Evidence Against Emotion Inference Deficits in Children with ADHD

Erica L. Wells, MS, MEd[1], **Nicole B. Groves, MS**[1], **Taylor N. Day, MS**[1], **Sherelle L. Harmon, PhD**[2], **Elia F. Soto, MS**[1], **Caroline E. Miller, BA**[1], **Michael J. Kofler, PhD**[1]

[1]Florida State University, Department of Psychology

[2]Harvard University, Department of Psychology

Abstract

Inconsistent evidence suggests that pediatric ADHD may be associated with impairments in the ability to use context clues to infer the emotion states of others. However, the evidence base for these impairments is comprised of data from laboratory-based tests of emotion inference that may be confounded by demands on non-affective cognitive processes that have been linked with ADHD. The current study builds on our previous study of facial affect recognition to address this limitation and investigate a potential mechanism underlying children's ability to infer emotion state from context clues. To do so, we used a fully-crossed, counterbalanced experimental design that systematically manipulated emotion inference and working memory demands in 77 carefully-phenotyped children ages 8–13 (M_{age}=10.46, SD=1.54; 66% Caucasian/Non-Hispanic; 42% female) with ADHD (n=42) and without ADHD (n=35). Results of Bayesian mixed-model ANOVAs indicated that using context clues to infer the emotion state of others competed for neurocognitive resources with the processes involved in rehearsing/maintaining information within working memory (BF_{10}=1.57×10^{19}, d=0.72). Importantly, there was significant evidence *against* the critical group x condition interaction for response times (BF_{01}=4.93), and no significant evidence for this interaction for accuracy (BF_{01}=2.40). In other words, children with ADHD do not infer emotions more slowly than children without ADHD (d=0.13), and their small magnitude impairment in accuracy (d=0.30) was attributable to their generally less accurate performance on choice-response tasks (i.e., across both emotion and control conditions). Taken together, the evidence indicates that emotion inference abilities are likely unimpaired in pediatric ADHD and that working memory is implicated in the ability to infer emotion from context for all children – not just children with ADHD.

Keywords

ADHD; emotion recognition; emotion inference; working memory

Corresponding Author: Michael J. Kofler, Ph.D., Florida State University | Department of Psychology, 1107 W. Call Street | Tallahassee, FL 32306-4301, Phone: (850) 645-0656, Fax: (850) 644-7739, kofler@psy.fsu.edu.

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Attention-deficit/hyperactivity disorder (ADHD) is a chronic and impairing neurodevelopmental disorder that affects approximately 5% of school-aged children worldwide (Polanczyk et al., 2007, 2014). Clinically elevated symptoms of inattention, hyperactivity, and/or impulsivity typify the disorder and result in family, peer, and/or academic impairment (APA, 2013). In addition, approximately half of children with ADHD experience clinically significant difficulties monitoring, evaluating, and adjusting their emotional responses to accomplish personal goals (i.e., emotion dysregulation; Bunford et al., 2014; Bunford et al., 2015; Graziano & Garcia, 2016, Shaw et al., 2015). Existing literature suggests that several foundational skills interact to facilitate adaptive emotion regulation, including awareness and conscious processing of emotions, as well as recognition and labeling of emotions (Berking et al., 2008; Feldman-Barrett et al., 2001; Graziano & Garcia, 2016; Lischetzke & Eid, 2003). Given that accurate identification of emotions is often a precursor to effective regulation of those emotions, it is important to understand the extent to which children with ADHD have underlying difficulties in emotion recognition. If children with ADHD exhibit deficits in emotion recognition (i.e., the detection and accurate labeling of discrete emotions; Young et al., 1997), this skill deficit would likely be an appealing intervention target and may help clarify the etiology of emotion dysregulation in ADHD.

Measurement of Emotion Recognition in ADHD

The pediatric ADHD literature is mixed with respect to emotion recognition in ADHD, with the majority of this literature focusing on facial affect recognition in others (Graziano & Garcia, 2016). Indeed, this literature appears to be characterized by a similar number of studies that find (Boakes et al., 2008; Da Fonseca et al., 2009; Pelc et al., 2006; Shin et al., 2008; Sinzig et al., 2008) and do not find that ADHD is associated with impairments on facial affect-based choice-response tasks (Berggren et al., 2016; Downs & Smith, 2004; Greenbaum et al., 2009; Guyer et al., 2007; Passarotti et al., 2010). The reason for these discrepant findings is unclear, but a compelling possibility is the uncontrolled presence of impairments that impact performance on *non-emotional aspects* of the tasks (Graziano & Garcia, 2016). For instance, several studies found that deficits in sustained attention, working memory, and inhibitory control predicted the performance of children with ADHD on affect recognition tasks, both in studies that concluded that the ADHD group exhibited affect recognition deficits (Shin et al., 2008; Sinzig et al., 2008) and in studies that concluded children with ADHD did not exhibit deficits (Berggren et al., 2016; Passarotti et al., 2010). Additionally, all but one (Downs & Smith, 2004) of the above-cited studies measured affect recognition with choice-response tasks.

Meta-analytic evidence indicates that children with ADHD perform more slowly, less accurately, and less consistently than non-ADHD groups on choice-response tasks in general, irrespective of task content (overall effect size = 0.76; Kofler et al., 2013). '*Choice-response task*' is a general term for tasks that require participants to select a response from among a set of competing options. Despite their extensive use for studying components of emotion processing in a wide range of child, adolescent, and adult neurotypical and clinical populations (Babbage et al., 2011; Baron-Cohen et al.,1997; Brune, 2005; Collin et al., 2013; Hooker & Park, 2002; Shean et al., 2007; Uekermann et al., 2010), the use of choice-response tasks for understanding emotion recognition abilities in children with ADHD may introduce key confounds due to this population's well-documented difficulties with these types of tasks even in the absence of emotion-specific stimuli (e.g., Kofler et al., 2013). Choice-response tasks inherently require attention to task stimuli, maintenance of task rules in working memory, and efficient responding demands that are likely to impair the performance of children with ADHD (Butler et al., 2011; Metin et al., 2013; Rowe et al., 2000).

