the PFR. Therefore, the PFR was thought to measure EDC more than IDC.

The EDC parameter set also assumes that attention devoted to forming new episodic associations between items and mental context decays exponentially across a study episode, such that early items are better encoded than later items. This is consistent with the notion that primacy results from a decrease in the efficacy of encoding processes across a study episode (Serruya, Sederberg, & Kahana, 2014). One parameter, ϕ_s, controls the initial level of attention, and the second parameter, ϕ_d, serves as a negative exponent that controls the rate at which attention decays. Weak EDC may reflect less initial attention and/or more rapid decay of attention and result in a smaller primacy effect.

Thus, encoding is heavily dependent on the EDC parameter set to process stimuli. By contrast, the IDC parameter set is critical during memory search, particularly for shaping mental context to provide an effective retrieval cue. The parameter β_{rec} operates during recall to determine the extent to which each successfully recalled item reinstates its mental context. When β_{rec} is high, the context of recalled items dominates the context representation, which provides a good retrieval cue for other items that were presented nearby in time, creating strong contiguity and forward temporal asymmetry effects. When it is low, less of the item’s context is incorporated into the retrieval cue, reducing the two effects. Recalling an item is an internal event, thus β_{rec} can be taken as a measure of IDC focused on reinstating the internal mental context of memories.

In addition to these two parameter sets that map onto EDC and IDC, the model includes two other groups of parameters: one that controls learning rate and one that controls recall-stopping behavior.

The learning parameter set includes a single parameter, γ_{FC}, which sets the baseline efficiency of the process that forms new episodic associations between item features (F) and context (C). Specifically, after each item is presented, that item forms a new association with the current state of mental context via a Hebbian outer product learning rule—this product is weighted by $\gamma_{FC.}$ Larger values of γ_{FC} produce a higher baseline learning rate, lower values produce a lower rate (this baseline is then modulated by the ϕ_s and ϕ_d parameters described above).

The stopping-parameter set simulates the recall-stopping process. After each item is recalled, there is some probability that the model will stop recalling. This probability increases exponentially as more items are recalled, eventually reaching 1. The initial probability of stopping is controlled by θ_s and the rate at which this probability approaches 1 is controlled by θ_r. Higher values of either of these parameters lead the model to stop sooner and therefore recall fewer items overall. Another parameter, τ, controls how likely the item that best matches the current state of context is to be recalled.

Current Study and Predictions

Here we assessed EDC and IDC as a function of diagnostic status (ADHD vs. control) by combining and reanalyzing the verbal IFR results previously reported by Gibson et al. (2010) and Gibson et al. (2018). We fit the RCM to the PFR, SPC, and lag-CRP. If the ADHD group exhibited impaired EDC, we predicted that they would show lower overall recall and a reduced primacy effect, along with differences in the model parameters associated with EDC. If the ADHD group also exhibited impaired IDC, we predicted they would also exhibit a weaker forward temporal asymmetry effect in the lag-CRP and differences in the IDC parameters. However, if the ADHD group exhibited intact IDC, the forward temporal asymmetry effect would be preserved in the ADHD group relative to the control group.

Method

Participants

The data, obtained from Gibson et al.'s (2010) and Gibson et al.'s (2018) study participants, were collected from 111 adolescents between the ages of 10 and 14 ($M = 12.43$ years, $SD = 1.02$ years). Fifty adolescents had study-confirmed presence of ADHD ($M = 12.26$ years, $SD = 1.10$ years; 36 boys) and 61 had study-confirmed absence of ADHD ($M = 12.57$ years, $SD = 0.92$ years; 25 boys). The participants were recruited from three middle schools (Grades 6 to 8) in a midwestern public school district. For both studies, the primary caregiver and student began by providing informed consent and assent, respectively, in a laboratory located in the Psychology Department at the University of Notre Dame. The Institutional Review Board at the University of Notre Dame approved all procedures (protocol title: An Investigation of Cue-Dependent Retrieval in Early Adolescents; Protocol Number 08–056).

