Working Memory and Information Processing in ADHD: Evidence for Directionality of Effects

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Abstract

Objective: Children with ADHD demonstrate impaired performance on a wide range of neuropsychological tests. It is unclear, however, whether ADHD is associated with many neurocognitive deficits or whether a small number of impairment(s) broadly influence test performance. The current study tests competing model predictions regarding two candidate causal mechanisms in ADHD: information processing speed and working memory.

Method: A well-characterized sample of 86 children (M_{age}=10.52, SD_{age}=1.54; 34 girls; 64% Caucasian/Non-Hispanic) with ADHD (*n*=45) and without ADHD (*n*=41) completed eight fully-crossed experimental tasks that systematically manipulated working memory ($BF_{10}=1.80\times10^{93}$) and information processing speed (drift rate; $BF_{10}=7.61\times10^{6}$).

Results: Bayesian mixed-model ANOVAs indicated that increasing working memory demands produced significant reductions in information processing speed (drift rate; $BF_{10}=5.82\times10^{96}$). In contrast, experimentally reducing children's information processing speed did not significantly change their working memory performance (BF_{10}=1.31). ADHD status interacted with the working memory manipulation, such that the ADHD and Non-ADHD groups showed equivalently high accuracy under the encoding-only conditions (BF_{01}=3.45) but differed significantly under high working memory conditions (encoding+recall; BF_{10}=19.58). Importantly, however, ADHD status failed to interact with (a) the working memory manipulation to differentially affect information processing speed, and (b) the information processing speed manipulation to differentially affect working memory performance (all BF_{01}>4.25).

Conclusions: These findings indicate that top-down executive control exerts significant effects on children's ability to quickly process information, but that working memory deficits and slowed information processing speed appear to be relatively independent impairments in ADHD.

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The authors have no conflicts to report.

Keywords

ADHD; working memory; processing speed; drift rate

ADHD is a chronic and heterogeneous disorder that has been linked with impaired performance on a wide range of neuropsychological tests (Willcutt et al., 2005; Frazier et al., 2004), but it is unclear whether these findings indicate that ADHD is associated with a large number of neurocognitive deficits or whether the data may be explained more parsimoniously by a small number of impairment(s) that broadly influence cognitive test performance (Coghill et al., 2013; Sonuga-Barke et al., 2008). Establishing a taxonomy of neurocognitive impairments in ADHD has the potential to improve treatment targeting (Chacko et al., 2014), refine theoretical models of ADHD pathogenesis (Coghill et al., 2005), and improve the science and technology of ADHD assessment and diagnosis (Rapport et al., 2000). That is, our understanding of the neurocognitive mechanisms underlying the ADHD phenotype is likely to be enhanced by efforts to determine which task-related impairments reflect (a) primary and causal neurocognitive deficits, (b) secondary neurocognitive deficits that arise due to primary underlying neurocognitive deficits, and (c) spurious findings attributable to uncontrolled primary/secondary neurocognitive deficits that impede task performance due to the poor specificity of many common neuropsychological tests (Snyder et al., 2015).

The current study contributes to these efforts by assessing directionality of the effects between two core neurocognitive functions that have garnered particular interest in recent years and been proposed as candidate causal mechanisms in ADHD: information processing speed and working memory (Karalunas & Huang-Pollock, 2013; Rapport et al., 2008). As described below, we used a counterbalanced, fully-crossed experimental design to determine the extent to which ADHD-related impairments in working memory are attributable to more basic impairments in information processing speed (Weigard & Huang-Pollock, 2017), and/or whether impairments on assessments of information processing speed are an outcome of reduced working memory functioning that impairs these children's ability to maintain consistent top-down control (Wiemers & Redick, 2018).

Working Memory Deficits in ADHD

Working memory refers to the active, top-down manipulation of information held in short-term memory, and includes interrelated functions of the mid-lateral prefrontal cortex that guide behavior via the updating, dual-processing, and temporal/sequential manipulation of internally-held information (Nee et al., 2013; Wager & Smith, 2003). Working memory deficits in ADHD are well established, with overall meta-analytic effect sizes of d=0.69–0.74 that may be potentially as large as d=2.01–2.15 when using recall-based tasks with prominent executive demands and a sufficient number of trials (Kasper et al., 2012). Deficits in this core executive function (Miyake & Friedman, 2012) are present in a substantial portion of children with ADHD (Sonuga-Barke et al., 2008), and importantly cannot be attributable to low motivation (Dovis et al., 2012, 2013), visual inattention during testing

(Kofler et al., 2010), disinhibition (Alderson et al., 2010), or response variability (Kofler et al., 2014).

Experimental studies suggest a potential causal role of working memory dysfunction for evoking ADHD-related inattentive and hyperactive behavior (Kofler et al., 2010; Rapport et al., 2009). Working memory deficits also covary longitudinally with ADHD symptom severity (Halperin et al., 2008; Salari et al., 2017; van Lieshout et al., 2016), and age-related reductions in ADHD symptoms appear limited to a subset of children who show age-related improvements in working memory (Karalunas et al., 2018). Converging evidence also links ADHD-related working memory impairments with ecologically valid functional outcomes, including social/peer difficulties (Aduen et al., 2018; Bunford et al., 2014; Tseng & Gau, 2013), parent-child relational problems (Kofler et al., 2017b), organizational difficulties (Kofler et al., 2017a), and underachievement in reading and math (Friedman et al., 2016, 2017; Simone et al., 2018).

Although the role of working memory deficits in ADHD has been well established in experimental, cross-sectional, and longitudinal studies, emerging conceptual models of ADHD suggest that these impairments may be driven, at least in part, by impairments in basic information processing speed (for review, see Weigard & Huang-Pollock, 2017), and that insufficient targeting of these processing speed deficits may in turn provide a parsimonious explanation for the inefficacy of working memory training for ADHD (Raiker et al., 2018). *Information processing speed* (i.e., central cognitive processing efficiency) refers to the rate at which information accumulates toward a decision (Voss et al., 2013), is associated with anterior cingulate (Konrad et al., 2006) and fronto-parietal cortical regions (Cao et al., 2008) among others, and has garnered increased interest in recent years as a potentially etiologically important mechanism in ADHD (Karalunas & Huang-Pollock, 2013). In the next section, we describe the evidence for impairments in information processing speed in ADHD, before reviewing the evidence for and against directional effects in the link between information processing speed and working memory.

Slowed Information Processing Speed in ADHD

Meta-analytic evidence suggests that ADHD is associated with small impairments in overall response speed (mean reaction time; MRT: d=0.29; Huang-Pollock et al., 2012). However, these slower MRTs appear to be driven primarily by a small subset of long RTs, such that youth with ADHD may exhibit *faster* response speeds when accounting for inconsistent responding that skews overall estimates of response times (d= −0.22; Kofler et al., 2013). In contrast, computational models that combine response times and accuracy to isolate performance specifically attributable to information processing speed (i.e., *drift rate* in computational modeling terminology) suggest ADHD-related deficits in processing speed as high as d=0.63–0.75 (Fosco et al., 2017; Huang-Pollock et al., 2012; Karalunas et al., 2014). Slow information processing speed has been linked with impairments in multiple domains implicated in ADHD, including inattentive and hyperactive symptom severity (Mulder et al., 2011), parent- and teacher-reported social problems, teacher-reported academic success (Kofler et al., 2016), and lower attainment in reading (Jacobson et al., 2011), math, and written expression (Mayes & Calhoun, 2007).

Information Processing Speed and Working Memory in ADHD

Information processing speed and working memory abilities show strong latent associations (*r*=.68; Schmiedek et al., 2007). Recent models and empirical evidence, however, provide conflicting accounts of the extent to which information processing speed produces individual differences in working memory performance (Weigard & Huang-Pollock, 2017) versus working memory abilities affecting the consistency with which individuals can maintain consistent performance during information processing tasks (Wiemers & Redick, 2018).

Information processing speed: Effects on working memory capacity.

Applying the time-based resource-sharing model (Portrat et al., 2009) to ADHD, Weigard & Huang-Pollock (2017) argued that slowed processing speed reduces working memory capacity in ADHD by decreasing the time available to refresh memory items. In this view, the same capacity-limited attentional focus is responsible for processing concurrent tasks and refreshing items held in working memory; the slower that the concurrent tasks are completed, the less time available to refresh working memory items before they are lost to decay.

Evidence supporting this model includes moderate-to-strong relations between age-related improvements in processing speed and working memory across childhood (Fry & Hale, 2000). In addition, cross-sectional studies consistently find that information processing speed partially mediates the link between ADHD and working memory deficits based on studies using computational approaches such as diffusion modeling (Karalunas & Huang-Pollock, 2013) and ex-Gaussian modeling (Kofler et al., 2014), or experimental disassociation of information processing components (Raiker et al., 2018). In addition, experimentally reducing information processing speed may disrupt working memory capacity in children with and without ADHD (Weigard & Huang-Pollock, 2017), collectively supporting the potential for directionality in this relation.