To that end, the precursor to the current study used an experimental, dual-task design to dissociate facial affect recognition from more general choice-response difficulties in ADHD (Wells et al., 2019). Using four counterbalanced tasks and a Bayesian analytical approach, we found significant evidence *against* deficits in emotion recognition in ADHD. That is, carefully-phenotyped children with and without ADHD demonstrated equivalent emotion recognition accuracy, and children with ADHD did not show disproportionate slowing relative to controls when shown emotion vs. non-emotion stimuli. However, Wells et al. (2019) examined simple facial affect recognition rather than more complex aspects of emotion recognition – a key limitation given that in vivo emotion recognition is a dynamic process that requires the decoding and interpretation of complex information beyond facial affect (e.g., Barrett et al., 2007, 2011; Da Fonseca et al., 2009). For example, individuals may need to infer the emotion state of others (i.e., emotion inference) using observable cues beyond facial expression, such as voice tone and volume, body posture, current situational factors, and, importantly for the current study, contextual clues in one's environment (Graziano & Garcia, 2016; Barrett et al., 2011; Gunes & Piccardi, 2007).

To our knowledge, only two studies have examined more complex aspects of emotion recognition in pediatric ADHD via carefully-controlled tasks that require children to evaluate contextual clues to infer someone's emotional response (i.e., emotion inference; Da Fonseca et al., 2009; Shin et al., 2008). While findings from both studies indicated poorer performance on emotion inference tasks in their ADHD relative to Non-ADHD control groups (Da Fonseca et al., 2009; Shin et al., 2008), only Da Fonseca and colleagues (2009) included a non-emotion control task to examine the specificity of this finding. Consistent with Wells et al. (2019), Da Fonseca et al. (2009) reported a non-significant group x condition interaction, suggesting that their results may be more parsimoniously attributed to basic choice-response errors independent of the task's emotion content. The current study builds on this experimental design by including non-emotion control tasks along with tasks that experimentally manipulate both context-based emotion inference and top-down working memory demands to clarify the extent to which, and circumstances in which, children with ADHD exhibit impairments in their ability to accurately and efficiently use context clues to infer another individual's emotion state.

Working Memory Deficits and Emotion Recognition in ADHD

Children with ADHD also exhibit impairments in working memory (Kasper et al., 2012), and these underlying working memory deficits have been linked behaviorally and cognitively with impaired performance across a broad range of clinic- and laboratory-based tests, tasks, and paradigms (Hudec et al., 2015; Kofler et al., 2010; Patros et al., 2017;

Rapport et al., 2009). Working memory is a core executive function responsible for the temporary storage and manipulation of information held in short-term memory, and includes interrelated processes associated with serial/temporal reordering, continuous updating, and dual-processing for use in guiding behavior (Wager & Smith, 2003). Importantly for our purposes, working memory has been linked with top-down cortical networks associated with emotion recognition (Dickstein & Castellanos, 2011) and has been shown to predict facial affect recognition abilities (Wells et al., 2019) and social skills deficits in children with (Bunford et al., 2014; Kofler et al., 2011, 2018) and without ADHD (Phillips et al., 2008).

To our knowledge, only one ADHD study has experimentally manipulated working memory demands within the context of an emotion recognition task. Using a subset of the current sample, Wells et al. (2019) found that working memory demands significantly disrupted children’s facial affect recognition efficiency, with these effects occurring equivalently for children with and without ADHD. However, no study to date has examined the extent to which this finding applies to more complex aspects of emotion recognition such as evaluation of environmental cues – a critical omission given behavioral and neuroimaging evidence suggesting that more complex aspects of emotion recognition may place significantly greater demands on top-down cognitive control processes (for review, see Dickstein & Castellanos, 2011). Given the dynamic nature of emotion recognition that requires children to encode and simultaneously process multiple interpersonal and environmental cues (Phillips et al., 2007), we hypothesized that children with ADHD may experience difficulty processing emotion-related information due to a ‘bottleneck’ that prevents them from concurrently inferring another’s emotion state and maintaining other relevant information in mind (Aduen et al., 2018). In other words, emotion inference based on contextual clues requires interpretation of environmental information (e.g., situation, body language), inference of the likely emotion state associated with the context, knowledge of emotion labels, and maintenance of all of this information in the working memory system (where the ‘bottleneck’ – or cognitive gridlock – likely occurs).

As argued by Wells et al. (2019), dual-task methodologies are well-suited for assessing the extent to which two cognitive processes compete for resources (i.e., rely at least in part on the same underlying neurocognitive networks; Kofler et al., 2019). By experimentally manipulating demands on a candidate causal process (e.g., working memory) and measuring the impact of this manipulation on a hypothesized outcome (e.g., emotion inference), this methodology can provide strong evidence for directionality by demonstrating a cause-and-effect relation between a hypothesized mechanism and behavioral outcome (Wang & Gathercole, 2013). For example, finding that children demonstrate a reduced ability to accurately and efficiently infer others’ emotion state under high working memory demands would indicate that they process emotion-related stimuli, at least in part, within the working memory system. In contrast, finding that the working memory manipulation does not reduce children’s emotion inference performance would indicate that emotion inference involves functionally distinct neural systems from those implicated in working memory, and provide strong evidence that the association between working memory and emotion inference is not likely causal in nature.

Current Study

The current experiment builds on Wells et al. (2019) to evaluate the extent to which an additional component of emotion recognition previously reported to be impaired in pediatric ADHD – one's ability to infer another's emotional state using contextual clues – was more parsimoniously explained by uncontrolled task-related confounds and/or evoked/exacerbated under conditions that taxed their underdeveloped working memory system. The current study examines children's ability to infer emotions in others based on contextual clues like situation and body language (subsequently called "emotion inference"). Children completed four fully-crossed and counterbalanced tasks that systematically manipulated demands on both emotion inference (no/yes) and working memory (low/high). Similar to the two studies described above (Da Fonseca et al., 2009; Shin et al., 2008), the emotion inference task required children to use contextual clues to identify the 'hidden' emotion felt by a target individual without reference to that target's facial expression (Figure 1). This task was in turn paired with an otherwise-identical choice-response task (inferring a 'hidden' animal based on context), and both of these tasks were in turn paired with otherwise-identical working memory 'complex span' variants as described below.

The ADHD group was expected to respond more slowly and less accurately across all four tasks, regardless of emotional content or concurrent working memory demands. Of critical interest were the group x condition interaction effects. Concluding that ADHD is associated with emotion inference deficits would require evidence for disproportionate performance decrements when emotion-specific inference was required (i.e., the interaction would provide evidence that any difficulties with the emotion inference task could not be explained more parsimoniously by ADHD-related difficulties with choice-response tasks). In addition, we predicted disruptions in emotion inference efficiency (i.e., speed) for both the ADHD and Non-ADHD groups when working memory demands were experimentally induced (Wells et al., 2019).