Table S1 in the supplemental materials provides a complete list of the behavioral measures and cognitive tasks used in Gibson et al. (2010) and Gibson et al. (2018). In both studies, the presence versus absence of ADHD was based on a structured interview conducted with the primary caregiver—NIMH's Computerized Diagnostic Interview Schedule for Children, Version IV (C-DISC-IV; Shaffer, Fisher, Lucas, Dulcan, & Schwab-Stone, 2000). The C-DISC-IV's default scoring algorithms generated a discrete diagnosis of ADHD (or not) without subtyping. The presence versus absence of oppositional defiant disorder (ODD), generalized anxiety disorder (GAD), and major depressive disorder (MDD) was also examined during the structured interview. In the ADHD group, 20 adolescents had a comorbid diagnosis of ODD, two had GAD, and two had MDD. In contrast, in the control group, one adolescent had a diagnosis of ODD, one had GAD, and none had MDD. The 40% ODD comorbidity rate observed in the ADHD group of the present study is consistent with other estimates suggesting that it occurs in 44%–50% of adolescents with ADHD (Nigg & Barkley, 2014).

The primary caregiver and one teacher also rated each of the 18 ADHD symptoms from the *Diagnostic and Statistical Manual of Mental Disorders* (4th ed.; *DSM–IV*; APA, 1994) on a scale from 0 to 3, where 0 = *never or rarely*, 1 = *sometimes*, 2 = *often*, and 3 = *very often*. On average, parent ratings of the ADHD and control groups were 18.32 ($SD = 6.55$) versus 3.48 ($SD = 4.71$) on the Inattentive dimension, $p < .0001$ and 11.15 ($SD = 6.04$) versus 1.67 ($SD = 2.97$) on the Hyperactive/Impulsive dimension, $p < .0001$. Likewise, teacher ratings of the ADHD and control groups were 12.42 ($SD = 7.45$) versus 2.96 ($SD = 4.00$) on the Inattentive dimension, $p < .0001$ and 5.17 ($SD = 5.01$) versus 1.20 ($SD = 2.60$) on the Hyperactive/Impulsive dimension, $p < .0001$. In addition, the ADHD group had significantly more Inattentive symptoms than Hyperactive/Impulsive symptoms across both raters (both $ps < .0001$). Although these ratings cannot be used to subtype the individuals in the ADHD group, they suggested that the sample consisted of primarily Inattentive and Combined subtypes.

The Wechsler Abbreviated Scale of Intelligence (Wechsler, 1999) was administered to obtain a general measure of cognitive functioning. A full-scale IQ (FSIQ) of 70 or above was required for inclusion in both studies. FSIQ was significantly lower in the ADHD group ($M = 97.64$, $SD = 15.43$) than in the control group ($M = 108.92$, $SD = 12.89$), $p < .0001$.

IFR Tasks

In both studies, parents were instructed to withhold any ADHD medication (stimulant or nonstimulant) for at least 24 hr prior to any cognitive testing. Although both verbal and spatial IFR tasks were administered, the present study focused exclusively on the verbal IFR task because mental context, as defined within the framework of the RCM, refers to the ensemble of semantic, episodic, and affective associations that are elicited by each list item.

In the verbal IFR task, participants were presented with 15 lists of 12 unrelated words. The words ranged in length from four to six letters and were high-frequency based on the Zipf scale (Van Heuven, Mandera, Keuleers, & Brysbaert, 2014). In this scale, word-frequency scores can range from 1 to 7, with scores at or above 4 considered to be high in frequency. The average Zipf score for these 180 words was $M = 5.12$ ($SD = 0.57$, range = 3.84 to

6.76). The words were printed in 20-point font and all words appeared white against the black background of a standard cathode-ray-tube monitor.

The onset of each IFR trial was controlled by the experimenter, who initiated the trial only when the participant indicated readiness verbally. Each word was presented consecutively for 1 s in the middle of the computer screen. Following the presentation of a single list, question marks appeared in the center of the screen, prompting participant response. Participants in Gibson et al.'s (2010) study were told that they could recall the words in any order, and participants in Gibson et al.'s (2018) study were given the same instructions, but with the additional constraint that they should begin recalling words from the end of the list first (though in no particular order). In addition, participants were given 30 s to recall the lists, and they were required to wait the full 30 s before proceeding to the next trial. Participants reported their answers into a microphone connected to a standard cassette recorder. Three practice trials using letter stimuli preceded the test trials. The word lists were presented in the same random order to all subjects. The order and number of correct and incorrect recall responses were recorded for each participant.

