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A New Spin on Spatial Cognition in ADHD: A Diffusion Model Decomposition of Mental Rotation

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Abstract

Objectives: Multiple studies have found evidence of task non-specific slow drift rate in ADHD, and slow drift rate has rapidly become one of the most visible cognitive hallmarks of the disorder. In this study, we use the diffusion model to determine whether atypicalities in visuospatial cognitive processing exist independently of slow drift rate. **Methods:** Eight- to twelve-year-old children with ($n = 207$) and without ADHD ($n = 99$) completed a 144-trial mental rotation task. **Results:** Performance of children with ADHD was less accurate and more variable than non-ADHD controls, but there were no group differences in mean response time. Drift rate was slower, but nondecision time was faster for children with ADHD. A Rotation × ADHD interaction for boundary separation was also found in which children with ADHD did not strategically adjust their response thresholds to the same degree as non-ADHD controls. However, the Rotation × ADHD interaction was not significant for nondecision time, which would have been the primary indicator of a specific deficit in mental rotation *per se*. **Conclusions:** Poorer performance on the mental rotation task was due to slow rate of evidence accumulation, as well as relative inflexibility in adjusting boundary separation, but not to impaired visuospatial processing specifically. We discuss the implications of these findings for future cognitive research in ADHD.

Keywords: ADHD, Drift rate, Boundary separation, Visuospatial reasoning, Neuropsychology, Children

INTRODUCTION

Spatial cognition refers to the perception, organization, maintenance, and revision of information about the spatial relationships (i.e., distance, direction, and rotation) of the parts within an object, or between an object and its environment (de Vega, Intons-Peterson, Johnson-Laird, Denis, & Marschark, 1996). These abilities are shared by humans and non-humans (Landau & Jackendoff, 1993; Thinus-Blanc, 1996) and are critical to environmental learning and navigation, perspective taking, and the execution of locomotor and visually guided actions (Kessler & Thomson, 2010; Pham & Hicheur, 2009; Wolbers & Hegarty, 2010). Given the regularity with which humans rely on these functions in daily life, understanding the mechanisms underlying those processes has long been a focal area of research.

Among the most widely used tasks to evaluate spatial cognition in research is Shepard and Metzler's (1971) mental rotation task. In the most common version, participants are shown two unfamiliar shapes, each at different angular rotations, and are asked to decide if the two stimuli are identical. A large body of evidence suggests that individuals complete the task using analog spatial representations (Zacks, 2008). First, observers encode a stimulus in the form of an abstract representation which is maintained in memory *via* rehearsal (Prime & Jolicoeur, 2010). The stored representation is then mentally rotated to match the orientation of the stimulus to which it is being compared. Finally, comparisons are drawn between the two stimuli, which informs the parity judgment. Dating back to Shepard and Metzler's (1971) seminal study, research has consistently found that mean response time (RT), error rate, as well as activation in the superior parietal cortex (an area of the brain that codes target locations in space) all increase as a function of angular disparity between the stimuli (Zacks, 2008). This effect has been attributed to the longer period of time required to rotate the analog stimulus to alignment.

Since Shepard and Metzler's early work, cognitive psychology has been interested in better understanding how experimental manipulations may impact one's ability to perform mental rotations. For example, studies have examined the influence of: practice (Meneghetti, Borella, & Pazzaglia, 2016), cognitive load (Pannebakker et al.,

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2011), and stimulus dimensionality and complexity (Bethell-Fox & Shepard, 1988). However, using the standard metrics of mean RT (MRT) and mean accuracy makes it difficult to identify where in the stream of information processing (i.e., encoding/rehearsing, rotating, decision-making) that any observed effects may originate. This in turn poses a challenge for efforts to reliably quantify the independent contributions of rotation-specific and more general decision-making processes on performance.