Method

Open Data and Open Science Disclosure Statement

Detailed results output and the de-identified raw dataset (.jasp) are available on the Open Science Framework (OSF) at: https://osf.io/r6vwx/. We report how we determined our sample size, all data exclusions, all manipulations, and all measures in the study (Simmons et al., 2012).

Participants

The sample included 86 children ages 8–13 years consecutively recruited or referred to a university-based children's learning clinic (CLC) through community resources (e.g., pediatricians, community mental health clinics, school system personnel, self-referral) from 2015 to 2017 (as detailed below, 9 of these 86 children were assessed but excluded). The CLC is a research-practitioner training clinic known to the surrounding community for conducting developmental and clinical child research and providing *pro bono* comprehensive diagnostic and psychoeducational services. Its client 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. Exclusionary criteria for the study included gross sensory, motor, or neurological impairment; non-stimulant medications that could not be withheld for testing; and intellectual disability, psychosis, seizure, or autism spectrum disorder (n=9), resulting in the final N of 77 (42 ADHD, 35 Non-ADHD).

Institutional Review Board approval was obtained/maintained, and all parents and children gave informed consent/assent. Psychoeducational evaluations were provided to the parents of all participants. Sample ethnicity was mixed with 51 Caucasian/Non-Hispanic (66.2%), 10 Hispanic/Latinx (13%), 9 African American (11.7%), 3 Asian American (3.9%), and 4 mixed race children (5.2%). All participants spoke English.

Group Assignment

All children and caregivers completed an identical, comprehensive evaluation that included detailed, semi-structured clinical interviewing and multiple norm-referenced parent and teacher questionnaires. A detailed account of the comprehensive psychoeducational evaluation can be found in the preregistration for our ongoing intervention study: https://osf.io/abwms. Briefly, the ADHD group included 42 children (16 girls; 26 combined, 13 inattentive, 3 hyperactive/impulsive presentation) who met all of the following criteria: (1) DSM-5 diagnosis of ADHD by the directing clinical psychologist based on semi-structured clinical interviewing with parents (K-SADS; Kaufman et al., 1997) and review of all available clinical information indicating onset, course, duration, and severity of ADHD symptoms consistent with the ADHD neurodevelopmental syndrome; (2) clinical/borderline elevations on at least one teacher and one parent ADHD rating scale, and (3) current impairment based on parent report. Psychostimulants ($N_{prescribed}$=21) were withheld ≥24 hours for testing. To promote the generalizability of study findings, common comorbidities were not exclusionary and included anxiety (26.2%), depressive (9.5%), and oppositional defiant disorders (14.3%).[1]

Thirty-five consecutive case-control referrals did not meet ADHD criteria and were included in the Non-ADHD group (46% girls). Neurotypical children (45.7%) in the Non-ADHD group were recruited through community resources and had nonclinical parent/teacher ratings and unremarkable developmental histories. Children who were diagnosed with clinical disorders other than ADHD were also included in the Non-ADHD group to control for comorbidities in the ADHD group to maximize the likelihood that ADHD/Non-ADHD between-group differences could be attributable to ADHD specifically rather than psychopathology generally. Comorbidities reflect clinical consensus best estimates (Kosten & Rounsaville, 1992), and included anxiety (34.3%), depressive (8.6%), and oppositional defiant disorders (5.7%). Importantly, Bayesian χ^2 analyses indicated that the ADHD group was equivalent to the Non-ADHD in terms of inclusion of children diagnosed with disorders other than ADHD both overall (BF_{01}=3.98) and across diagnostic categories (anxiety: BF_{01}=3.27; depression: BF_{01}=4.18; ODD: BF_{01}=2.21). A subset of children screened positive for learning disabilities (7.14% ADHD, 0% Non-ADHD) based on Kaufman Test of

[1]As recommended in the KSADS, ODD was diagnosed only with evidence of multi-setting symptoms/impairment.

Educational Achievement (KTEA-3; Kaufman et al., 2014) Reading and Math Composite score(s) >1.5 SD below age-norms.

Procedures

To minimize order/fatigue effects, tasks were counterbalanced within and across a larger test battery that required children's presence for two, 3-hour sessions. To minimize fatigue, breaks were scheduled every 2–4 tasks; brief breaks were also provided between each task. The examiner monitored children's performance at all times from just out of the child's view (outside of the testing room) to minimize examiner demand characteristics while maintaining a structured setting (Gomez & Sanson, 1994).

Experiment Overview

Four tasks were designed to systematically manipulate emotion inference and working memory demands. The computerized tasks and task stimuli were designed/selected using a layered approach to address core questions regarding the mechanisms and processes associated with emotion inference abilities in ADHD while also addressing questions regarding cognitive efficiency and reading skills in ADHD (Kofler et al., 2019). The tasks were identical in every aspect except for the manipulated processes to provide a fully-crossed, 2×2 experiment with one task each per emotion inference (no vs. yes) x working memory (low vs. high) combination (Figure 1). This experiment was accomplished by pairing an emotion inference task ('hidden emotion') with an otherwise identical 'hidden animal' task to test the hypothesis that ADHD-related impairments in emotion inference were an artifact of task demands unrelated to emotion content (i.e., attributable to their difficulties with choice-response tasks generally rather than emotion inference specifically). Both tasks were then paired with high working memory versions to test the extent to which the ADHD group's hypothesized emotion inference deficits were evoked or exacerbated by their underdeveloped working memory abilities (Figure 1).

Task Stimuli

Emotion inference (*emotion context*) stimuli.—The computerized emotion inference tasks included photographs of situations in which people are experiencing one of six basic emotions (sad, angry, happy, afraid, disgust, surprise; Ekman, 1992). As shown in Figure 1, each of these *emotion context* photographs presented a target individual experiencing a 'hidden emotion' (i.e., the target's face was fully covered with a white oval). Following Da Fonseca et al. (2009), the target's face was covered to require children to infer emotion state based on context rather than facial affect. Forty high-quality, color photographs of each 'hidden emotion' were selected based on >90% correct identification by the study team during task development. The photos were then assigned randomly to the Emotion Context Processing and Emotion Context Span tasks (see below).