Rationale for Restricting Recall Strategy

Inclusion in Gibson et al. (2010) and Gibson et al. (2018) required use of a recency-recall strategy because this strategy enabled a clearer interpretation of the primary outcome measures used in those studies (i.e., the number of items recalled from primary and secondary memory). The present study also enforced this recall-strategy restriction, albeit for a different reason, namely, the RCM was fit to group averages, and we did not want to bias these averages by introducing bimodality to the distribution. We evaluated use of the recency strategy examining PFR and SPCs. For each measure, responses were averaged across the first three primacy positions and across the last three recency positions for each participant. Participants were classified as having used a recency strategy if the difference between the average recency and primacy responses was .10 or greater on at least one measure (see footnote 1 in Unsworth, Brewer, & Spillers, 2011).

Results

The results focused exclusively on the 111 participants (*n* = 50 with ADHD) who used a recency-recall strategy. Overall recall scores were highly consistent across the 15 trials (Cronbach's α = .903) and remained high when they were estimated within each diagnostic group separately (Cronbach's α = .867 for both groups). Note that the present analyses did not distinguish between the 32 participants from Gibson et al. (2010) who spontaneously adopted a recency strategy (*n* = 18 with ADHD) versus the 77 participants from Gibson et al. (2018) who were explicitly instructed to use this strategy (*n* = 32 with ADHD). A more comprehensive examination of recall strategy, including the 28 participants from Gibson et al. (2010) who spontaneously used a nonrecency-recall strategy (*n* = 14 with ADHD), was provided in the online supplemental materials; suffice it to say here that the exclusion of other recall strategies did not limit generalizability because none of the main effects or interactions involving diagnostic group reported below interacted with recall strategy. Likewise, other analyses also failed to show higher-order interactions when gender or ODD comorbidity were included (separately) as factors (all *F*s $\leq$ 1).

Analyses of Retrieval Dynamics

The top row of Figure 1 shows (from left to right) the three measures of retrieval dynamics: PFR, SPC, and lag-CRP for each of the two groups.

PFR was analyzed using a two-way, mixed analysis of variance (ANOVA) with serial position (1 to 12) as the within-subjects variable, and group (ADHD vs. control) as the between-subjects variable. Mauchly's test was used to evaluate the sphericity assumption for all variables with more than two levels in this and all subsequent analyses; when the assumption was violated, *df*s were corrected using Greenhouse–Geisser estimates. There was a significant main effect of serial position, $F(1.51, 164.70) = 545.79$, $p < .0001$, $\eta_p^2 = 0.83$, indicating a strong recency effect, which was expected given that participants were either selected (Gibson et al., 2010) or explicitly instructed (Gibson et al., 2018) to begin their recall toward the end of the list first. We did not report the main effect of group for this measure because the probabilities were constrained to equal 1.00 when they were summed across the 12 serial positions within each group (unless one or more of the first responses was an error, therefore not counted). Although the probability of recalling the 12th item first was numerically lower in the ADHD group ($M = 0.70$, $SE = .04$) than in the control group ($M = 0.77$, $SE = .03$), the Serial Position × Group interaction did not attain significance, $F(1.51, 164.70) = 2.14$, $p = .14$, $\eta_p^2 = 0.02$.

Similarly, the SPC was also analyzed using a two-way, mixed ANOVA with serial position (1 to 12) as the within-subjects variable, and group (ADHD vs. control) as the between-subjects variable. There was a significant main effect of serial position, $F(4.04, 440.66) = 370.67$, $p < .0001$, $\eta_p^2 = 0.77$, indicating a strong recency effect and a weaker primacy effect. There was also a significant main effect of group, $F(1, 109) = 31.83$, $p < .0001$, $\eta_p^2 = 0.23$, indicating that overall accuracy was significantly lower in the ADHD group ($M = 0.29$, $SE = .01$) than in the control group ($M = 0.38$, $SE = .01$). Although this group difference (control–ADHD) was approximately twice as large when averaged over the first four items ($M_{\text{diff}} = 0.12$) relative to the middle four items ($M_{\text{diff}} = 0.06$) and the last four items ($M_{\text{diff}} = 0.08$), the Serial Position × Group interaction did not attain significance, $F(4.04, 440.66) = 1.54$, $p = .19$, $\eta_p^2 = 0.01$.

The lag-CRP function was analyzed using a three-way, mixed ANOVA with lag (1 to 5) and direction (forward vs. backward) as the two within-subjects variables, and with group (ADHD vs. control) as the between-subjects variable. In addition, nine participants (*n* = 6 in the ADHD group and *n* = 3 in the control group) had missing values at one or more of the 10 lag positions and were excluded in this analysis. Note that missing values were not created randomly across either lags or subjects. In general, missing values were more likely for large absolute values of lag and for subjects with overall lower levels of recall.