At the same time, the cross-sectional evidence consistently indicates that information processing speed accounts for only a minority of ADHD/Non-ADHD group differences in working memory (21%−29%), such that significant and large magnitude ADHD working memory impairments remain (Karalunas & Huang-Pollock, 2013; Kofler et al., 2014; Raiker et al., 2018). Similarly, despite Weigard & Huang-Pollock's (2017) sophisticated manipulation, concluding that slowed information processing speed explains working memory deficits in ADHD (or vice versa) may be premature because they were unable to test for directionality of effects.

Working memory abilities: Effects on information processing speed.

Alternatively, there is emerging evidence that working memory abilities may affect information processing efficiency. Extending the goal-maintenance (Engle & Kane, 2004) and dual mechanisms of control (Braver, 2012) models, Wiemers & Redick (2018) argued that reduced working memory capacity limits an individual's ability to maintain goal-relevant information in working memory during task completion. This leads to failures in cognitive control, such as slower and more variable response times, as well as more errors in situations where control is vital for performance. Further, they produced evidence that was inconsistent with a processing speed account of working memory (e.g., groups that differed in working memory capacity but not overall processing speed). Instead, they showed that low working memory capacity was associated with reduced ability to maintain *consistent* top-down control, which manifested as slowed response times only in the slowest tail of the response time distribution (i.e., increased intra-individual variability). In this view, performance on tests intended to measure information processing speed is directly impacted by working memory abilities.

Similar arguments have been proposed in the ADHD literature. For example, the functional working memory model (Rapport et al., 2008) posits that impairments in working memory result in increased motor activity (Rapport et al., 2009), mind wandering (Kane et al., 2007), visual inattention (Burgess et al., 2010; Kofler et al., 2010), and impulsive responding (Raiker et al., 2012) that temporarily disrupt task performance and result in response time and accuracy scores suggestive of slowed information processing speed (Kofler et al., 2014). Evidence supporting this model includes meta-analytic evidence that children with ADHD may exhibit significantly *faster* response speeds than their neurotypical peers (mu; Kofler et al., 2013), cross-sectional findings that working memory deficits may account for most if not all of the ADHD/Non-ADHD effect size for variability in information processing speed (Kofler et al., 2014), and evidence that individual differences in working memory predict how well individuals maintain consistent response times during processing speed tasks (Wiemers & Redick, 2018).

Current Study

Taken together, the literature suggests that ADHD is associated with impaired performance on tasks intended to measure information processing speed and working memory abilities, but it is unclear whether this is indicative of multiple, distinct deficits or a single deficit that broadly affects performance across both types of tasks (Sonuga-Barke et al., 2008). The current study is the first to experimentally manipulate both information processing speed and working memory demands to test competing, model-driven hypotheses regarding the directionality of these impairments in ADHD. Support for the time-based resource-sharing model (Portrat et al., 2009) of working memory deficits in ADHD (Weigard & Huang-Pollock, 2017) would include significant reductions in working memory performance as children's information processing speeds were experimentally reduced. In contrast, support for goal-maintenance/dual-mechanism models (Wiemers & Redick, 2018) of slowed information processing speed in ADHD (Kofler et al., 2014) would include significant slowing of the rate of information accumulation (i.e., drift rate; Voss et al., 2013) as working memory demands increased. Given previous evidence that ADHD and Non-ADHD groups show similar effects of experimentally reducing information processing speed on working memory performance (i.e., non-significant group x task interactions; Weigard & Huang-Pollock, 2017), we used Bayesian statistics because they can provide evidence of equivalence rather than just a lack of significant differences (Wagenmakers et al., 2016).

Method

Participants

The sample included 86 children aged 8–13 years (*M*=10.52, *SD*=1.54; 34 girls) from the Southeastern United States, consecutively recruited for participation in a research study at a university-based children's learning clinic (CLC) through community resources from 2015–2017. The CLC is a research-practitioner training clinic known to the surrounding community for conducting developmental and clinical child research. Its participant base consists of children with suspected learning, behavioral or emotional problems, as well as typically developing children (those without a suspected psychological disorder) whose parents agreed to have them participate in developmental/clinical research studies. Psychoeducational evaluations were provided to all caregivers. All parents and children gave informed consent/assent, and IRB approval was obtained/maintained. Sample ethnicity included Caucasian/Non-Hispanic (64%), African-American (13%), Hispanic (13%), multiracial (6%), and Asian-American (4%) children.

Group Assignment

All children and caregivers completed an identical evaluation that included detailed, semi-structured clinical interviewing (K-SADS; Kaufman et al., 1997). The K-SADS (2013 Update) allows differential diagnosis according to symptom onset, course, duration, quantity, severity, and impairment in children based on DSM-5 criteria, and was supplemented with parent and teacher ratings from the Behavior Assessment System for Children (BASC-2/3; Reynolds & Kamphaus, 2015) and ADHD Rating Scale-4/5 (ADHD-4/5; DuPaul et al., 2016).

Forty-five children met all of the following criteria and were included in the ADHD group (*n*=45; 38% girls): (1) DSM-5 diagnosis of ADHD Combined (*n*=34), Inattentive (*n*=9), or Hyperactive/Impulsive Presentation (*n*=2) by the directing clinical psychologist based on K-SADS; (2) borderline/clinical elevations on at least one parent and one teacher ADHD rating scale, and (3) current impairment based on parent report (K-SADS). All ADHD subtypes/presentations were eligible given the instability of ADHD subtypes (Valo & Tannock, 2010). Psychostimulants ($N_{prescribed}$=14) were withheld ≥24 hours for neurocognitive testing. To improve generalizability, children with comorbidities were included. Comorbidities reflect clinical consensus best estimates, and included anxiety (22%), oppositional defiant (11%), depressive (4%), and high-functioning autism spectrum disorders (7%).[1] Positive screens for reading (9%) and math learning disabilities (13%) were not exclusionary and were defined based on score(s) >1.5 *SD* below age-norms on one or more KTEA-3 reading and math core subtests, as specified in DSM-5 (APA, 2013).

The Non-ADHD group comprised 41 consecutive case-control referrals who did not meet ADHD criteria, and included both neurotypical children and children with psychiatric disorders other than ADHD. Neurotypical children (56%) had normal developmental histories and did not meet criteria for any psychiatric disorder. Children who met criteria for

[1]Results were unchanged when excluding children with autism spectrum disorders. As recommended in the K-SADS, oppositional defiant disorder was diagnosed clinically only with evidence of multi-informant/multi-setting symptoms.

other clinical disorders but not ADHD were also included in the Non-ADHD group. These Non-ADHD disorders were included to account for performance patterns that may be driven by common comorbidities rather than ADHD specifically. Best estimate diagnoses included anxiety (22%), high-functioning autism spectrum (12%), depressive (7%), and oppositional defiant disorders (3%). None of the Non-ADHD cases screened positive for learning disorders in reading or math. As detailed below, the ADHD and Non-ADHD groups were statistically equivalent in the proportion of non-ADHD clinical disorders overall and across diagnostic categories.

Children were excluded for gross neurological, sensory, or motor impairment; history of seizure disorder, psychosis, or intellectual disability; or non-stimulant medications that could not be withheld for testing.

Procedure

Testing occurred during a larger battery of two, 3-hour sessions. Tasks were counterbalanced within/across sessions to minimize order/fatigue effects. Children whose counterbalancing resulted in them completing one or more of the low memory tasks after previous exposure to one or more of the high memory task variant(s) described below were explicitly told not to remember the animals/emotions. Children received brief breaks after each task, and preset longer breaks every 2–3 tasks to minimize fatigue. Performance was monitored by an examiner stationed just outside the testing room to provide a structured setting while minimizing performance improvements associated with examiner demand characteristics (Gomez & Sanson, 1994).

Experiment Overview

A series of 8 computerized tasks were created to experimentally address the directionality of the relation between information processing speed and working memory in ADHD. Task stimuli were chosen to provide robust manipulations of information processing speed and working memory demands while also providing experimental data to address secondary questions regarding reading and emotion recognition in ADHD (Kofler et al., 2019; Wells et al., 2019). As described below, the current study uses all 8 tasks to improve generalizability via inclusion of multiple estimates per parameter. The 8 tasks were designed to vary systematically in a fully-crossed experiment that includes two tasks each per working memory (low vs. high) x information processing demands (low vs. high) combination (Figure 1). Four of the tasks were working memory complex span tasks based on the counting span and reading span tasks (Conway et al., 2005) adapted for use with children. The remaining four tasks were otherwise identical to their matched complex span task, without the memory demands (i.e., recognition tasks). Half of the working memory and half of the non-memory tasks elicited faster information processing speeds by presenting clearly identifiable archetypes of common animals and facial expressions (low information processing demands), and the other half evoked slower information processing speeds by requiring children to use context to infer a ‘hidden’ animal or facial expression (high information processing demands). As described below, there was decisive evidence indicating that the information processing speed and working memory manipulations were successful in evoking the intended changes in their target mechanisms.