One way of addressing this issue is through the use of the diffusion model (DM; Ratcliff & McKoon, 2008; Voss, Rothermund, & Voss, 2004), a computational model developed to explain rapid forced choice decision-making (e.g., do the stimuli match or not match?). The DM assumes that these types of decisions are made *via* three main information processing stages: encoding, accumulation of evidence toward a decision, and the planning/execution of a motoric response. After a stimulus is encoded, evidence accumulates toward one of the two possible responses (i.e., match *vs*. not-match). When the accumulation of evidence crosses either response boundary, the decision is reached and the appropriate behavioral response is then initiated. Drift rate (v) reflects the speed with which the information accumulation process occurs. The distance between the two response boundaries is referred to as the boundary separation (a). Boundary separation is wider when participants emphasize accuracy over speed (intrinsically or by instruction) and is narrower when speed is prioritized. There is also evidence that boundary separation increases when rotation angle increases, and when presented with mirrored (*vs*. identical) stimuli (Provost & Heathcote, 2015). Finally, nondecision time (Ter) reflects the amount of time it takes to complete all other processes that are not involved in the decision process, namely, the time it takes to encode a stimulus and the planning and execution of motor responses. There is considerable evidence that motor imagery, including mental rotation, engages areas of the premotor and supplementary motor cortex, which are also involved in motor planning and execution (Kosslyn, Ganis, & Thompson, 2001; Wexler, Kosslyn, & Berthoz, 1998). Given this, and that rotation is assumed to occur prior to the onset of the decision stage (Cooper & Shepard, 1973; Heil, 2002; Riečanský & Katina, 2010), a DM framework would assume the rotation process itself to be captured by Ter.

The DM performance parameters are produced based upon the shape of the RT distribution for both correct and error responses for each individual. That is, compared to traditional analytic techniques that rely solely on either the mean reaction time or mean accuracy of responses, the DM uses the entirety of the data to provide a more complete description of performance. And, unlike other statistical approaches such as Shifted Wald or ex-Gaussian modeling, the DM parameters have clearly defined psychological interpretations that have been experimentally validated in several studies since the model was first conceived in the 1970s (Matzke & Wagenmakers, 2009; Ratcliff & McKoon, 2008; Voss et al., 2004; Wagenmakers, 2009).

The DM has been particularly useful in understanding the cognitive correlates of childhood ADHD. Among the most consistent hallmarks of ADHD is slow, variable, and error-prone performance on experimental paradigms designed to measure many different types of executive and non-executive processes. Using this approach, the broad consensus has been that slow drift rate explains much of the ADHD-related variance observed in performance across a broad range of these cognitive paradigms (Fosco, White, & Hawk, 2017; Huang-Pollock, Karalunas, Tam, & Moore, 2012; Karalunas & Huang-Pollock, 2013; Karalunas, Huang-Pollock, & Nigg, 2012; Metin et al., 2013; Mulder et al., 2010; Weigard & Huang-Pollock, 2014, 2017; Ziegler, Pedersen, Mowinckel, & Biele, 2016). That is, slow drift rate has been found in ADHD regardless of the type of task on which it is measured.

That being said, small effects for timing-specific and sustained attention processes, independent of generally slow drift rate, have been documented (Huang-Pollock et al., 2020; Shapiro & Huang-Pollock, 2019). Specific deficits in spatial short-term memory, spatial planning, and visual recognition have also been noted (Chiang & Gau, 2014; Ferrin & Vance, 2012; Semrud-Clikeman, 2012) and can persist in adolescents who cease to meet full diagnostic criteria (Lin, Chen, & Gau, 2014). In fact, meta-analytic effect sizes for spatial working memory (WM) deficits in ADHD are among the largest across all neurocognitive domains (.63–1.06), are greater than effect sizes for verbal WM (.43–.55) (Martinussen, Hayden, Hogg-Johnson, & Tannock, 2005; Willcutt, Doyle, Nigg, Faraone, & Pennington, 2005), and have been shown to persist even after controlling for IQ, spatial memory span, and other rapid processing tasks (Lin et al., 2014). Nevertheless, specific weaknesses in manipulation of spatial information are less widely studied by comparison and often yield inconsistent interpretations across different tasks and metrics.