With respect to the contiguity effect, there was a significant main effect of lag, $F(3.20, 320.10) = 501.28$, $p < .0001$, $\eta_p^2 = 0.83$, indicating that overall lag-CRPs were greater when the study-list position was adjacent to the just-recalled item (*M* =

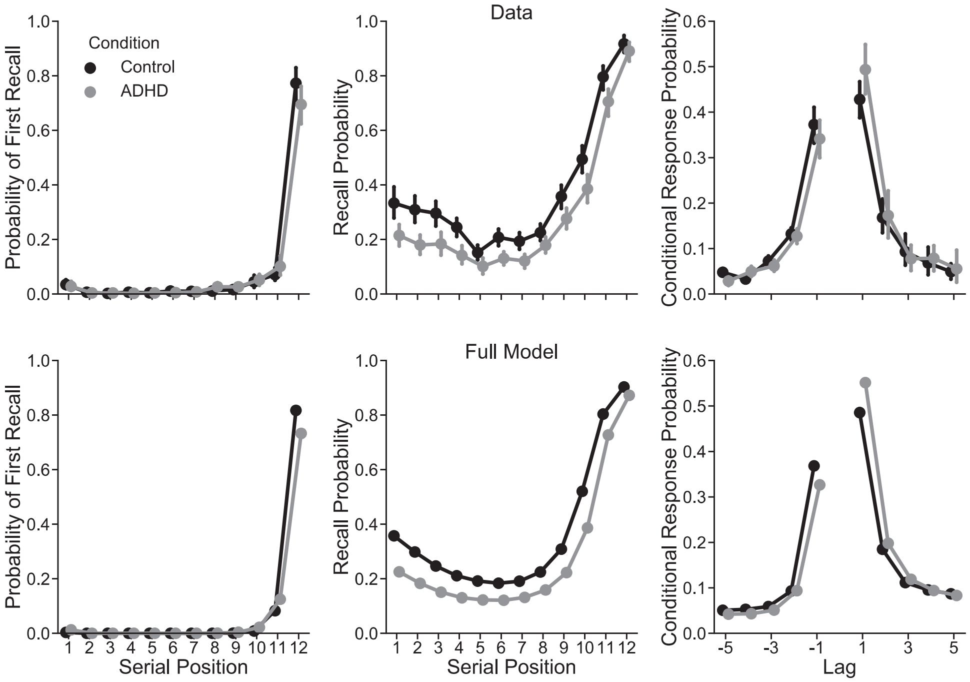

Figure 1. PFR curves (first column), SPCs (second column), and lag-CRP curves (third column) for the actual data (top row) and the best fitting parameterization of the RCM (bottom row). Error bars for actual data are standard errors.

0.40, *SE* = .01) than for more remote study-list positions (*M*s ranged from 0.14 to 0.05; corresponding *SE*s ranged from .01 to .005). With respect to the forward temporal asymmetry effect, there was a significant main effect of direction, $F(1, 100) = 36.95$, $p < .0001$, $\eta_p^2 = 0.27$, indicating that participants were more likely to recall items from study-list positions that occurred after the just-recalled item ($M = 0.16$, $SE = .004$) than from study-list positions that occurred before the just-recalled item ($M = 0.12$, $SE = .003$). In addition, there was a significant Lag × Direction interaction, $F(2.14, 214.13) = 8.24$, $p < .001$, $\eta_p^2 = 0.08$, indicating that the difference between forward and backward lags was greater for the adjacent list position than for more remote list positions. For instance, the forward temporal asymmetry effect (after–before) was 0.12 at Lag 1, $t(101) = 4.16$, $p < .001$; 0.02 at Lag 2, $t(101) = 1.58$, $p = .12$; 0.01 at Lag 3, $t(101) = 1.30$, $p = .20$; 0.03 at Lag 4, $t(101) = 2.95$, $p = .004$; and, 0.01 at Lag 5, $t(101) = 1.24$, $p = .22$. Thus, the present findings provide evidence that the expected contiguity and forward temporal asymmetry effects could be obtained in this sample of adolescents.