Animal inference (*animal context*) stimuli.—Animal photographs were selected to create control tasks that were matched as closely as possible with the emotion tasks (e.g., image size/quality, number of choice-response categories, highly familiar stimuli; Eimas & Quinn, 1994). In addition, animal stimuli produce overlapping but moderately weaker neural activation relative to human faces (Chao et al., 1999; Haxby et al., 2000), suggesting that the use of animal stimuli may provide improved control for isolating effects specific to inference of human emotions (Wells et al., 2019). Each *animal context* stimulus featured a scene that included a ‘hidden animal’ (a dog, fish, bird, lion, spider, or walrus fully covered by a white oval).[2] To match the emotion inference task, the animal was covered to require children to infer the animal’s identity based on context rather than simple recognition (Figure 1). Forty high-quality, color photographs of each ‘hidden animal’ were selected based on >90% correct identification by the study team during task development. The photos were then assigned randomly to the Animal Context Processing and Animal Context Span tasks (see below).

Task Overview

Each task comprised 36 trial pairs. Each stimulus-distractor pair required children to infer one ‘hidden’ animal or emotion and then process one distractor stimulus (a true/false sentence obtained from the WJ-III reading fluency subtest; Woodcock et al., 2001). As described below, the high working memory conditions also included a recall phase that occurred unpredictably after every 3–6 stimulus-distractor pairs (2 recall phases each at memory loads of 3–6 stimuli for a total of 8 recall phases). The onset of each recall phase was unpredictable based on evidence that this approach produces higher working memory demands relative to tasks with predictable memory sets (Kofler et al., 2015). The emotion or animal was presented first in each emotion/animal-sentence pair to ensure interference effects between the final emotion/animal and the recall phase (Unsworth & Engle, 2007). There was no recall phase by design during the low working memory conditions.[3] Children were explicitly told to remember or not remember the emotions/animals during the high and low working memory conditions, respectively, to account for counterbalancing. All 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, children practiced set size 3 trials until they got 2 full trials correct.

All tasks were self-paced and provided performance feedback (Engle et al., 1999). The primary outcomes were accuracy (percentage of the 36 emotion or animal stimuli identified correctly) and response speed (milliseconds) during the primary processing phase (i.e., when selecting the correct emotion/animal based on context). Internal consistency reliability in the current sample was α = .81–.85 (high working memory span tasks) and α = .78–.94 (low working memory tasks).

High Working Memory Conditions (Emotion Context Span, Animal Context Span)

The two high working memory tasks combined aspects of the classic counting span and reading ‘complex span’ tasks (Conway et al., 2005), adapted for use with children. These dual-processing working memory tasks (Engle et al., 1999) alternate between a primary encoding phase (identifying the to-be-recalled hidden animal or emotion) and a secondary distractor phase (Conway et al., 2005). The goal of the secondary task (evaluating a true/

[2]None of the participants had Specific Phobia(s) of any animals.

[3]We prefer the term “low working memory” rather than “no working memory” for these tasks 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., Rapport et al., 2009).

false sentence) is to create interference effects to maximize working memory demands, because both rehearsing/maintaining the names of the previously identified emotions/animals and reading/verifying text occur within the same limited-capacity short-term memory system (Conway et al., 2005). To ensure the integrity of the high working memory conditions, we examined child performance on the reading stimuli and determined that no children demonstrated below chance reading performance.

Emotion context span.—A photograph containing a 'hidden' emotion was displayed at the top of the screen. Below the image were the six response options, each containing an emotion label (sad, angry, happy, afraid, disgust, surprise; Figure 1). Children were instructed to infer the hidden emotion and click the corresponding response option (e.g., clicking 'surprise' when the context displayed in the picture indicated that the target individual was feeling surprised). After identifying the emotion, children completed a secondary distractor task (true/false sentence). After 3–6 emotion-sentence pairs, children completed a recall phase (clicking the previously-identified emotions in serial order). Each of the six emotions was shown a maximum of one time prior to each recall phase.

Animal context span.—As shown in Figure 1, this task was identical to the emotion context span task, except that children inferred hidden animals instead of hidden emotions.

Low Working Memory Conditions (Emotion Context Processing, Animal Context Processing)

Emotion context processing.—The emotion context processing and emotion context span task were identical, except that there was no recall phase in the emotion context processing task (i.e., children were not required to remember the emotion names; Figure 1, bottom).

Animal context processing.—This task was identical to the emotion context processing task, except that children inferred 'hidden' animals instead of emotions.

Intellectual functioning (IQ) and Socioeconomic Status (SES)

Intellectual functioning was estimated using the Wechsler Intelligence Scale for Children, 5^{th} edition (Wechsler, 2014) Verbal Comprehension Index (VCI). Hollingshead (1975) SES was estimated based on caregiver(s)' education and occupation.

Bayesian Analyses

Given the mixed findings regarding emotion inference in children with ADHD, we used Bayesian statistics because they can support the null hypothesis rather than just fail to reject it (e.g., Wagenmakers et al., 2016). Bayes factor mixed-model ANOVAs with JZS priors (Rouder & Morey, 2012; Wagenmakers et al., 2016) were conducted using JASP 0.8.5 (JASP Team, 2017). Instead of a *p*-value, Bayesian results are evaluated in terms of evidentiary value as expressed by a likelihood ratio called the Bayes Factor. BF_{10} is the Bayes Factor (BF) indicating how much more likely the alternative hypothesis (H_1) is relative to the null hypothesis (H_0). Values at/above 3.0 are considered moderate support for the alternative hypothesis (i.e., statistically significant evidence for group differences; Wagenmakers et al., 2016).

BF_{01} is the inverse of BF_{10} (i.e., BF_{01}=1/BF_{10}), and is reported when the evidence favors the null hypothesis (Rouder & Morey, 2012). BF_{01} is the Bayes Factor indicating how much more likely the null hypothesis (H_0) is relative to the alternative hypothesis (H_1). BF_{01} is interpreted identically to BF_{10} (≥3.0=moderate, >10.0=strong, >100=decisive evidence that the ADHD and Non-ADHD groups are *equivalent* on an outcome; Rouder & Morey, 2012). Thus, a finding of $BF_{10} = 10.0$ would indicate that the data are 10 times more likely under the alternative hypothesis of an effect than under the null hypothesis of no effect (i.e., strong evidence for an effect), whereas $BF_{01} = 10.0$ would indicate strong evidence *against* an effect (because the data are 10 times more likely under the null hypothesis than under the alternative hypothesis).