Task Overview

Thirty-six total trial pairs were completed for each task. Each trial pair included the recognition or inference of one primary stimuli (emotion or animal) followed by one distractor stimuli (true/false sentence). During the high working memory tasks described below, a recall phase was inserted after every 3–6 trial pairs (8 total recall phases, with 2 recall phases each at memory set size of 3–6 stimuli). Following Engle et al. (1999), children received performance feedback during both the primary and secondary task components. All tasks were self-paced. Children completed practice phases of 6 trial pairs (6 primary stimuli, 6 true/false sentences) prior to each low working memory condition (100% required). For the high working memory conditions, practice trials at memory set 3 were terminated after two 100% correct recall trials. Internal consistency reliability was excellent for the current sample for all 8 tasks (α=.84-.89).

High Working Memory Demands, Faster Information Processing Speeds

We created four task variants that combined aspects of the classic counting span and reading span tasks described by Conway et al. (2005), adapted for use with children, that exemplify dual-processing working memory based on the Engle et al. (1999) model. As detailed below, the two ‘span tasks’ (animal and emotion) elicited faster information processing speeds, whereas the two ‘context span’ tasks (animal context and emotion context) elicited slower information processing speeds. Detailed descriptions of task stimuli development and validation can be found in Wells et al. (2019, for the primary animal and emotion stimuli) and Kofler et al. (2019, for the secondary reading stimuli).

Animal span.—Children were sequentially shown screens containing a picture of a single animal at the top of the screen and six response boxes on the bottom of the screen (low information processing demands to evoke faster information processing speed; Figure 1). Children were instructed to click the response box that matched the picture (e.g., clicking ‘dog’ when viewing a picture of a dog). After each animal, children silently read and responded to a true/false sentence by clicking the corresponding button on screen. After a predetermined number of animal-sentence pairs (memory set sizes 3–6), children were asked to recall the animals in serial order. The sentences were presented last in each animal-sentence pair to ensure interference effects prior to recall (Unsworth & Engle, 2007).

Emotion span.—This task was identical to the animal span task except that children were shown clearly identifiable archetypes of children’s facial expressions (low information processing demands; Figure 1).

High Working Memory Demands, Slower Information Processing Speeds

Animal context span.—This task identical to the animal span task except that children had to infer which animal was hidden in each picture based on the context (high information processing demands; Figure 1). The manipulation to slow the rate of information accumulation (i.e., information processing speed/drift rate) was placed in the primary rather than secondary task phase based on the logic of the classic counting span task (Conway et al., 2005). That is, reducing information processing speed during the primary task provided opportunity to interfere with both the encoding of a given to-be-recalled stimulus and the maintenance of each previously presented stimulus. In contrast, reducing information processing speed during the secondary task provides opportunity to disrupt maintenance only. Secondary task demands based on the logic of the classic reading span task were also included to maximize working memory and not just short-term memory demands in our high working memory tasks, as described above, but were not manipulated across conditions by design.

In the classic counting span task, processing the primary stimulus (counting the number of dots on the screen) is intended to disrupt the participant's ability to remember the number of dots on previous screens. Applied to the current study, the information processing speed manipulation tested the extent to which the slowed information processing speed (i.e., smaller drift rates) evoked by having to infer which to-be-recalled stimulus to encode would interfere with the ability to maintain previously-encoded stimuli within working memory (e.g., the extent to which processing a photo to determine that a bird is missing disrupts the child's ability to remember that she has previously seen a dog, walrus, and lion, relative to an otherwise identical condition that evoked faster information processing speeds during encoding by presenting a clearly identifiable archetype of a bird).

Emotion context span.—This task was identical to the emotion span task except that children had to infer which facial expression was hidden in each picture based on the context (high information processing demands; Figure 1).

Low Working Memory Demands, Faster Information Processing Speeds

Animal recognition.—This task was identical to the animal span task, except that children were not required to remember the animal names (i.e., the recall phase was omitted; Figure 1, bottom).

Emotion recognition.—This task was identical to the animal recognition task, except that children were shown clearly identifiable archetypes of children's facial expressions.

Low Working Memory Demands, Slower Information Processing Speeds

Animal context recognition.—This task was identical to the animal recognition task, except that children had to infer which animal was hidden in each picture based on the context (Figure 1).

Emotion context recognition.—This task was identical to the animal context recognition task, except that children had to infer which facial expression was hidden in each picture based on the context.

Primary Outcomes: Working Memory

The proportion of stimuli correct per trial (% correct) was used to assess working memory capacity as recommended (Conway et al., 2005). Performance was assessed for each child at each memory load (set sizes 3–6), separately for each of the four complex span tasks, and combined into a single score for each task (% correct). There was no recall phase by design during the low working memory conditions. Therefore, scores from these conditions reflect the accuracy of initial encoding during the primary stimulus presentation. In other words, the low working memory conditions control for encoding, such that the 'low' vs. 'high' working memory manipulation is evaluated as encoding-only vs. encoding + maintenance/recall (or alternatively, single- vs. dual-task, with the latter conceptualized as primarily reflecting processes attributed to working memory in prominent cognitive models; e.g., Conway et al., 2005)[2]. As described below, we also conducted exploratory analyses using the recall data at each memory load (set size) during the four high working memory conditions to probe the extent to which the effects of experimentally reducing information processing speed vary as a function of working memory load. Higher scores reflect better working memory.

Primary Outcomes: Information Processing Speed

Most cognitive tasks extract reaction time and/or accuracy parameters to evaluate performance. Yet, these metrics are comprised of numerous psychologically-distinct processes, making the interpretation of reaction times or accuracy difficult. Well-validated computational stochastic accumulator models were therefore used to decompose performance data into theoretically-linked components of information processing speed (Donkin et al., 2009; Voss et al., 2013). Linear ballistic accumulator (LBA) models were used as recommended for multiple-choice data (Donkin et al., 2009). These models assume that, when faced with a simple decision, individuals accumulate information continuously until they reach a threshold, at which point they have sufficient information to make a decision. The length of time required to make a response can be described by three computationally and psychometrically distinct processes: drift rate, response caution, and non-decision time. Drift rate (v) is the primary indicator of information processing speed (Voss et al., 2013), and refers to the speed of information uptake; smaller drift rate values indicate less rapid information uptake/greater processing demands. Response caution (a) refers to the quantity of information considered before a decision is executed; higher upper boundary indicates a slower, more accurate decision style (i.e., more reflective response style) and is often interpreted as evidence of a speed-accuracy trade-off (Voss et al., 2013). Non-decision time (t_0) captures aspects of reaction time performance unrelated to decision making, including stimulus encoding and response execution speed; higher non-decision time reflects slower encoding and/or motor speed, which are not separable in these models.

LBA parameters were modeled using the R package hBayesDM (hierarchical Bayesian modeling of Decision-Making tasks; Ahn, Haines, & Zhang, 2017; Annis et al., 2016) using 3 Markov Chain Monte Carlo (MCMC) chains, each with 2000 samples and a 1000 sample burn-in. From this modeling, each participant had 6 estimates of drift rate per task (one for each of the 6 response options); thus, an additional within-subjects factor (response option, coded 1–6 clockwise from top left as shown in main text Figure 1) was added to all analyses with drift rate as the DV and treated as a nuisance variable (i.e., covaried). An expanded

[2]We refer to the conditions without explicit recall demands as "low" rather than "no" working memory demands to acknowledge that some working memory demands are required for performance on most if not all tasks (e.g., maintaining the rule set/instructions and internal focus of attention to the task demands) as argued previously (e.g., Baddeley, 2007; Rapport et al., 2009). Thus, the "low working memory" conditions refer to conditions without explicit recall phases (encoding-only), whereas the "high working memory" conditions refer to otherwise identical tasks with explicit recall phases intermittently inserted (i.e., encoding + maintenance/recall).

description of model assumptions as applied to our data and evidence for model fit and convergence are included in the supplementary online materials[3].

Intellectual Functioning (IQ), Socioeconomic Status (SES), & Reading Skill

IQ was assessed using the WISC-V Verbal Comprehension Index (Wechsler, 2014). SES was estimated using the Hollingshead (1975) scoring based on caregiver(s)' education and occupation. Reading skill was screened using the KTEA-3 (Kaufman & Kaufman, 2014) Letter-Word Identification subtest.