In addition, we also examined the extent to which these two lag-CRP effects varied as a function of group. There was a significant Direction × Group interaction, $F(1, 100) = 3.875$, $p = .05$, $\eta_p^2 = 0.04$. This interaction indicated that the overall forward temporal asymmetry effect was actually greater in the ADHD group (0.17 – 0.12 = 0.05) than in the control group (0.16 – 0.13 = 0.03). However, neither the main effect of group, nor any of the other interactions involving group were significant (all *p*s ≥ .16).

In summary, when compared across three separate measures of controlled retrieval dynamics obtained from a verbal IFR task—PFR, SPC, and lag-CRP—the ADHD group was found to have substantially lower scores on only one measure, the SPC, the difference of which was greater for the first few items than for the last few items (though the interaction was not significant). This finding is consistent with the notion that EDC was impaired in the ADHD group. In contrast, the lag-CRP functions did not show a deficit in the ADHD group. In fact, the ADHD group actually showed an *enhanced* forward temporal asymmetry effect relative to the control group. This finding is consistent with the notion that IDC was enhanced in the ADHD group. In the next section, we apply the RCM to these data to help understand the pattern of group differences observed across the three measures of retrieval dynamics.

Model Simulations of Retrieval Dynamics

Our aim was to determine which model mechanisms could account for the similarities and differences between the ADHD and control groups. Our basic approach was to determine how well the model could fit the ADHD data when all model mechanisms were free to vary between the ADHD and control groups and then ask how close we can get to that theoretical best fit by allowing only specific mechanisms to vary.

We began by fitting the model to the ADHD group's average value on each of the 34 outcome variables (12 in the PFR, 12 in the SPC, and 10 in the lag-CRP) using a cross-validation procedure in which the total ADHD sample was split into a fitting sample and a hold-out sample. The full model, allowing all parameters to vary, was fit to the average values of the fitting sample. Simulated data from these best fitting parameters were then compared with the hold-out sample to provide a cross-validated χ^2 measure of fit. To allow for a statistical test, we computed bootstrapped CIs around the full model's cross-validated χ^2 by repeating this entire procedure 500 times, each time using a different random sample from the fitting group. This provided us with a 95% CI around the best fit the full model could provide to the ADHD data. We also fit the full model to the control group's average data; we fit the full sample rather than splitting it into a fitting and hold-out sample because it was used as a baseline comparison.

The second row of Figure 1 shows the simulated data from the best fitting models for each group. The model captured the essential features of the pattern of group differences: a slightly reduced recency effect in the PFR in the ADHD group, reduced recall accuracy across most of the SPC that was more pronounced for the first few items in the ADHD group, and increased temporal contiguity in the forward direction of the lag-CRP in the ADHD group.

Standardized ADHD–control group differences in the parameter values are depicted in the top row of Figure 2. Values above 0 indicate that the ADHD group's best fitting value was higher than the control group's best fitting value. We did not provide error bars because we could have made them arbitrarily small by increasing the number of iterations of the bootstrapping procedure. Instead, fit statistics are depicted in the bottom row. The group differences in the EDC parameters are consistent with the notion that ADHD reflects impaired EDC during encoding. The lower value of ϕ_s in the ADHD group suggests that they devoted less attention to encoding at the beginning of each trial. The higher value of ϕ_d in the ADHD group suggests that they also showed faster waning of attention across the list. Figure 3 shows the group differences in the exponential attentional decay function implied by these parameter differences. In addition to differences in attention, the lower β_{enc} parameter value for the ADHD group indicates that they had slower mental context drift during encoding. That is, external stimuli had a *smaller* effect on internal mental context for the ADHD group.

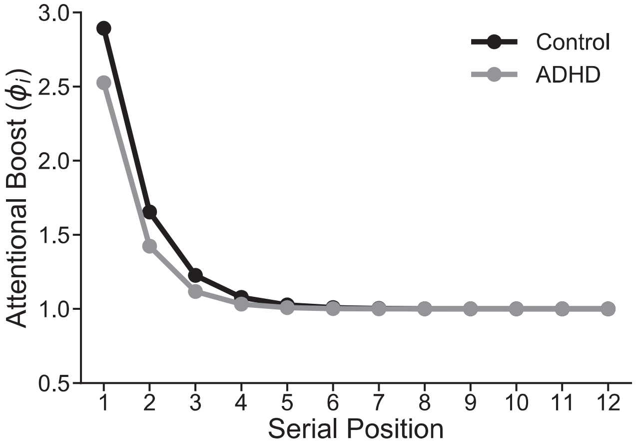

Figure 3. Group differences in primacy gradients implied by the model. For each serial position, i, the gradients give the value of ϕ_i, by which the strengths of newly formed associations are multiplied.