Data Analysis Overview

A series of two Bayesian mixed-model ANOVAs were conducted to test the hypotheses that (a) children with ADHD have a unique deficit in emotion inference that is not more parsimoniously explained by their general difficulties on choice-response tasks, and (b) working memory is implicated in children's ability to accurately and efficiently infer the emotion states of others. These ANOVAs were used also to assess the extent to which emotion inference is impaired in children with ADHD generally, or only in situations that tax their underdeveloped working memory systems. Accuracy (% emotions/animals identified correctly) and response times (milliseconds) were modeled separately. For each Bayesian mixed-model ANOVA, we identified the best fitting model (criteria: combination of main and interactions effects with highest $BF_{10} \geq 3$), and then each additional effect was tested relative to this best-fitting model (Rouder & Morey, 2012). The pattern and interpretation of results is unchanged if null hypothesis significance testing (i.e., *p*-values) are used instead of Bayes Factors, except that nonsignificant *p*-values cannot be interpreted as evidence of equivalence. Finally, an exploratory set of analyses were run to examine the extent to which the primary findings were qualified by differences as a function of specific emotions (sad, angry, happy, afraid, disgust, surprise). Findings are presented in the Supplementary Online materials; the pattern and interpretation of results is unchanged when assessing each emotion separately, and there was significant evidence *against* interactions between ADHD status and emotion type for both accuracy and speed (both $BF_{01} > 5.94$).

Results

Bayesian Power Analysis

Study power was estimated using the BayesianPowerTtest R script (Lakens, 2016; Zimmerman, 2016). Results indicated that our N of 77 is powered at .80 for detecting working memory deficits in ADHD (parameters: d=0.74; r-scale=1; k=100,000 simulated experiments; BF threshold=3.0). The effect size of d=0.74 was selected based on the mean effect size for working memory deficits reported in the Kasper et al., 2012 meta-analysis. That is, assuming a true effect size of d=0.74, 80% of simulations correctly supported H_1 at $BF_{10} \geq 3.0$, 19% provided equivocal support ($1/3 < BF_{10} < 3$), and only 1% incorrectly supported H_0. Similarly, results indicated power=.66 for detecting at least moderate evidence for impaired emotion inference in ADHD based on the meta-analytic effect size of *d*=0.64 for affect recognition (Graziano & Garcia, 2016): 66% of simulations correctly supported H_1 at $BF_{10} \geq 3.0$, 30% provided equivocal support ($1/3 < BF_{10} < 3$), and only 4% incorrectly supported H_0. For both constructs, power=.77 for supporting the null if true (i.e., for *d*=0.0; 77% of simulations supported H_0, 22% provided equivocal support, and only 1% incorrectly supported H_1). Taken together, the likelihood of incorrectly supporting the null or alternative hypotheses is low (i.e., false positive rates of 1%−4%), suggesting adequate power.

Of note, the BayesianPowerTtest R script estimates power for independent sample t-tests only, and thus does not account for the increased power associated with our use of multiple tasks per outcome. To our knowledge, power analysis for Bayesian mixed-model ANOVAs is not yet available. However, power analysis based on null hypothesis significance testing (G*Power 3.1; Faul et al., 2007), with alpha=.05, power=.80, 2 groups (ADHD, Non-ADHD), and 4 task conditions (2×2 emotion x working memory) indicates that our *N*=77 can reliably detect between-group effects of *d*=0.52, within-group effects of *d*=0.27, and the critical group x condition interaction effects of *d*=0.27 or larger. Thus, the study is sufficiently powered to address its primary aims.

Preliminary Analyses

Outliers defined as values greater than two interquartile ranges outside of the within-group median were winsorized. This process affected 11 (ADHD) and 9 (Non-ADHD) outcome data points. The groups were equivalent in terms of age (BF_{01}=3.03) and there was no evidence to support gender (BF_{01}=2.91), SES (BF_{01}=2.11), or IQ differences (BF_{10}=1.70); we therefore report simple model results with no covariates. Performance data on the secondary reading tasks are reported for the current sample in Kofler et al. (2019). Most participants in the current study also participated in the Wells et al. (2019) study of basic emotion recognition; there is no overlap in the tasks reported across these studies.

Accuracy of Emotion Inference

The 2 (group: ADHD, Non-ADHD) × 2 (condition: Animal, Emotion) × 2 (working memory: Low, High) Bayesian mixed-model ANOVA provided the strongest support for the model that included main effects of condition and group ($BF_{10}=1.78\times10^{35}$, Cohen's *d*=1.55 and 0.30, respectively). Relative to this model, there was significant evidence *against* a main effect of working memory (BF_{01}=5.94, *d*= −0.10). With reference to the main effects model, there was also significant evidence *against* interactions of condition × working memory (BF_{01}=5.28) and group x working memory (BF_{01}=5.87). There was no significant evidence to support the group x condition (BF_{01}=2.63) or the 3-way interaction (BF_{01}=1.19). These findings indicate that inferring basic emotions was less automatic/more difficult than inferring common animals. In addition, the ADHD group was less accurate at inferring emotions than the Non-ADHD group, but this effect was attributable to their generally less accurate performance on choice-response tasks. That is, children with ADHD did not perform differentially worse when inferring emotions relative to common animals (i.e., there was no evidence to support the critical group x condition interaction; Figure 2, top).

Speed of Emotion Inference

The 2 (group: ADHD, Non-ADHD) × 2 (condition: Animal, Emotion) × 2 (working memory: Low, High) Bayesian mixed-model ANOVA provided the strongest support for the model that included main effects of condition and working memory (BF_{10}=1.57×10^{19}; Cohen's *d*=1.10 and 0.72, respectively). Relative to this model, there was no significant evidence to support a main effect of group (BF_{01}=2.40; *d*=0.13). With reference to the main effects model, there was significant evidence *against* the group x condition interaction (BF_{01}=4.93) and the 3-way interaction (BF_{01}=4.25). There was no significant support for the group x working memory (BF_{01}=2.97) or condition x working memory (BF_{01}=1.88) interactions. That is, children in both groups took longer to accurately infer basic emotions than to infer common animals. In addition, working memory is involved in children's ability to use context clues to infer others' emotion state (i.e., the processing of the current emotion/ animal competed for cognitive resources with the rehearsal of previously encoded stimuli). Importantly, there was significant evidence against a deficit in the speed of basic emotion inference in children with ADHD (i.e., group x condition interaction; Figure 2, bottom).

Taken together, there was no significant evidence to suggest that ADHD is associated with a unique deficit in the ability to infer basic emotions based on context. That is, adding emotion content affected the ADHD and Non-ADHD groups equivalently, and the small magnitude between-group difference in accuracy was more parsimoniously explained by the overall less accurate performance of the ADHD group on choice-response tasks (i.e., it was unrelated to the task's emotion content). Interestingly, the working memory manipulation produced large reductions in speed but not accuracy for both groups, indicating that children were unable to efficiently infer emotions (and animals) while rehearsing the prior stimuli because the two processes competed for cognitive resources and therefore could not be completed simultaneously.