Three previous studies have utilized mental rotation tasks to evaluate the status of spatial cognition in ADHD (Silk et al., 2005; Vance et al., 2007; Williams, Omizzolo, Galea, & Vance, 2013), but all had unacceptably high error rates for RT to be confidently used as valid indices of performance (error rates ranging from 30 to 73% for ADHD and 8–44% for controls). When RTs are used as the sole index of performance, error trials are usually removed from analysis to prevent confounds to the interpretation of RT. However, when error rates are high, basic assumptions about the cognitive process that occurred to produce that RT can no longer be made confidently, including assumptions that participants were sufficiently engaged with the task (Shepard & Cooper, 1982). A fourth study reported lower accuracy among children with ADHD *versus* non-ADHD controls, but the speed with which they made those decisions was not reported (Jakobson & Kikas, 2007). Thus, the status of visuospatial processing in ADHD is unresolved.

In the present study, we examine visuospatial cognition in children with and without ADHD using a mental rotation task. We selected this task because it is one of the most heavily researched tasks of visuospatial cognitive ability that allows both accuracy and RT to be measured in a trial-by-trial fashion. Mental rotation was also an attractive option for the current study because it has previously been studied in adults using evidence accumulation models similar to the DM (Larsen, 2014; Provost & Heathcote, 2015). If specific difficulties in the mental rotation process exist, it would be captured by a significant ADHD × Rotation interaction for *Ter*, where group differences increase with angle of rotation. Otherwise, main effects of diagnostic group in the absence of an interaction with rotation would suggest that poor ADHD-related performance is better attributed to task or process non-specific performance deficits. We apply the DM, which produces parameters based on the RTs to error as well as correct responses, to evaluate these possibilities.

METHODS

Participants

Three hundred and six children with ($n = 207$, 142 boys) and without ($n = 99$, 48 boys) ADHD participated. They were recruited through advertisement *via* local schools, newspaper and radio ads, and fliers distributed throughout Centre and Dauphin counties in Pennsylvania. All children were between 8 and 12 years of age and were ethnically representative of the region: 74% Caucasian, 6% Caucasian/Hispanic, 8% African American/non-Hispanic, 1% African American/Hispanic, 1% Other Hispanic, 1% Asian, and 8% mixed/unknown. Children who were prescribed a non-stimulant psychoactive medication; who had an estimated Full Scale IQ below 80 based on a two-subtest short form (i.e., vocabulary and matrix reasoning, predictive validity = .87) of the Wechsler Intelligence Scale for Children (Wechsler, 2003); and those with a history of parent-reported head injuries, psychosis, neurological, developmental, intellectual, or sensorimotor disabilities were excluded from the study.

Children with ADHD

Children with ADHD met DSM criteria (any presentation type), including duration, age of onset, and multi-context impairment (American Psychiatric Association, 2013). Parent report of symptomology was obtained *via* the Diagnostic Interview Schedule for Children-IV (DISC-IV; Shaffer, Fisher, & Lucas, 1997). To demonstrate cross-situational impairment, at least one parent and one teacher report of behavior on the Attention, Hyperactivity, or ADHD subscales of the Behavioral Assessment Scale for Children (BASC-2; Reynolds & Kamphaus, 2004) or the Conners' Rating Scales (Conners'; Conners, 2001) were required to exceed the 85th percentile (i.e., T-score ≥ 61), and at least 3 symptoms were required to be present at an impairing level at school. Both the BASC-2 and Conners' are commonly used, well-validated measures for the evaluation of ADHD. Following DSM-IV field trials (Lahey et al., 1994), diagnostic determination and final symptom counts followed an "or" algorithm to integrate parent responses on the DISC with teacher reports on the ADHD Rating Scale (DuPaul, Power, Anastopoulos, & Reid, 1998). Children prescribed stimulant medication ($n = 68$) were asked to discontinue medication use for 24–48 h (Mean washout = 103.43 h).

Non-ADHD controls

Controls did not meet ADHD criteria on DISC-IV, had T-scores below the 80th percentile (T-score < 58) on all ADHD-related parent and teacher rating scales, and had never been previously diagnosed or treated for ADHD. All had ≤ 4 total symptoms and ≤ 3 symptoms per ADHD dimension according to the "or" algorithm.