Bayesian Analyses

Bayesian analyses were selected because they allow stronger conclusions by estimating the magnitude of support for both the alternative and null hypotheses (Rouder & Morey, 2012). That is, Bayesian methods can confirm the null hypothesis rather than just fail to reject it (Wagenmakers et al., 2016). Bayes factor mixed-model ANOVAs with default prior scales (Rouder & Morey, 2012; Wagenmakers et al., 2016) were conducted using JASP 0.8.5 (JASP Team, 2017). Instead of a *p*-value, these analyses provide BF_{10}, which is the Bayes Factor of the alternative hypothesis (H_1) against the null hypothesis (H_0). BF_{10} is an odds ratio, where values above 3.0 are considered moderate evidence supporting the alternative hypothesis (i.e., statistically significant evidence for the alternative hypothesis). BF_{10} values above 10 are considered strong (>30=very strong, >100=decisive/extreme support; Wagenmakers et al., 2016). A finding of BF_{10}=10 for example, would indicate that the data are 10 times more likely under the alternative hypothesis than under the null hypothesis (i.e., strong support for an effect).

Conversely, BF_{01} is the Bayes Factor of the null hypothesis (H_0) against the alternative hypothesis (H_1). BF_{01} is the inverse of BF_{10} (i.e., $BF_{01}=1/BF_{10}$), and is reported when the evidence indicates a lack of an effect (i.e., favors the null hypothesis; Rouder & Morey, 2012). BF_{01} values are interpreted identically to BF_{10} (>3=moderate support for the null hypothesis that the ADHD and Non-ADHD groups are *equivalent* on an outcome; Rouder & Morey, 2012).

Interpretation of results was unchanged when examining frequentist *p*-values instead of Bayes Factors with one exception footnoted below and detailed in the Supplementary Online Materials.

Data Analysis Overview

The current study used a fully-crossed 2×2 experimental design (information processing demands low/high x working memory demands low/high) with two groups (ADHD, Non-ADHD), and two tasks per information processing speed/working memory combination (animals/emotions). We thus examined the study's primary hypotheses via two Bayesian mixed-model ANOVAs. Tier 1 probed for effects of experimentally reducing information processing speed on working memory performance (DV: percent correctly encoded or

[3]We also modeled the data under diffusion model assumptions based on the extension of this model to multiple-choice data as discussed in Voss et al. (2013). The pattern and interpretation of results is highly similar to those reported in the main text (reported in the Supplementary Online materials).

encoded+recalled). Tier 2 tested for effects of increasing working memory demands on information processing speed (DV: drift rate). Exploratory analyses were conducted in Tier 3 to probe the effects of (1) our *a priori* decision to combine the clinical and neurotypical control subgroups into a combined Non-ADHD group, and (2) our inclusion of the encoding-only data from the low working memory conditions in the Tier 1 analyses (Supplementary Online).

Stimulus type (animal/emotion) was included as an additional within-subjects factor in all models and treated as a nuisance variable (i.e., controlled) to remove any stimulus-specific effects given our goal of examining domain-general neurocognitive processes. As described above, its inclusion was to ensure that all results are based on multiple tasks per outcome to maximize power and effect specificity, and to ensure that the findings could not be attributed to task-specific or random error factors rather than the primary constructs of interest.

Results

Bayesian Power Analysis

A simulation study was conducted to estimate power for between-group tests using the R BayesianPowerTtest script (Zimmerman, 2016), with parameters as follows (*N*=86; r-scale=1; *k*=100,000 simulated experiments; BF threshold=3.0). Results indicated power=.81 for supporting the alternative hypothesis based on a true effect of *d*=0.74 (81% of simulations correctly supported H_1 at $BF_{10} \geq 3.0$, 18% provided equivocal support at BF_{10} values between 1/3 and 3, and only 1% incorrectly supported H_0). The expected effect size of *d*=0.74 was selected based on meta-analytic estimates of *d*=0.74 for working memory (Kasper et al., 2012) and *d*=0.75 for drift rate (Huang-Pollock et al., 2012). Power=.78 for supporting the null if true (i.e., for *d*=0.0; 78% of simulations supported H_0, 21% provided equivocal support, and only 1% incorrectly supported H_1). Taken together, our false positive and false negative rates are both 1% (i.e., low odds of incorrectly supporting the null hypothesis if the alternative hypothesis is true, and vice versa), suggesting adequate power.

Of note, these Bayesian power estimates are for single variable comparisons (i.e., independent samples t-tests) and thus do not account for the increased power obtained by our use of multiple tests per outcome. To our knowledge, Bayesian power analysis for repeated-measures ANOVA is not yet available. Power analysis based on traditional NHST, with alpha=.05, power=.80, 2 groups, and 8 measurements (the 8 tasks described above) indicates that our *N*=86 can reliably detect within-group and interaction effects of *d*=0.21, and between-group effects of *d*=0.46 or larger. Within-group and interactions effects of *d*=0.25, and between-group effects of *d*=0.48, are detectable for analyses that include 4 measurements. Thus, the study is sufficiently powered to address its primary aims.

Preliminary Analyses

Outliers ≥3 *SD* were winsorized relative to the within-group distribution (ADHD, Non-ADHD; 0.81% of data points). All parent and teacher ADHD symptom ratings were higher for the ADHD than Non-ADHD group as expected (Table 1). The ADHD and Non-ADHD groups were equivalent in the proportion of non-ADHD clinical disorders overall (44% for each group; BF01=3.81) and across most diagnostic categories (anxiety: BF01=4.55;

depression: BF_{01}=6.54; ASD: BF_{01}=4.45; ODD: BF_{01}=2.37; $SLD_{Reading}$: BF_{01}=1.70; SLD_{Math}: BF_{10}=2.27). The ADHD/Non-ADHD groups were equivalent or did not differ significantly with regard to gender (BF_{01}=3.65), ethnicity (BF_{01}=13.55), age (BF_{01}=1.53), IQ (BF_{10}=1.94), or SES (BF_{10}=1.73); therefore, these variables were not included as covariates.

Manipulation Check

The current study included two experimental manipulations in a fully crossed 2×2 design (working memory demands low/high x information processing demands low/high). Evidence supporting the success of these two experimental manipulations would be that (1) significantly fewer stimuli were recalled correctly during the high working memory (encoding + recall) conditions than were correctly encoded during the low working memory (encoding-only) conditions (i.e., that manipulating working memory successfully engaged working memory processes), and (2) significant reductions in drift rate as information processing speed was experimentally reduced (i.e., that the high information processing condition successfully slowed information processing speed relative to the low information processing condition). As detailed below, there was decisive evidence to support the integrity of both experimental manipulations, such that the data were over 7 million times more likely under the hypothesis that these manipulations were successful than under the null hypothesis that these manipulations failed.

Specifically, there was decisive evidence that our manipulation to reduce information processing speed successfully decreased the speed of information uptake (drift rate; $BF_{10} = 3.85 \times 10^{202}$, d=2.52; Figure 2 bottom left). Post-hoc tests revealed also that the experimental manipulation of information processing speed was successful at reducing drift rate as expected based on decisive support for this effect at all levels of group and working memory demands (all $BF_{10} > 7.46 \times 10^{85}$). In other words, placing the information processing manipulation within the primary task successfully reduced information processing speed as intended. Likewise, there was decisive evidence for an effect of working memory load on performance in both the primary Tier 1 (BF_{10}=1.92×10^{93}, d=1.61; Figure 2 top right) and exploratory Tier 3 analyses (BF_{10}=6.25×10^{25}, d=1.20 between set sizes 3 and 6; d_{median}=0.66 for each increase in set size; Figure S1). In other words, the manipulation evoked high working memory demands during the high working memory conditions as intended, both relative to the low-working-memory control (encoding) conditions (Tier 1), as well as with each increase in memory load within the high working memory tasks (Tier 3).

In the ensuing sections, we test whether these manipulations produced cross-domain reductions as hypothesized, and whether these effects occurred differentially for children with vs. without ADHD. In other words, did the increase in working memory demands differentially slow children with ADHD's information processing speed as hypothesized by goal-maintenance and dual mechanisms of control models? Or, alternatively, did the experimental reduction in information processing speed during the primary task differentially interfere with their encoding and/or maintenance of information within working memory as hypothesized by the time-based resource-sharing model? Throughout the Results, the descriptive labels 'low/high working memory demands' refer to the encoding-only vs. encoding+recall conditions, respectively. Similarly, the 'low/high information processing demands' labels refer to the conditions that evoke faster and slower information processing speeds, respectively,

Tier 1: Effects of information processing speed on working memory performance (working memory performance as DV)

The 2 (information processing: low/high) x 2 (working memory: low/high) x 2 (group: ADHD/Non-ADHD) Bayesian mixed-model ANOVA with working memory performance as the DV provided significant evidence for a main effect of group (ADHD<Non-ADHD; BF_{10}=8.30). The main effect of the working memory manipulation on working memory performance is described in the *Manipulation Check* section above. With regard to interactions between ADHD status and the working memory manipulation, there was strong evidence for the group x working memory interaction ($BF_{10}=3.27\times10^4$), with post-hoc tests indicating that the ADHD and Non-ADHD groups were statistically equivalent during the low working memory conditions (BF_{01}=3.45, *d*=0.21) but that the ADHD group showed disproportionate performance decrements between encoding and working memory recall (BF_{10}=19.58; *d*=0.35).