Discussion

The current study was the first to experimentally evaluate emotion inference based on contextual information, alongside a potential underlying mechanism (i.e., working memory), in children with and without ADHD. Additional strengths of the experiment include the well-characterized sample, the fully-crossed experimental manipulation, the use of objective tests of emotion inference, and the inclusion of other clinical disorders in both groups to maximize external validity/generalizability and specificity of effects for ADHD (Wilens et al., 2002). With respect to both emotion inference accuracy and speed, large magnitude effects of condition indicated that our experimental manipulation successfully imposed emotion inference demands; children required more time and were less accurate in their inference of emotion states when compared to inference of common animals in context. However, as discussed below, this effect was not unique to children with ADHD.

Our results include evidence that emotion inference speed and accuracy are unlikely to be deficits associated with ADHD, and they further corroborate findings from our previous study that indicated equivalent basic emotion recognition abilities in children with and without ADHD (Wells et al., 2019). Importantly, Wells et al. (2019) and the current study examined emotion recognition within experimental paradigms that controlled for the presence of task demands beyond emotion recognition and processing. In most prior studies of emotion recognition in children with ADHD, it was often unclear whether detected deficits were uniquely due to emotion recognition abilities or were more parsimoniously explained by general choice-response task demands. Our results support the latter explanation, as do studies that examined interference effects of core ADHD behavioral symptoms on emotion recognition task performance (e.g., Sinzig et al., 2008).

Based on prior findings, we expected the ADHD group to demonstrate overall slower and less accurate performance relative to the Non-ADHD group (e.g., Kofler et al., 2013, Wells et al., 2019). This hypothesis was partially supported: The ADHD group demonstrated small magnitude impairments (d=0.30) in their ability to accurately infer both emotions and animals in context, but there was no significant evidence to support between-group differences with respect to response speeds across the emotion and animal tasks. Importantly, there was no evidence to indicate that ADHD is associated with a unique deficit in emotion inference that cannot be explained more parsimoniously by their difficulties with non-emotion aspects of the choice-response tasks. That is, there was no significant evidence to support the group x condition interaction for accuracy, and there was significant evidence *against* this interaction for response times. In other words, children with ADHD were not differentially worse than children without ADHD at processing emotions vs. animals in context. Given the lack of evidence for a unique emotion recognition or emotion inference deficit in both Wells et al. (2019) and the current study, it appears that emotion recognition abilities are likely intact in pediatric ADHD, although replication in independent samples is warranted (Da Fonseca et al., 2009).

We further predicted that increasing working memory demands would interfere with children's ability to efficiently infer the emotion state of others, and that this effect would be particularly pronounced in the ADHD group because working memory impairments are implicated in the disorder (Kasper et al., 2012). Again, this hypothesis was partially supported, such that increased working memory load disrupted emotion inference speed (d=0.72) but not accuracy. In other words, holding to-be-recalled information in working memory competed for cognitive resources with using context clues to infer emotions (and animals). The finding that these working memory demands affected speed but not accuracy suggests that children likely engaged in serial processing of the competing task demands (Meyer & Kieras, 1997). That is, children presumably engaged in a deliberate strategy in which they slowed down to allow time to sequentially process the current stimuli and rehearse the prior stimuli because the two processes could not be completed simultaneously. This hypothesis is consistent with previous findings that working memory is implicated in children's basic facial affect recognition abilities (Wells et al., 2019), as well as neuroimaging evidence of overlapping cortical networks that support working memory and emotion recognition (Erk et al., 2007; Schmeichel et al., 2008; Van Dillen et al., 2009).

Collectively, results of the current study are consistent in indicating that pediatric ADHD is not associated with a unique deficit in inferring emotions based on context clues. In fact, there was significant evidence *against* a deficit in the speed of emotion inference in children with ADHD. Children with ADHD responded as quickly as children without ADHD, but made slightly more errors (i.e., were less accurate; d=0.30) when inferring both emotions and animals. The small magnitude between-group differences in accuracy were attributable to task demands that were independent of the tasks' emotion content, and provide strong evidence against deficits in emotion inference in ADHD when combined with the finding that the ADHD and Non-ADHD groups were equivalent with regards to how quickly they were able to infer emotions based on context. Importantly, the present study used choice-response tasks to investigate emotion inference in children with ADHD, but these laboratory tasks often tax cognitive systems beyond the specific mechanism(s) of interest (Mulder et al., 2010; Yuill & Lyon, 2007). Thus, our findings further emphasize the importance of control stimuli in similar choice-response tasks. Individuals with ADHD often demonstrate impaired ability to maintain task instructions, attend to target stimuli, prepare responses, and efficiently respond to changing task demands (Hervey et al., 2004; Martinussen et al., 2005; Willcutt et al., 2005), which are abilities required for successful performance on a wide range of laboratory- and clinic-based tasks.

Interestingly, to our knowledge there have been only three studies of ADHD and emotion recognition to use control conditions, and none of them (including the current study) have found evidence for deficits in emotion recognition that could not be explained more parsimoniously by more basic choice-response errors that were independent of the type of stimuli presented (Da Fonseca et al., 2009; Wells et al., 2019). In the current study, adding concurrent working memory demands interfered with emotion inference for *both* groups, suggesting that working memory is taxed similarly when children with and without ADHD are required to efficiently infer someone's emotion state based on contextual information (Dickstein & Castellanos, 2011). Overall, findings from our carefully controlled experimental methodology indicate that working memory is implicated in children's ability to infer emotions from contextual clues, but that there is not a unique deficit in emotion inference in children with ADHD.

Limitations

The current study used a fully-crossed experimental design to clarify the extent to which – and conditions under which – children with ADHD demonstrate a unique deficit in emotion inference. The current findings are consistent with Da Fonseca et al. (2009) and Wells et al. (2019) and provide strong empirical support to suggest that children with ADHD do not have unique impairments in the ability to infer the emotion state of others based on facial affect or non-verbal context clues. The following limitations must be considered when interpreting results despite these and additional strengths of the study (e.g., control for effects of comorbidity, Bayesian modeling). First, replication with independent samples is warranted given the overlap in participants between our studies of emotion recognition (Wells et al., 2019) and emotion inference (the current study).