Descriptive statistics of groups are provided in Table 1. The presence of anxiety, depression, oppositional defiant, and conduct disorders was not exclusionary for either group. To control for the potential confounding effects of IQ on the high end of the spectrum, controls were required to have estimated IQs < 115. No upper IQ limit was set for children with ADHD. Compared to controls, children with ADHD had more symptoms of hyperactivity/impulsivity and inattention (both $p \leq .001$, both $\eta^2 \geq .54$). There were no group differences in estimated IQ or age (both $p \geq .61$, both $\eta^2 \leq .001$).

Procedures

Informed written consent from parents and verbal assent from children were obtained prior to participation. Parents were provided with $100 and clinical feedback; children were given their choice of a small prize. The mental rotation paradigm completed by participating children was one of a battery of tasks associated with a larger study investigating neurocognitive deficits in childhood ADHD. The Pennsylvania State University Institutional Review Board (IRB#32126) approved all study procedures.

Mental Rotation

Task description

There were three blocks of 48 trials (144 total trials). For each trial, the word "Ready?" first appeared for 500 ms (see Figure 1(a)). Children were then shown the comparison stimulus alongside a target stimulus and asked to indicate whether the two were the same by pressing either "yes" or "no" on a response box. The comparison was always an upright stick figure with a yellow dot on the figure's right hand and a blue dot on the figure's left foot. Stimuli remained on the screen until a response was made, after which the child was given visual feedback (i.e., "Right!" or "Wrong!") for 1000 ms. Five practice trials preceded the experimental trials.

Half of the targets were congruent (i.e., matching), and the other half were incongruent (i.e., mirror image) to the comparison. Each target was rotated at one of the eight angular rotations (i.e., 0°, 45°, 90°, 135°, 180°, 225°, 270°, or 315°) from

Table 1. Means (SD) of group descriptives

	ADHD ($n = 207$)	Control ($n = 99$)	F(1,304)
Age	9.55 (1.25)	9.61 (1.32)	.13,$\eta^2 < .001$, $p = .72$
Male:Female	142:65	48:51	–
IQ	103.06 (13.68)	103.82 (7.77)	.26, $\eta^2 = .001$, $p = .61$
#Hyper/Imp symptoms	5.59 (2.81)	.23 (.47)	353.30, $\eta^2 = .54$, $p < .001$
Parent BASC-2	65.63 (13.74)	42.59 (4.89)	262.35, $\eta^2 = .46$, $p < .001$
Parent Conners’	68.29 (14.37)	45.98 (3.52)	231.47, $\eta^2 = .43$, $p < .001$
Teacher BASC-2	60.91 (12.04)	43.63 (3.83)	194.26, $\eta^2 = .39$, $p < .001$
Teacher Conners’	60.15 (12.15)	45.31 (3.20)	142.82 $\eta^2 = .32$, $p < .001$
#Inattention Symptoms	8.02 (1.35)	.55 (.70)	2691.87, $\eta^2 = .90$, $p < .001$
Parent BASC-2	66.66 (6.70)	43.04 (6.38)	857.98, $\eta^2 = .74$, $p < .001$
Parent Conners’	70.85 (10.82)	45.91 (4.00)	493.20, $\eta^2 = .62$, $p < .001$
Teacher BASC-2	62.66 (6.58)	43.34 (5.56)	636.00, $\eta^2 = .68$, $p < .001$
Teacher Conners’	61.20 (11.56)	46.47 (4.31)	150.47, $\eta^2 = .33$, $p < .001$
ADHD Subtype (H:I:C)	4, 68, 108	–	
#ODD, CD	79, 23	2, 0	
#GAD, MDD, DD	24, 11, 3	1, 0, 0	
#LD	28	10	