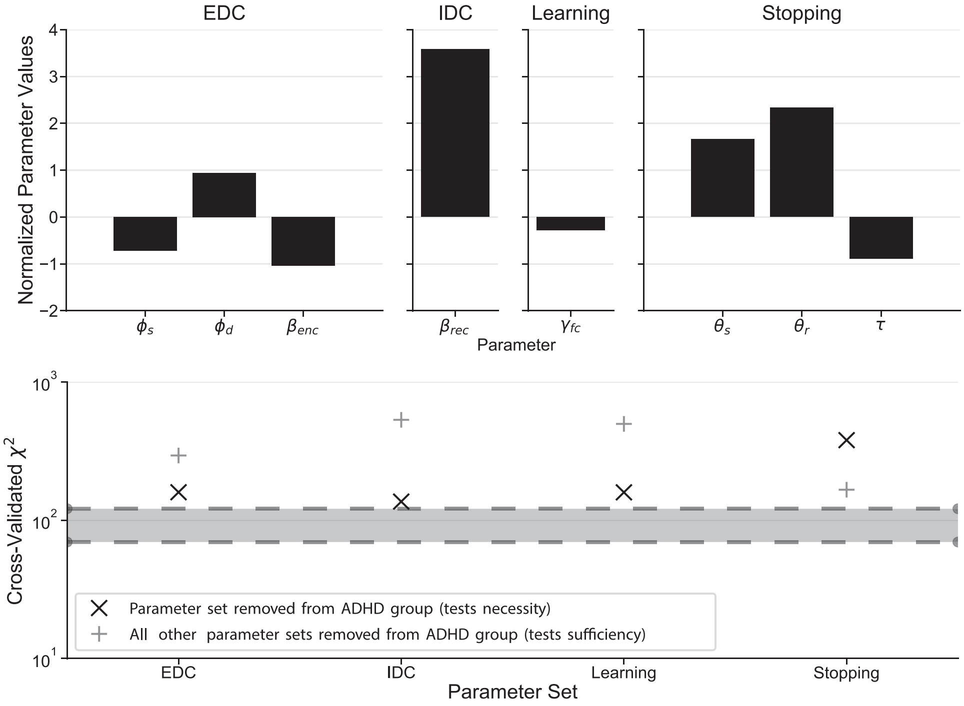

Figure 2. The top row shows the best fitting parameter values for the ADHD group normalized relative to the M and SD (across bootstrap iterations) of the control-group values $\left(\frac{M_{\text{ADHD}} - M_{\text{control}}}{SD_{\text{control}}}\right)$. The bottom row shows the fit quality of the submodels versus the full model (note the log scale on the y axis). The shaded region is the middle 95% of the distribution of cross-validated χ^2 values for the full-model fit to the ADHD group.

There were also group differences in the IDC parameter. Specifically, the ADHD group had higher values of the β_{rec} parameter, which indicates faster mental context drift during recall. That is, internal stimuli (recalled items) had a *larger* effect on internal mental context for the ADHD group.

In addition to these group differences in EDC and IDC, there were differences in the learning and stopping parameters. The ADHD group had slightly lower values of γ_{FC}, which sets the baseline efficiency of learning. They also had higher values of both θ parameters, which results in a higher initial probability of stopping recall that approaches 1 more rapidly as the recall period progresses (see Figure 4).

These initial fits show that the model is capable of accounting for the differences between the ADHD and control groups by assuming that the groups differed on all four model mechanisms (EDC, IDC, learning, and stopping). But one can ask whether a more parsimonious account of the data can be provided by assuming group differences on just a subset of the mechanisms. We conducted two additional sets of simulations to illuminate this issue. The basic logic is to ask whether each model mechanism was (a) sufficient and (b) necessary to account for the group differences. Note that when comparing submodels, we deliberately chose to use χ^2 as our measure of fit rather than a measure such as the Bayesian information criterion, which corrects for the number of free parameters. We made this choice to be conservative and avoid ruling out the influence of a model mechanism simply because it included many free parameters.

To test whether a particular mechanism was sufficient, we attempted to fit the ADHD data by allowing the parameters associated with that mechanism to vary while fixing all the other parameters to the best fitting control-group value. If the mechanism was sufficient to account for the group difference, then the fit of this restricted submodel should have been indistinguishable from the fit of full model, in which all parameters were free. The + symbols in the bottom row of Figure 2 show that none of the mechanisms was sufficient.