Second, our decision to include children with anxiety, depression, oppositional defiance, etc. was valuable in our effort to promote generalizability/external validity because co-occurring conditions are conceptualized as the rule rather than the exception in children with ADHD (Wilens et al., 2002). In consideration of both internal and external validity, we recruited two groups that were matched for the proportion of these non-ADHD clinical disorders. However, these additional clinical syndromes may impact emotion inference in ways we did not predict or that might not be perfectly controlled by matching the number of children with each condition in each group. Alternatively, previous reports of emotion recognition and emotion inference deficits in ADHD may be artifacts of unassessed or uncontrolled symptoms of co-occurring disorders in previous studies – a compelling possibility given the relatively high number of failures to replicate emotion recognition deficits in ADHD as reviewed above. Future work that excludes these conditions would clarify how well our matching process balanced internal and external validity/generalizability.

Third, the increased experimental control associated with the fully-crossed design and laboratory setting may come at the cost of reduced ecological validity. Our study imposed careful experimental control in an effort to examine emotion inference and a specific underlying mechanism of interest. However, the extent to which our findings generalize across home, school, and social settings remains unknown, and investigations of emotion inference within dynamic interpersonal interactions is needed within the study of ADHD, as well as the study of pediatric psychopathology more generally.

Finally, our control conditions used animal stimuli that provided important control for stimuli familiarity and task demands associated with processes other than emotion inference (e.g., image size/quality, number of choice-response categories, highly familiar photographs of living beings; Eimas & Quinn, 1994). However, non-living/non-biological control stimuli have been used in other studies (e.g., household objects, geometric shapes; Da Fonseca et al., 2009; Hariri et al., 2002a,b). Given the decisive support for the integrity of this experimental manipulation (i.e., large magnitude reductions in response times and accuracy for the emotion relative to animal conditions; d=1.10–1.55), it seems likely that our choice of ‘hidden animals’ improved the certainty with which we can interpret results in terms of inference of emotion states rather than inference in general. Future studies may care to use less familiar/more ambiguous stimuli, non-biological objects, and/or a broader array of stimulus categories (Greif et al., 2006).

Clinical Implications and Future Directions

Results from the current study contribute to mixed findings in the literature and suggest that emotion inference is intact in pediatric ADHD. Consistent with the only two other studies (to our knowledge) that used control tasks (Da Fonseca et al., 2009; Wells et al., 2019), our findings suggest strongly that prior reports of emotion recognition and processing deficits in ADHD may be artifacts of the well-documented difficulties that children with ADHD exhibit on choice-response tasks (Kofler et al., 2013), regardless of stimuli content. Taken together, these findings suggest that social impairments and emotion dysregulation in children with ADHD (Bunford et al., 2015; McConaughy et al., 2011) are likely to result from deficits in processes other than the basic recognition and inference of emotions. Future work is needed to determine which process(es) lead to the impairing social problems and emotion dysregulation associated with ADHD. Increased emotional reactivity/lability (Pietromonaco & Barrett, 2009) and/or deficits in the ability to regulate emotion (Bunford et al., 2015; Shaw et al., 2014), as well as neurocognitive mechanisms that may underlie these processes (Kofler et al., 2011; Walcott & Landau, 2004), represent promising areas for future study. Furthermore, the functional impairment attributed to emotion dysregulation in

ADHD (Barkley & Fischer, 2010; Bunford et al., 2015; Shaw et al., 2014) may be most effectively mitigated if intervention approaches target processes that are impaired in ADHD, such as emotion reactivity and regulation rather than emotion recognition and inference, or underlying cognitive capacities such as working memory.

Additionally, the current study examined emotion inference based on contextual information, but there are many additional elements of emotion processing that were beyond the scope of the current study and represent compelling areas of focus in future studies of children with and without ADHD (e.g., in vivo interpretation of nonverbal cues like eye contact, voice tone, volume; emotion recognition within oneself; identification of internal physiological markers of emotion). Finally, the current study and Wells et al. (2019) indicate that working memory is implicated in the recognition of emotion as well as the inference of emotion from context for all children – not just children with ADHD. Future work is needed to further elucidate how and when working memory and information processing facilitate and impair children's ability to recognize and infer the emotion states of others (Ochsner et al., 2009).

Supplementary Material

Refer to Web version on PubMed Central for supplementary material.

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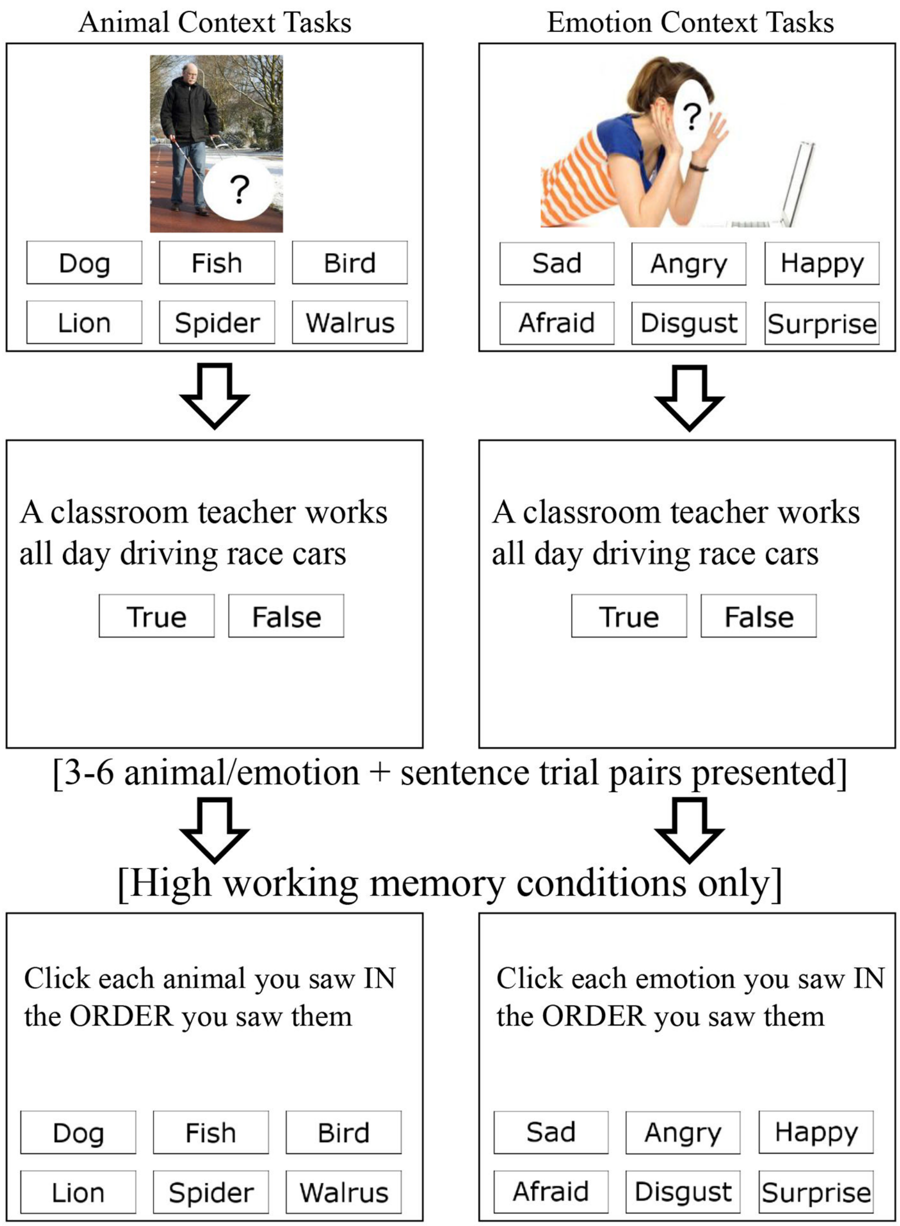