BASC-2 = Behavioral Assessment Scale for Children; Conners’ = Conners’ Rating Scales; H = Primarily hyperactive/impulsive subtype; I = Primarily inattentive subtype; C = Primarily combined subtype; ODD = Oppositional Defiant Disorder; CD = Conduct Disorder; GAD = Generalized Anxiety Disorder; MDD = Major Depressive Disorder; DD = Dysthymic Disorder; LD = Learning Disability.
Rating scales reported in T-scores.

the comparison (see Figure 1(b)), so that there were 18 trials per rotational angle. To allow enough trials for parameter recovery, trials with target stimuli oriented at 0°, 45°, and 315° were classified as “small” rotations, while those with 135°, 180°, and 225° angle rotation trials were classified as “large” rotations (72 trials per bin). Stimuli rotated at either 90° or 270° ultimately require the same amount of rotation to the upright position and did not differ from one another in either MRT, $F(1,11014) = 3.22$, $\eta^2 < .001$, $p = .073$, or accuracy, $F(1,11014) = .63$, $\eta^2 < .001$, $p = .43$. Therefore, the random case selection functionality in SPSS was used to classify half of each of the 90° and 270° trials (independently) into “small” and “large” rotations. Results did not vary when all 90° and 270° stimuli were classified as small and large, respectively, or when categorized in the reverse.

Data Analysis Plan

Anticipatory responses faster than 300 ms were discarded per DM convention (Ratcliff, Love, Thompson, & Opfer, 2012; Ratcliff & Tuerlinckx, 2002). In line with a prior accumulator analysis of mental rotation, trials slower than 7000 ms were also excluded (Provost & Heathcote, 2015; Provost, Johnson, Karayanidis, Brown, & Heathcote, 2013). Twenty-two children with ADHD and two non-ADHD controls were excluded from analysis based on task performance (i.e., if overall accuracy <50%, or if >25% of trials fell outside of the RT cut-offs). Children with ADHD who were removed from analysis were younger than children with ADHD who remained in analysis ($M = 8.50$ *vs*. 9.55 years, $F(1,227) = 15.07$, $\eta^2 = .062$, $p < .001$). Because there were no significant differences in IQ, $F(1,227) = .003$, $\eta^2 < .001$, $p = .96$, number of inattentive symptoms, $F(1,227) = 1.01$, $\eta^2 = .004$, $p = .32$, or number of hyperactivity/impulsivity symptoms, $F(1,227) = .43$, $\eta^2 = .002$, $p = .51$, among children with ADHD who were removed *versus* retained from analysis, we were reassured that our exclusionary criteria did not skew our sample toward greater or lesser severity and remained representative of children with ADHD. Additionally, children with ADHD and a comorbid learning disability who were retained in the final sample did not differ from those without a comorbid learning disability on any performance metric (all $p > .066$, all $\eta^2 < .016$).

The original sample included 229 children with ADHD and 101 children without ADHD, resulting in the final N reported earlier: $n = 207$ children with ADHD and $n = 99$ non-ADHD controls.

Diffusion modeling

Trial-by-trial RT and accuracy data for each subject were input into the Fast-dm modeling program (downloadable at http://www.psychologie.uni-heidelberg.de/ae/meth/fast-dm; Voss & Voss, 2007) to provide individual estimates of drift rate, boundary separation, and nondecision time by block and rotation condition. Response bias (z) was fixed to $a/2$, and inter-trial variability parameters were fixed to zero, as they are difficult to estimate and contribute little to the shape of the distribution (Voss & Voss, 2007). AIC model selection favored this model over others in which Ter was fixed across conditions and drift and response bias varied by match/nonmatch trials (Supplemental Table 1).