To test whether a particular mechanism was necessary to account for the group differences, we attempted to fit the ADHD data by fixing the parameters associated with that mechanism to the control-group values and allowing all the other parameters to vary. If the mechanism was necessary, this restricted submodel should have provided a fit that is significantly worse than the fit of the full model. The X symbols in the bottom row of Figure 2 show that all four mechanisms were necessary—removing any of them significantly lowered the fit. In short, no single parameter was sufficient; they were all necessary.

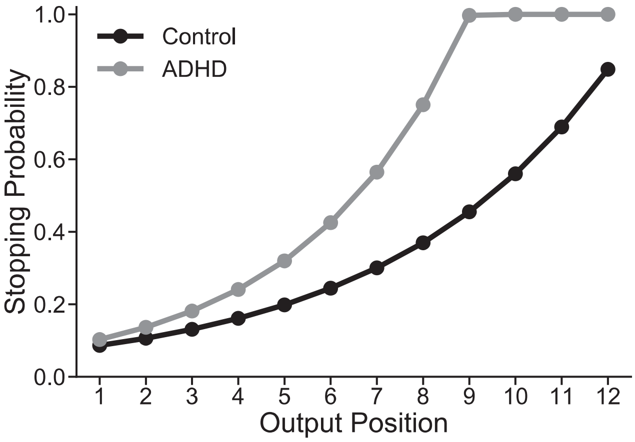

Figure 4. Group differences in stopping probability gradients implied by the model. For each output position, *j*, the gradients give the probability, $p_{(\text{stop},\ j)}$, that the model will fail to retrieve an item and halt recall.

General Discussion

The present study has reinforced the clinical relevance of the distinction between EDC and IDC by providing important new evidence that ADHD reflects impaired EDC and enhanced IDC under conditions in which both forms of attention had the potential to contribute positively to task performance. Indeed, the fine-grained pattern of group differences observed across the three measures of retrieval dynamics in the present study was different than the pattern of group differences that had been previously associated with other group types. In these previous studies, a reduction in recall accuracy across the SPC was matched by a reduction in the Lag-CRP effects. In other words, impaired EDC typically coexists with impaired IDC in verbal IFR tasks.

However, although the ADHD group showed a reduction in recall accuracy across the SPC in the present study, this group did not show a corresponding reduction in the contiguity and forward temporal asymmetry effects. In fact, the ADHD group showed a slight enhancement of the forward temporal asymmetry effect relative to the control group. Thus, the present findings provide important new evidence that group differences observed on the SPC can be dissociated from group differences observed on the lag-CRP functions. In other words, the present findings suggest that impaired EDC during encoding can be dissociated from intact (or enhanced) IDC during retrieval in ADHD. Furthermore, the fact that this dissociation was observed in the ADHD group of the present study, but not in the anxious group (Pajkossy et al., 2017) or the psychosis group (Polyn et al., 2015; Murty et al., 2018) of previous studies provides some evidence that the present pattern of findings does not simply reflect a general aspect of psychopathology or intellectual impairment.

In addition to the empirical findings, this dissociation was also reinforced by the RCM of memory search. To account for the main performance deficit in the ADHD group relative to the control group—that is, reduced recall accuracy in the SPC, and a slightly reduced recency effect in the PFR—the RCM required deficits in the EDC parameter set. In contrast, to account for the main performance benefit in the ADHD group relative to the control group—that is, increased forward temporal asymmetry effect—the RCM required benefits in the IDC parameter set.

With respect to EDC, the values of the two ϕ parameters reflect the initial state and decay rate of externally directed attention on the study-list items during encoding, and the modeling results suggested that the ADHD group devoted less external attention to the study-list items at the beginning of each trial, and this lower initial state also decayed faster over the first few items (see Figure 3). The present findings are therefore consistent with other studies that have inferred modulatory or energetic differences between ADHD and non-ADHD groups during externally directed sustained attention tasks (e.g., Sergeant et al., 1999). However, the present findings also extend these previous studies by suggesting that such modulatory differences may operate during immediate memory tasks to reduce the encoding of, and subsequent memory for, the first few items of the study list.