Figure 1.
Emotion context (‘hidden emotion’) and animal context (‘hidden animal’) tasks. Each of the four counterbalanced tasks presented 36 randomly selected emotion/animal context stimuli and sentences. Each low/high working memory trial pair (emotion context/emotion context span, animal context/animal context span) was identical except for the omission or addition of concurrent working memory demands. Words/icons outside the six large boxes were not shown on screen, but are included here to illustrate differences across the four experimental task variants. Photos used under license from dreamstime.com.

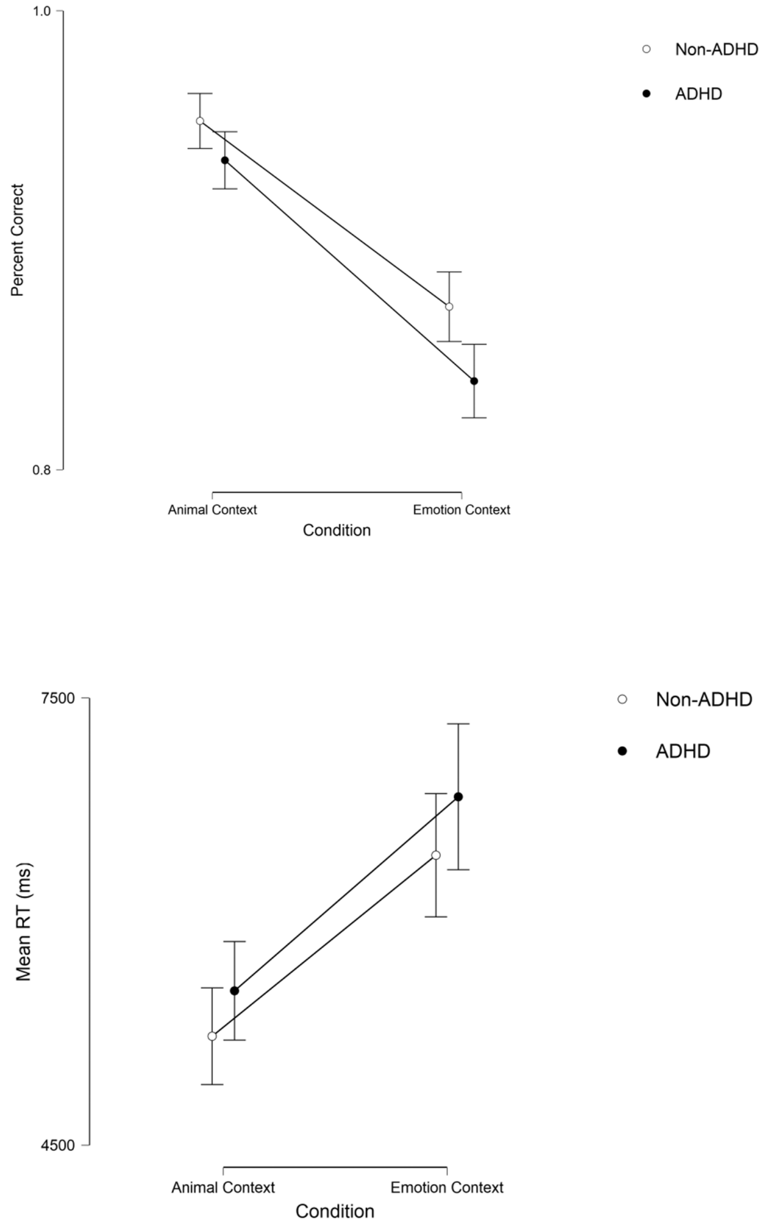

Figure 2.

Emotion and animal processing accuracy (top) and speed (bottom) as a function of ADHD status (ADHD, Non-ADHD). Error bars reflect Bayesian 95% credibility intervals.

Table 1.

Sample and demographic variables.

Variable	**ADHD**		**Non-ADHD**		**Cohen's *d***	***BF_{10}***	***BF_{01}***
	M	***SD***	***M***	***SD***			
N (Boys/Girls)	42 (26/16)		35 (19/16)		--		2.91
Age	10.32	1.53	10.63	1.56	0.17		3.03
SES	47.32	11.85	50.71	11.53	0.25		2.11
WISC-V VCI	103.07	15.01	109.86	12.16	0.44	1.70	
Task Accuracy Data (percent correct)							
Animal Context Recognition	0.934	0.045	0.952	0.032	0.39	1.21	
Emotion Context Recognition	0.837	0.079	0.865	0.064	0.34		1.20
Animal Context Span	0.936	0.044	0.952	0.037	0.35		1.10
Emotion Context Span	0.841	0.082	0.877	0.070	0.42	1.47	
Task Response Time Data (milliseconds)							
Animal Context Recognition	5030.39	1179.53	4903.00	1211.72	0.09		3.84
Emotion Context Recognition	6125.48	1609.63	5880.91	1383.76	0.14		3.40
Animal Context Span	6041.09	1829.96	5559.32	1471.22	0.25		2.14
Emotion Context Span	7548.66	2795.35	7009.60	2066.47	0.19		2.87
Working Memory Recall (z-scores based on stimuli correct per trial)							
Omnibus (combined across tasks)	−0.24	1.06	0.28	0.86	0.47	2.35	

Note. BF = Bayes Factor. SES = socioeconomic status; VCI = WISC-V Verbal Comprehension Index (IQ; standard scores).