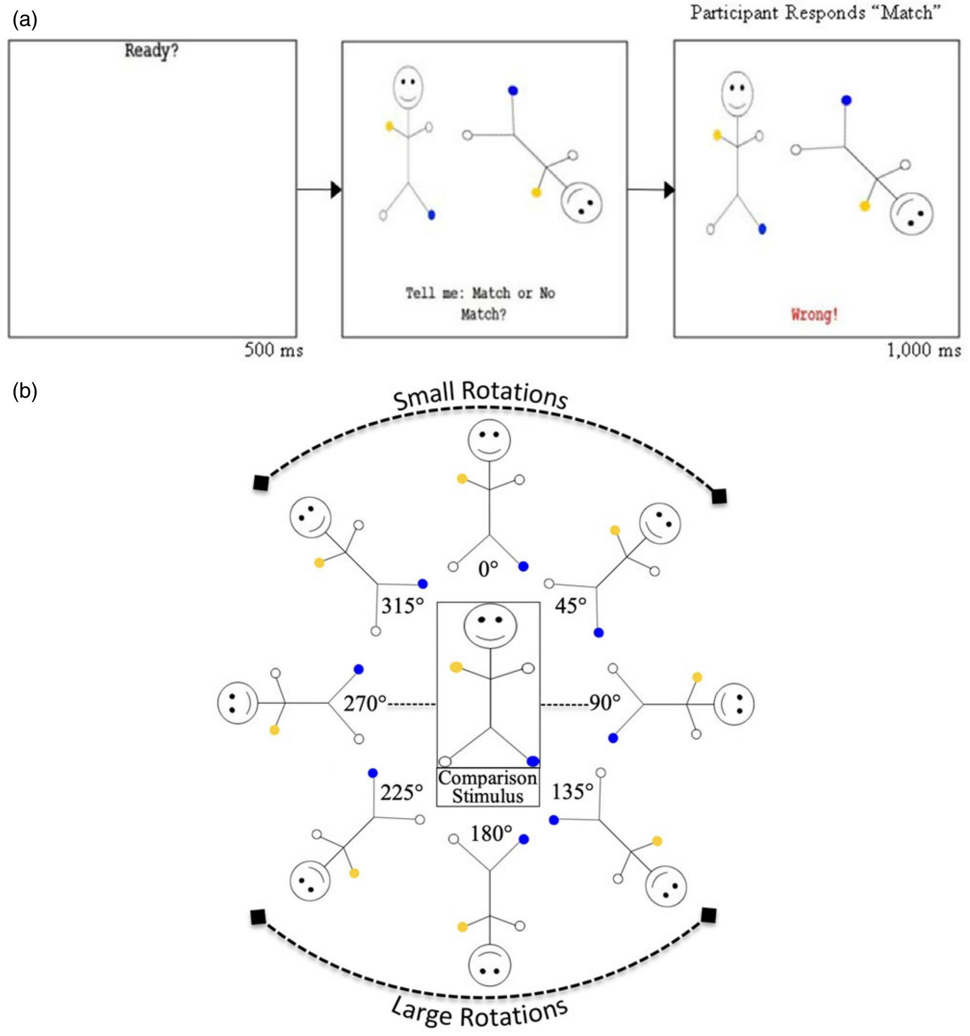

Fig. 1. (a) The mental rotation paradigm and illustration of rotation angle groupings. (b) Illustration of rotation angle groupings.

During the modeling process, and for each individual participant, the shapes of the observed RT distributions for both correct and error responses are statistically compared against the shapes of RT distributions that are predicted to occur given a set of DM parameter values. Multiple parameter sets are successively tested until optimal fit between the actual and predicted distributions is obtained (Voss et al., 2004). With as few as 20 trials per condition, Fast-dm parameter estimates are consistent with those obtained from 2000-trial model simulations (Voss & Voss, 2007). Within the current data set, Fast-dm was able to fit the data of all participants well, as indicated by nonsignificant *p*-values for all model fits (all $p > .18$).

Data analytic approach

The experiment generated a Rotation (2: small/large) × Block (3) × Diagnosis (2: ADHD/Control) mixed between- and within-subjects ANOVA. Dependent variables were MRT for correct trials, standard deviation of response time (SDRT) for correct trials, accuracy, drift rate, boundary separation, and nondecision time.

RESULTS

Table 2 provides summary statistics for all conditions and dependent variables. Table 3 provides summary F, η^2, p, and *df* values for all analyses.