Likewise, the value of the β_{enc} parameter reflects the rate at which mental context drifts during encoding, and the modeling results suggested that the ADHD group had a slower drift rate during encoding which in turn led to a slightly reduced recency effect in the PFR. As mentioned in the Introduction, although we have interpreted the value of β_{enc} in the ADHD group as primarily reflecting weaker EDC, it may actually reflect a more complex interaction between EDC and IDC. As such, a weaker value of encoding could arise from weaker EDC to the study-list items, stronger IDC to the corresponding activated representations stored in memory, or a combination of both. Indeed, a case could be made for the combination of a weak EDC and strong IDC, given the interpretation of the ϕ and β_{rec} (see below) parameters. Such an interpretation would be consistent with other studies that have inferred that ADHD reflects a tendency for IDC to interfere with EDC (Sonuga-Barke & Castellanos, 2007).

With respect to IDC, the value of the β_{rec} parameter reflects the focus of internally directed attention on the just-recalled item and its associated context during retrieval, and the modeling results suggest that the ADHD group devoted more internal attention to the just-recalled item such that the context associated with this item was more active than the context associated with previously recalled items. The present findings are therefore consistent with other studies that have inferred a smaller retrieval deficit than encoding deficit in ADHD, relative to controls, by observing similar magnitude impairments across recall (encoding plus retrieval) and recognition (encoding only) tasks (Skodzik et al., 2017). The present findings also extend and strengthen these previous studies by showing that a similar dissociation between encoding and retrieval can also be observed using more specific measures derived from the same task.

The enhanced forward temporal asymmetry effect observed in the ADHD group in the present study is important because it is thought to be mediated by a more general representation of internal temporal history, that is, a representation of "what" occurred "when" (Howard, Shankar, Aue, & Criss, 2015). As Howard et al. noted, such a mechanism is not unique to episodic memory, but is also important for a variety of other cognitive abilities such as temporal judgments and conditioning. Recently, evidence has accumulated to suggest that individuals with ADHD may have a temporal processing deficit (see, e.g., Sonuga-Barke, Bitsakou, & Thompson, 2010); however, the tasks used to assess this ability have all involved externally directed attention only. By focusing on internally directed attention, the present study has provided important evidence that the mechanisms underlying temporal processing may be intact in ADHD.

Although the present study only included those participants who used a recency recall-initiation strategy, future applications of the RCM to ADHD could accommodate all recall strategies by fitting the RCM to individual data, though this approach would require approximately at least twice as many IFR trials (see Healey & Kahana, 2016). Such efforts would likely be worthwhile, though, because they would enable a more fine-grained examination of how individual differences in EDC and IDC parameters are related to each other, as well as to other relevant variables (e.g., inattentive symptoms). In addition, a critical question for future research concerns the extent to which the apparent weakness in EDC can be selectively ameliorated in ADHD without harming the apparent strength in IDC, for it remains possible that increases in EDC lead to decreases in IDC, at least for individuals with ADHD.

Although the present study focused on the EDC and IDC parameter sets, it should be noted that the modeling results also showed differences in the learning and stopping parameter sets. That is, the ADHD group tended to form weaker episodic associations (a result of lower values of the γ_{FC} learning parameter) and had a higher probability of stopping recall before the allotted time was up (a result of differences in the θ stopping parameters; see Figure 4). Although we did not directly measure motivation, one possible interpretation is that both findings are linked by reduced motivation to focus on the task during encoding and/or to recall items during the recall period, which is consistent with other studies that have reported motivational differences between ADHD and non-ADHD groups (Sonuga-Barke, 2005; Volkow et al., 2011). However, further discussion of this issue is beyond the scope of the present article.

In conclusion, in the present study, we used a verbal episodic memory task involving immediate free recall to assess the integrity of EDC and IDC in a sample of 111 adolescents, 50 with study-confirmed diagnoses of ADHD. The ADHD group was found to have significantly worse scores on outcomes measuring EDC during encoding (serial position), and significantly better scores on outcomes measuring IDC during retrieval (lag-CRPs). In addition, model parameters estimating the contribution of EDC and IDC processes were fit to these data using the RCM of memory search. During encoding, the model suggested that the ADHD group had slower mental context drift, which is indicative of weaker externally directed attention to the list items, as well as deficiencies in their ability to allocate and sustain attention when the study list first appeared. In contrast, during retrieval, the model suggested that the ADHD group had faster mental context drift, which is indicative of stronger internally directed attention to retrieved context. These findings provide novel evidence that ADHD reflects impaired EDC and enhanced IDC, and they reinforce the clinical relevance of distinguishing EDC and IDC in future studies.

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