Importantly, there was no detectable effect of reducing information processing speed on working memory performance, such that the data were almost equally likely under the null and alternative hypotheses (main effect of information processing speed: BF_{10}=1.31, *d*=0.44)[4] (Figure 2). There was also significant evidence *against* the group x information processing speed (BF_{01}=5.97), information processing speed x working memory (BF_{01} = 6.13), and the 3-way interaction (BF_{01}=4.13), indicating that experimentally slowing information processing speed impacted the working memory recall of children with and without ADHD equivalently. Taken together, these analyses confirm that ADHD is associated with impaired working memory, but provide significant evidence *against* the hypothesis that slowed information processing speed explains reduced working memory capacity in ADHD. As described in the Tier 3 analyses below, these findings were robust to alternate analytic methods in which we probed for information processing speed effects as a function of working memory load specifically during the high working memory conditions.

Tier 2: Effects of working memory demands on information processing speed (drift rate as DV)

Results of the 2 (working memory: low/high) x 2 (information processing: low/high) x 2 (group: ADHD/Non-ADHD) Bayesian mixed-model ANOVA indicated decisive support for

[4]The main effect of information processing speed on working memory was significant based on null hypothesis significant testing (*p* < .001). Because NHST only evaluates the likelihood of the data under the null hypothesis, whereas Bayesian methods evaluate the strength of the evidence for both the null and alternative hypotheses, this discrepancy seems to indicate that neither the null nor alternative hypotheses provide an adequate explanation for the data (see Wagenmakers et al., 2018 Figure 5 for a NIHMS1047828-supplement-Supplemental_Material.pdf parsimonious depiction of this scenario). Interestingly, this is the NIHMS1047828-supplement-Supplemental_Material.pdf same pattern observed in Weigard & Huang-Pollock (2018). All *p*-values are equally likely under the null hypothesis, suggesting that the significant *p*-value may most parsimoniously be an artifact of Type 1 error. Alternatively, exploratory analyses reported in the Supplemental Online materials provide preliminary evidence that slowed information processing speed may disrupt working memory under specific circumstances, but must be considered very tentative given the unsupportive omnibus effects.

an effect of increasing working memory demands on reducing information processing speed ($BF_{10} = 5.87 \times 10^{96}$). There was insufficient evidence to rule out a main effect of group ($BF_{01} = 2.01$) but this effect must be considered in the context of significant interaction effects. Relative to the main effects model, there was significant evidence for 2-way interactions of information processing speed x working memory ($BF_{10} = 2.09 \times 10^{5}$) and group x information processing speed ($BF_{10} = 118.89$), but significant evidence *against* the group x working memory interaction ($BF_{01} = 4.66$) for effects on drift rate. The 3-way group x information processing speed x working memory interaction was also supported ($BF_{10} = 8.15$). Post-hoc tests for these interactions indicated that the ADHD group demonstrated slower information processing speed (i.e., slower drift rate) than the Non-ADHD group only during conditions with both low working memory and low information processing demands. That is, at low working memory demands there was a significant group x information processing speed interaction ($BF_{01} = 4302.87$) that reflects the finding that the ADHD group demonstrates slower drift rate during low information processing speed ($d = -0.30$) but not high information processing speed conditions ($d = 0.10$). Likewise, at high working memory demands there is significant evidence *against* group ($BF_{01} = 6.09$) and group x information processing speed ($BF_{01} = 7.72$) effects that reflect a lack of between-group differences in drift rate during under both low ($d = -0.11$) and high ($d = -0.06$) information processing demands.

Taken together, results of the LBA model were consistent in documenting significant reductions in information processing speed due to increasing working memory demands, while suggesting that ADHD may be associated with slowed information processing speed (drift rate) only under relatively low-level task demands.

Tier 3: Sensitivity Analyses

First, we probed the extent to which individual differences in reading skill impacted the current results by repeating all analyses reported above covarying for KTEA-3 Letter-Word Identification subtest standard scores (age norms; Kaufman & Kaufman, 2014). The pattern of results was unchanged when controlling for reading skills as expected because the eight conditions were equivalent in their inclusion of interleaved sentence reading, and any subtle differences in processing demands across sentences was controlled by random presentation from a database of 196 simple sentences.

Next, additional analyses were conducted to probe the extent to which results were impacted by our *a priori* decision to include both neurotypical and clinical control children in the Non-ADHD group. This process involved repeating the Tiers 1 and 2 analyses after splitting the Non-ADHD group into separate neurotypical and clinical control subgroups (Supplementary Online Appendix A). Overall, the pattern and interpretation of results were highly consistent with those reported in the main text; the ADHD group showed impairments relative to both control groups, and there were no interactions between group and the information processing speed/working memory experimental manipulations for producing cross-domain effects.

Finally, we probed for potential effects of experimentally reducing information processing speed as a function of working memory load. This process involved repeating the Tier 1 analyses using memory load data from the 4 high working memory conditions (performance at set sizes 3–6). As shown in the Supplementary Online materials (Appendix B), the pattern and interpretation of results is unchanged, with the exception that the data did not support an interaction between group and working memory load (BF_{01}=77.54; i.e., the magnitude of between-group differences was similar across all memory loads, supporting our decision to analyze overall recall performance in the main text). All other effects were highly consistent with those reported in Tier 1, including significant ADHD/Non-ADHD group differences (BF_{10}=26.11), support for the integrity of the experimental manipulation (i.e., recall performance decreased as memory load increased; $BF_{10}=6.25\times10^{25}$, d = 1.20; Supplementary Figure 2), and evidence against interactions with information processing speed (all $BF_{01} > 9.57$). Taken together, results of the sensitivity analyses were highly consistent with the results reported in the main text. Expanded reporting of these alternate analytic approaches can be found in the Supplementary Online materials, where we also describe exploratory analyses based on modeling drift rate under diffusion model assumptions and explore a discrepancy between frequentist and Bayesian results as footnoted above.

Discussion

The current study was the first to concurrently manipulate information processing speed and working memory demands to inform the directionality of effects, with implications for conceptual models of neurocognitive functioning in children with ADHD. The data provided decisive evidence that both experimental manipulations were successful, with large decrements in working memory recall when working memory demands were experimentally increased and large reductions in drift rate when information processing speed was experimentally slowed. Additional strengths of the experiment include the use of multiple tasks to estimate each parameter, use of computationally-defined estimates of information processing speed (Voss et al., 2013), and inclusion of a carefully-phenotyped sample of children with and without ADHD equated for the number of non-ADHD disorders (Wilens et al., 2002). Overall, results replicate existing evidence that children with ADHD demonstrate reduced working memory capacity while suggesting more nuanced findings regarding slowed information processing speed in ADHD (Kasper et al., 2012; Karalunas et al., 2014).

Of primary interest in the current study was the nature of the information processing speed/ working memory relation in ADHD, and the extent to which this relation is causal and directional. Taken together, the data provide decisive evidence for the hypothesis that working memory abilities are involved in maintaining information processing efficiency. This conclusion is based on the finding that information processing speed was significantly slowed by concurrent working memory demands, is consistent with prior work demonstrating strong relations between working memory and processing speed (e.g., Schmiedek et al., 2007), and extends prior work via an experimental design that provides evidence for directionality. In contrast, there was insufficient evidence to support an effect of reducing information processing speed on working memory performance, such that the data were almost as likely under the null hypothesis as under the alternative hypothesis (BF_{10} = 1.31). This finding is highly similar to Bayesian re-analysis of the summary statistics (JASP Team, 2017) reported in the only other ADHD study (to our knowledge) to assess effects of experimentally reducing information processing speed on working memory performance (BF_{10}=2.10) (W eigard & Huang-Pollock, 2017). Thus, across both ADHD studies, the data do not provide sufficient evidentiary value for concluding that information processing speed affects children's working memory performance, such that the data are only 1.3–2.1 times more likely under the alternative than null hypothesis. In addition, neither study found an interaction between ADHD status and the information processing speed manipulation, providing significant evidence *against* the hypothesis that slowed information processing speed explains reduced working memory capacity in ADHD.