Task Validation

Using standard indices of performance, there was a main effect of Rotation in which children were faster, less variable, and made fewer errors on small (*vs*. large) rotations (all $p < .001$, all $\eta^2 \geq .094$). There was also a main effect of Block, in which RTs became faster and SDRT became smaller with practice (both $p < .001$, both $\eta^2 \geq .030$; see Figure 2). Finally, a Block × Rotation interaction was also found in which SDRT decreased over time on large, but not small rotations, $F(2,608) = 3.67$, $\eta^2 = .012$, $p = .026$.

These main effects of Rotation and Block were driven by changes in drift rate, boundary, and *Ter* (all $p < .001$, all $\eta^2 > .097$; see Figure 2). Compared to large rotations, small rotations had smaller boundary separations; drift rates and *Ter* were also faster. With practice, boundary separation

Table 2. Mean (*SD*) for Response Times, SDRT, Accuracy, *v*, *a*, and *Ter* by Block, Rotation, and Diagnostic Group

	Small rotations			Large rotations		
	Block 1	Block 2	Block 3	Block 1	Block 2	Block 3
MRT						
Control	2703.00 (690.25)	2271.48 (634.61)	2030.20 (572.74)	3259.39 (762.56)	2845.54 (767.58)	2541.78 (712.62)
ADHD	2825.15 (714.30)	2306.71 (692.57)	2076.72 (615.60)	3304.10 (689.29)	2743.95 (769.56)	2508.30 (680.66)
SDRT						
Control	1336.89 (645.35)	1196.35 (690.66)	1107.68 (658.03)	2036.29 (1146.11)	1605.42 (815.13)	1399.02 (768.75)
ADHD	1878.08 (1398.16)	1899.65 (1420.88)	1672.46 (1758.50)	2913.25 (4213.85)	2408.10 (2962.21)	1960.43 (1517.04)
ACC						
Control	.94 (.10)	.95 (.07)	.95 (.08)	.91 (.11)	.92 (.10)	.92 (.09)
ADHD	.92 (.10)	.91 (.11)	.92 (.10)	.87 (.14)	.86 (.15)	.88 (.14)
v						
Control	.84 (.27)	1.03 (.35)	1.10 (.39)	.69 (.29)	.72 (.29)	.84 (.34)
ADHD	.77 (.31)	.90 (.44)	.97 (.45)	.60 (.29)	.64 (.37)	.75 (.40)
a						
Control	2.93 (.53)	2.90 (.52)	2.68 (.56)	3.11 (.45)	3.06 (.53)	2.96 (.57)
ADHD	3.14 (.53)	2.99 (.61)	2.81 (.62)	3.17 (.43)	3.03 (.54)	2.96 (.53)
Ter						
Control	1344.48 (520.43)	972.38 (487.27)	887.02 (408.15)	1697.55 (726.04)	1272.05 (661.84)	1115.33 (598.58)
ADHD	1242.76 (584.13)	822.44 (489.28)	779.62 (449.53)	1576.85 (724.87)	1143.52 (651.75)	988.70 (504.36)

became smaller; drift rate and *Ter* became faster. The Rotation × Block interaction was similarly influenced by drift rate, boundary separation, and *Ter* (all $p \leq .024$, all $\eta^2 \geq .012$). With practice, trials with small (*vs*. large) rotations showed greater increases in drift, greater decreases in boundary separation, but somewhat more shallow improvement in *Ter*.

ADHD Effects

With respect to diagnostic group differences, using standard indices of performance, there was a main effect of ADHD in which children with ADHD had more variable RTs and were less accurate than non-ADHD controls (both $p \leq .002$, both $\eta^2 \geq .032$). This was due to slower drift, $F(1,304) = 9.13$, $\eta^2 = .029$, $p = .003$, and faster *Ter*, $F(1,304) = 4.83$, $\eta^2 = .016$, $p = .029$.