Predictions from the time-based resource-sharing model were partially supported, in that the maintenance/rehearsal of memory items and the processing of the secondary task competed for cognitive resources (i.e., information processing speeds were significantly slower during high vs. low memory load conditions). Indeed, the current results do not argue against the interfering effects of same-modality distractors on one's ability to actively rehearse information – that type of manipulation (i.e., simple span vs. complex span) was not tested in the current study, and such effects are well established and provide the empirical basis for the use of complex span tasks as indicators of working memory rather than just short-term memory (Conway et al., 2005; Unsworth & Engle, 2006). Instead, the insufficient evidence for effects of reducing information processing speed on working memory functioning across studies appears inconsistent with a time-based resource-sharing account of working memory deficits in ADHD. This pattern of results is consistent with ADHD functional working memory model predictions (Kofler et al., 2014; Rapport et al., 2008), goal-maintenance and dual mechanisms of control theories (Braver, 2012; Engle & Kane, 2014), experimental effects of executive function demands on information processing speed in ADHD (Alderson et al., 2008), and recent evidence from the cognitive literature for effects of working memory on information processing speed rather than vice versa (Wiemers & Redick, 2018). For example, Wiemers & Redick (2018) provided evidence against a processing speed explanation for individual differences in working memory, while demonstrating that low working memory capacity is associated with reduced ability to maintain consistent top-down control that manifests as increased intra-individual variability in the slow tail of the response time distribution. These findings parallel results from the ADHD literature, including (a) overall findings of impaired working memory (Kasper et al., 2012); (b) increased reaction time variability that appears attributable to a subset of abnormally slow responses (Karalunas et al., 2014); (c) meta-analytic evidence that response speed may be a strength in ADHD (or at least not impaired) when accounting for this subset of extreme trials (Kofler et al., 2013); (d) cross-sectional evidence that group differences in reaction time variability are no longer detectable after covarying working memory abilities (whereas working memory deficits remain large when covarying response variability; Kofler et al., 2014); and (e) the current findings that working memory demands reduce information processing speed (but not vice versa).

Taken together, there does not appear to be convincing evidence to support an information processing speed explanation for ADHD's well-documented impairments in top-down executive control (Sonuga-Barke et al., 2008). It is important to note, however, that a processing speed explanation cannot be ruled out conclusively due to lack of sufficient support for the null hypothesis. Future work may care to determine whether information processing speed exerts effects on working memory performance under specific conditions, for specific functions of working memory beyond dual-processing (e.g., serial/temporal reordering, continuous updating; Wager & Smith, 2003), and/or for specific short-term storage subsystems (e.g., verbal/visual vs. spatial; Nee et al., 2013). For example, our exploratory analyses suggested an effect of reducing information processing speed on working memory only at the highest working memory load. Although this finding must be interpreted with caution due to the unsupportive omnibus effect, it may be that information processing speed serves to facilitate the maintenance of information within working memory only when children are attempting to preserve more items than they can store in short-term memory. Alternatively, it may be that processing speed provides a better fit for modeling short-term memory rather than working memory (i.e., in relation to items degrading from passive storage over time rather than top-down/secondary memory processes involved in actively manipulating or retrieving these items after they have been lost; Gibson et al., 2018).

Interestingly, the current study was the only one of four recent experimental studies to detect an interaction between ADHD status and the information processing speed/executive function manipulation (current study; Alderson et al., 2008; Fosco et al., 2019; Weigard & Huang-Pollock, 2017). This interaction was detected for the information processing speed and working memory manipulations, but only when the manipulated process was the outcome (i.e., no cross-domain interaction effects that would suggest that impairments in one process are attributable to impairments in the other). These findings collectively indicate that (1) working memory deficits in ADHD cannot be explained by more basic task demands associated with the rate at which information is encoded, (2) the ADHD group's reduced information processing speed may be most detectable under conditions that allow relatively fast information processing speed and place relatively low demands on working memory (despite being relatively unaffected by changes in inhibition demands; Fosco et al., 2019), whereas conditions that evoke slower information processing speed/higher working memory demands differentially affect non-ADHD children who then perform more similarly to children with ADHD, and (3) children with ADHD have disproportionate difficulties retaining information across a delay, which occurs even when not faced with external distractors that produce interference effects and/or reallocate attention to prevent rehearsal of to-be-recalled stimuli (Bolden et al., 2012; Lemaire & Portat, 2018).

Importantly, however, these interactions were not found in exploratory analyses of memory load, or when modeled under alternative diffusion assumptions, and as such appear to be related specifically to the central executive demands associated with dual-processing working memory tasks rather than the short-term storage demands evoked when increasing memory load (Baddeley, 2007). A parsimonious conclusion based on these cross-study findings could be that information processing speed, inhibitory control, short-term memory, and working memory cannot account for ADHD-related impairments in the other processes (i.e., that they are relatively independent impairments in the case of information processing speed and working memory and/or intact in most children with ADHD in the case of inhibitory control and short-term memory; Alderson et al., 2007; Rapport et al., 2013). In other words, increasing demands on these processes affects ADHD and Non-ADHD groups similarly, despite pre-existing differences in these abilities. The observed pattern of selective, task-demand-specific drift rate deficits has also been observed in prior studies; for example, Huang-Pollock et al. (2016) reported that children with ADHD demonstrated impaired drift rate during an inhibition task under slow but not fast event rates.

Importantly, however, both groups showed reduced working memory capacity and slower information processing speeds as demands on these abilities were increased. As argued by Hudec et al. (2015), the combination of a pre-existing vulnerability and this additional decrement may push the ADHD group to a level associated with functional impairment, whereas the Non-ADHD group remains at subthreshold levels even under high demands on these processes. As a metaphor, a child with nearsightedness may not show impairments in the classroom until she is moved to a desk further away from the whiteboard than her visual acuity can accommodate. Thus, a child with ADHD may be able to process social bids quickly enough during a one-on-one interaction (lower working memory demands) but may struggle to do so during complex group interactions that require her to keep track of multiple conversation lines, integrate multiple sets of verbal/nonverbal communications, prepare her response in consideration of her prior experience, and hold that response until it is socially appropriate to respond (higher working memory demands; Aduen et al., 2018). Similarly, slowed information processing may not impair comprehension when reading structurally simple sentences (lower working memory demands) but may create a bottleneck that prevents the end of a more complex sentence (higher working memory demands) from entering the phonological storage/rehearsal system before the beginning of the sentence fades from memory (Friedman et al., 2016). Research identifying neurocognitive performance levels associated with impairments in ecologically-valid outcomes are needed to test this hypothesis.

Limitations

The current study was the first to concurrently manipulate demands on both working memory abilities and information processing speed in a relatively large and carefully-phenotyped sample of children with and without ADHD. Yet, several caveats must be considered. Given that co-occurring conditions are common in ADHD (Wilens et al., 2002), inclusion of children with these comorbidities in the ADHD group was important to maximize external validity and generalizability of our findings. We attempted to balance external and internal validity threats by recruiting a Non-ADHD group matched for the number of these Non-ADHD disorders; however, controlling for the number of other disorders does not perfectly equate the groups. Independent replications across developmental periods with larger samples, naturalistic outcomes, and a broader sampling of children with other clinical disorders are needed to assess the extent to which the directionality of effects identified herein are robust; if so, it may provide a meaningful framework for developing next-generation neurocognitive interventions for ADHD (Chacko et al., 2014).

Our tasks were self-paced to match the response phases of most working memory tasks used to establish the evidence base for working memory deficits in children with ADHD (Kasper et al., 2012) as well as the presentation phases of many neuropsychological tests of working memory. Despite the improved ecological validity for linking the findings with the extant evidence base, there are important differences in task design that merit careful scrutiny despite the consistency in results across studies. When compared to the only other ADHD study to examine effects of experimentally reducing information processing speed on working memory, we find that both studies manipulated information processing speed within the context of a complex span task (Weigard & Huang-Pollock, 2017) as opposed to manipulating simple vs. complex span as would be done to evoke working memory demands by inducing interference/decay effects in short-term memory (e.g., Conway et al., 2005). In addition, both studies manipulated information processing speed by manipulating stimulus complexity, but did so at different points in the flow of the experiment (i.e., during the primary encoding vs. secondary distractor task). Further, the current study controlled for the quantity of stimuli processed vs. controlling for processing duration, and manipulated both information processing speed and working memory and as such measured processing duration rather than controlling for it. These design differences appear in large part related to differences in the conceptual model used to build the experiment. That is, the Weigard & Huang-Pollock (2017) manipulation appears consistent with the logic of the classic reading span task, wherein easily-encoded primary stimuli are presented (e.g., single letters) and dual-processing demands are evoked via the addition of a secondary distractor task similar to the current study's interleaved true/false sentences (which were a constant across all 8 tasks in the current study). In contrast, our information processing speed manipulation followed the logic of the classic counting span task, wherein the initial encoding of stimuli is processing-intensive and evokes interference effects even in the absence of a secondary processing task (Conway et al., 2005). Importantly, however, there was decisive evidence that we successfully manipulated information processing speed (i.e., robust decreases in drift rate under the slower vs. faster information processing conditions), and the equivocal evidence for effects of information processing speed on working memory was highly consistent with Bayesian re-analysis of Weigard & Huang-Pollock's (2017) summary statistics. Replications that manipulate additional *working* (e.g., updating, reordering; Wagers & Smith, 2003) and *memory* (e.g., spatial storage, verbal and spatial rehearsal mechanisms; Bolden et al., 2012) subcomponents of working memory beyond the current study's verbal dual-processing demands are needed to clarify the specificity of the directional effects of working memory on information processing speed and will be particularly important given that children with ADHD often show larger impairments on updating/reordering tasks relative to dual-processing/complex span tasks (Fosco et al., under review; Kasper et al., 2012). Finally, despite conclusive evidence that our experimental manipulations successfully increased demands on their target processes, it is possible that they produced additional, unmeasured changes in other processes as well. Identification and manipulation/measurement of these processes will help clarify the extent to which the effects reported herein were specifically due to the constructs of interest.

Clinical and Research Implications

Taken together, current and recent findings indicate that top-down executive control exerts a significant effect on tasks intended to measure information processing speed (Alderson et al., 2008; Wiemers & Redick, 2018). In contrast, slowed information processing speed does not appear to be a viable explanation for reduced working memory capacity in either ADHD (current study; Weigard & Huang-Pollock, 2017) or non-clinical samples (Wiemers & Redick, 2018), although there was insufficient evidence to conclusively rule out such an influence. Our exploratory analyses suggested that future research may provide improved evidentiary value by identifying specific scenarios in which information processing speed may affect working memory performance (e.g., at memory loads that exceed children's short-term storage/rehearsal capacity). In that context, the significant evidence *against* interactions between ADHD status and both manipulations on the cross-domain process suggests that neither impairment can provide a parsimonious explanation for the poor performance of children with ADHD on tasks intended to assess the competing process (i.e., the working memory manipulation did not differentially produce processing speed deficits for children with ADHD, nor did the information processing speed manipulation differentially produce working memory deficits for children with ADHD). Thus, it appears that working memory deficits and slowed information processing speed are relatively independent impairments in ADHD, although of course it remains possible that another deficit not examined herein may broadly influence both working memory and information processing speed performance. More generally, the current findings suggest that these processes exert relatively independent effects on task performance, although only working memory demands affected performance on both. Consideration of both of these mechanisms, and how they fit into the broader taxonomy of neurocognitive and behavioral impairments in ADHD, will be important for developing next-generation neurocognitive interventions (Chacko et al., 2014), clarifying neurocognitive heterogeneity in ADHD (Coghill et al., 2014; Nigg, 2005), and improving the science and technology of ADHD assessment and diagnosis (Rapport et al., 2000).

Supplementary Material

Refer to Web version on PubMed Central for supplementary material.

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Public Significance Statement

Children with ADHD have difficulties on tests intended to measure a broad range of neuropsychological functions. However, it is unclear whether this means that children with ADHD have many distinct deficits or whether they have a smaller number of deficits that broadly influence their performance on these types of tests. The current study focused on two key neuropsychological functions implicated in ADHD – information processing speed and working memory. We found that working memory abilities impact children's information processing speed, but that working memory and slowed information processing speed are likely independent impairments in ADHD.

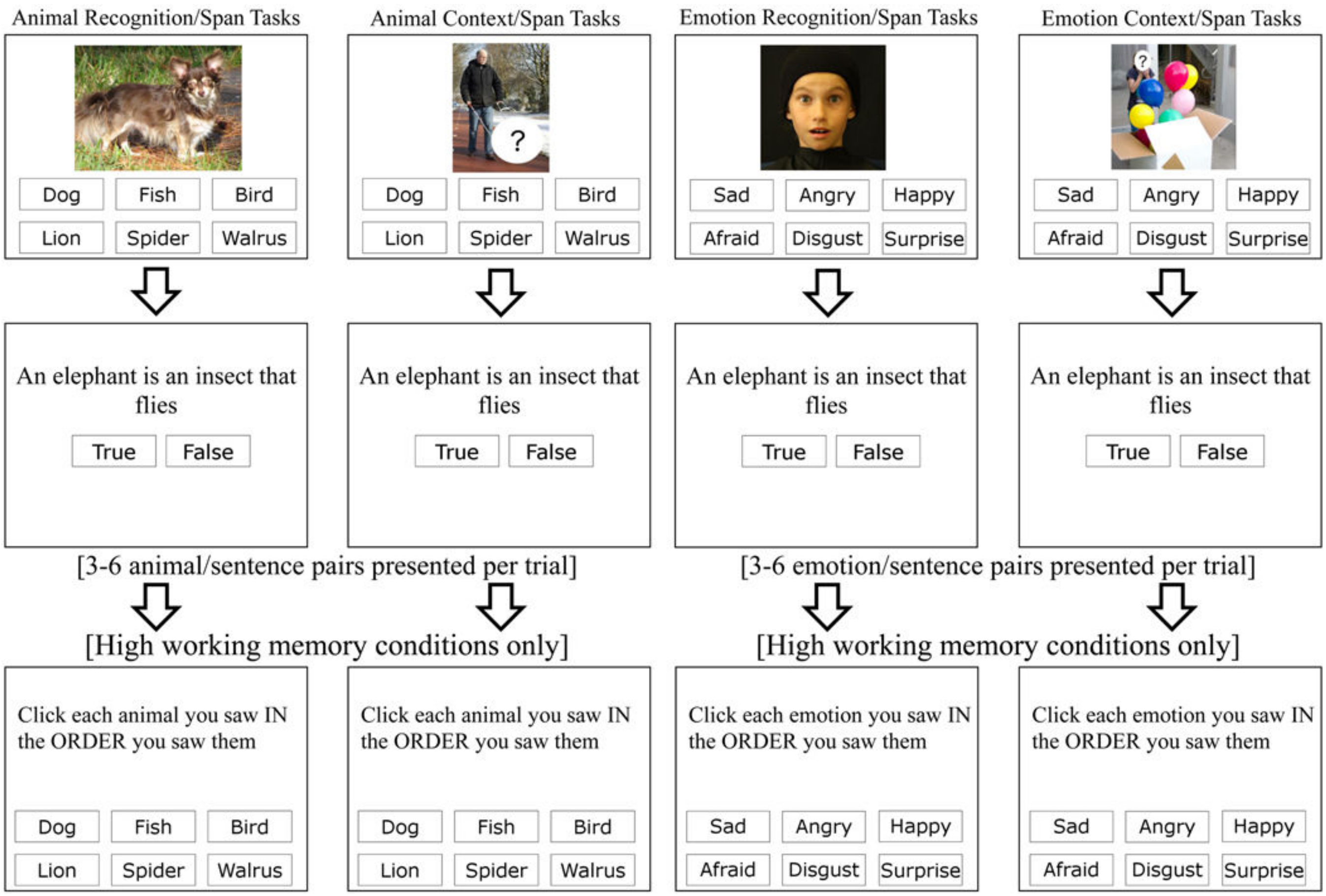

Figure 1.

Fully-crossed experimental manipulation of working memory and information processing demands. Each of the eight counterbalanced tasks presented 36 randomly selected emotions/ animals and sentences. Each of the four low/high working memory task pairs (recognition/ span) were identical except for the omission or addition of concurrent working memory demands. Each of the four low/high information processing demands task pairs (recognition/ context recognition) were identical except for the presentation of clearly identifiable archetypes (faster information processing speeds) vs. contexts from which the target must be inferred (slower information processing speeds). Words/icons outside the large boxes were not shown on screen, but are included here to illustrate differences across the eight otherwise identical experimental tasks. The parent of the child model provided written informed consent for publication of their child's photographs (used under license from the Dartmouth Database of Children's Faces; Dalrymple et al., 2013). The remaining photos are used with permission of the author ("Scampy" in the animal recognition photo) or used under license from shutterstock.com.

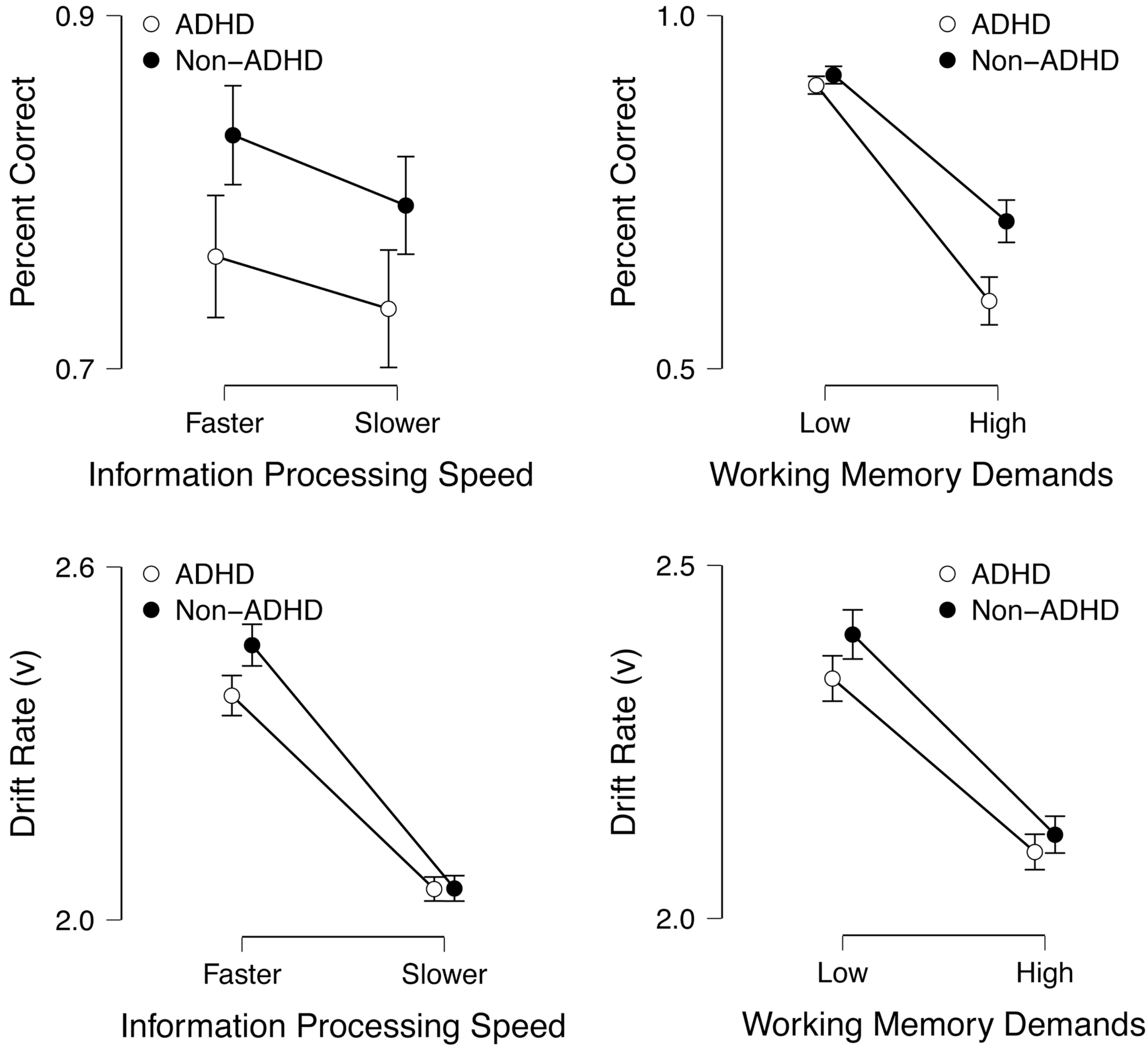

Figure 2.
Effects of the information processing speed and working memory manipulations. Top: Effects on working memory performance (DV: percent correct) as a function of experimentally reducing information processing speed (top left) and increasing working memory demands (top right). Bottom: Effects on information processing speed (DV: linear-ballistic-accumulator-modeled drift rate) as a function of experimentally reducing information processing speed (bottom left) and increasing working memory demands (bottom right). In the bottom Figures, faster and slower information processing speed were evoked by the low and high information processing demand conditions, respectively.

Table 1.

Sample and demographic variables

Variable	ADHD (*n*=45)		Non-ADHD (*n*=41)		Cohen's *d*	*BF*$_{10}$	*BF*$_{01}$	*P*
	M	***SD***	***M***	***SD***				
Gender (Boys/Girls)	28/17		24/17		--		3.65	.73, *ns*
Ethnicity (AA/A/C/H/M)	6/0/32/4/3		5/3/24/7/2		--		13.55	.28, ns
Age	10.27	1.49	10.79	1.56	−0.34		1.53	.12, *ns*
SES	46.00	12.19	51.48	11.08	−0.47	1.73		.03
WISC-V VCI (Standard Score)	102.80	14.58	109.02	10.78	−0.48	1.94		.03
KTEA-3 Letter Word Identification	98.09	12.91	108.17	14.24	−0.74	33.07		<.001
KTEA-3 Reading Comprehension	97.13	13.07	104.66	12.52	−0.59	5.34		.008
BASC-2/3 Attention Problems (T-score)								
Parent	65.82	8.60	59.34	10.44	0.68	15.15		.002
Teacher	62.51	8.65	55.61	11.20	0.69	17.77		.002
BASC-2 Hyperactivity (T-score)								
Parent	67.89	12.71	56.41	12.71	0.90	301.22		< .001
Teacher	60.84	14.91	54.63	13.09	0.44	1.37		.04
Working Memory Recall Performance (Percent Stimuli Correct/Trial)								
Animal Span Set Size 3	0.73	0.27	0.92	0.15	−0.83	204.03		<.001
Animal Span Set Size 4	0.73	0.28	0.82	0.24	−0.35	1.32		.11, *ns*
Animal Span Set Size 5	0.68	0.30	0.79	0.26	−0.41	2.02		.06, *ns*
Animal Span Set Size 6	0.65	0.24	0.68	0.30	−0.11		2.95	.62, *ns*
Emotion Span Set Size 3	0.61	0.31	0.77	0.28	−0.56	7.70		.01
Emotion Span Set Size 4	0.59	0.35	0.77	0.25	−0.56	8.29		.01
Emotion Span Set Size 5	0.52	0.30	0.64	0.29	−0.38	1.69		.08, *ns*
Emotion Span Set Size 6	0.49	0.30	0.63	0.23	−0.52	5.62		.02
Animal Context Span 3	0.76	0.27	0.89	0.16	−0.54	6.69		.01
Animal Context Span 4	0.67	0.27	0.78	0.25	−0.41	2.12		.06, *ns*
Animal Context Span 5	0.62	0.30	0.71	0.26	−0.32	1.06		.14, *ns*
Animal Context Span 6	0.50	0.30	0.64	0.22	−0.54	6.44		.02
Emotion Context Span 3	0.69	0.34	0.82	0.22	−0.45	2.85		.04
Emotion Context Span 4	0.59	0.29	0.69	0.29	−0.35	1.29		.11, *ns*
Emotion Context Span 5	0.50	0.27	0.57	0.29	−0.25		1.41	.25, *ns*
Emotion Context Span 6	0.47	0.29	0.57	0.27	−0.37	1.52		.09, *ns*
Drift Rate (Seconds)								
Animal Recognition	2.89	0.36	3.03	0.32	−0.40	1.02		.07, *ns*
Emotion Recognition	2.15	0.24	2.28	0.22	−0.60	6.28		.006
Animal Span	2.38	0.10	2.37	0.12	0.14		3.71	.53, *ns*
Emotion Span	1.94	0.04	1.93	0.05	0.19		3.16	.38, *ns*
Animal Context Recognition	2.41	0.27	2.48	0.25	−0.26		2.32	.23, *ns*
Emotion Context Recognition	2.08	0.21	2.08	0.17	−0.02		4.43	.94, *ns*

Variable	ADHD (n=45)		Non-ADHD (n=41)		Cohen's d	BF_{10}	BF_{01}	P
	M	***SD***	***M***	***SD***				
Animal Context Span	2.12	0.13	2.14	0.13	−0.17		3.44	.45, *ns*
Emotion Context Span	1.77	0.07	1.78	0.07	−0.07		4.22	.74, *ns*

Note. BF_{10} = Bayes Factor for the alternative hypothesis over the null hypothesis (values ≥ 3.0 indicate significant between-group differences). BF_{01} = Bayes Factor for the null hypothesis over the alternative hypothesis (values ≥ 3.0 indicate significant between-group equivalence; BF_{01} = $1/BF_{10}$). *P*-values are not corrected for family-wise error, and are included for illustrative purposes to allow interested readers to compare Bayesian and frequentist results. Drift rates are averaged across the 6 response options for each task. BASC = Behavior Assessment System for Children. Ethnicity: AA = African American, A = Asian, C = Caucasian Non-Hispanic, H = Hispanic, M = Multiracial. KTEA-3 = Kaufman Test of Educational Achievement, Third Edition. WISC-V = Wechsler Intelligence Scale for Children, Fifth Edition.