An ADHD × Rotation interaction for both MRT and accuracy was also found (both $p \leq .041$, both $\eta^2 \geq .014$). This interaction was driven by changes in boundary separation, $F(1,304) = 9.93$, $\eta^2 = .032$, $p = .002$ (see Figure 3). Among non-ADHD controls, boundary separation was wider for large *versus* small rotations, $F(1,98) = 38.96$, $\eta^2 = .28$, $p < .001$. Although the same effect was seen for children with ADHD, $F(1,206) = 9.30$, $\eta^2 = .043$, $p = .003$, it was not as pronounced and children with ADHD generally maintained larger boundaries. This inflexibility in the strategic adjustment of speed/accuracy trade-off has also been observed in previous studies (Mulder et al., 2010; Weigard & Huang-Pollock, 2014). The ADHD × Rotation effect was not significant for either drift or *Ter* (both $p \geq .49$, both $\eta^2 \leq .002$). The lack of an ADHD × Rotation effect for *Ter* suggests that performance differences were not due to difficulties in the rotational processes.

DISCUSSION

In the current study, we examined mental rotation among school-age children with and without ADHD. Traditionally, MRT to correct responses has served as the primary dependent variable of performance, and despite the fact that children with ADHD responded more variably and less accurately, no diagnostic-based differences in MRT were identified. Thus, the most basic interpretation would be that there is no evidence of a specific spatial processing/mental rotation atypicality in ADHD. However, this interpretive practice ignores the interdependency and distributional properties of RT and accuracy in such a way that renders them potentially misleading indicators of cognitive performance.

Applying the DM to the data, we found that greater variance and higher error rates observed in children with ADHD were primarily due to slower drift rates, a finding that has been extensively documented across a range of tasks and studies (Huang-Pollock et al., 2012; Karalunas & Huang-Pollock, 2013; Karalunas et al., 2012; Merkt et al., 2013; Metin et al., 2013; Mulder et al., 2010; Salum, Sergeant, et al., 2014; Salum, Sonuga-Barke, et al., 2014; Weigard & Huang-Pollock, 2014, 2017). Drift rate is conceptualized as a "signal" to "noise" ratio (i.e., accumulation of task-relevant vs. irrelevant information) in the neural systems involved in decision-making (Heekeren, Marrett, & Ungerleider, 2008; Ratcliff, Philiastides, & Sajda, 2009). As signal strength decreases (or as noise increases), drift rate slows.

Table 3. Diagnostic Group and Task Condition Effects for MRT, SDRT, Accuracy, *v*, *a*, and *Ter*

	F	$\eta 2$	*p*	*df*
Rotation				
MRT	623.14	.67	<.001	1,304
SDRT	31.54	.094	<.001	
Accuracy	77.00	.20	<.001	
v	277.35	.48	<.001	
a	44.72	.13	<.001	
Ter	201.43	.40	<.001	
Block				
MRT	289.45	.49	<.001	2,608
SDRT	9.39	.030	<.001	
Accuracy	2.04	.007	.13	
v	55.02	.15	<.001	
a	32.48	.097	<.001	
Ter	209.87	.41	<.001	
ADHD				
MRT	.07	<.001	.79	1,304
SDRT	22.53	.069	<.001	
Accuracy	9.90	.032	.002	
v	9.13	.029	.003	
a	3.10	.010	.079	
Ter	4.83	.016	.029	
Rotation × Block				
MRT	1.04	.003	.35	2,608
SDRT	3.67	.012	.026	
Accuracy	.35	.001	.70	
v	10.56	.034	<.001	
a	3.75	.012	.024	
Ter	6.00	.019	.003	
Block × ADHD				
MRT	1.83	.006	.16	2,608
SDRT	.36	.001	.70	
Accuracy	1.88	.006	.15	
v	.43	.001	.65	
a	1.56	.005	.21	
Ter	.15	<.001	.86	
Rotation × ADHD				
MRT	6.04	.019	.015	1,304
SDRT	.56	.002	.45	
Accuracy	4.22	.014	.041	
v	.48	.002	.49	
a	9.93	.032	.002	
Ter	.02	<.001	.89	
Block × Rotation × ADHD				
MRT	.52	.002	.60	2,608
SDRT	.31	.001	.73	
Accuracy	.16	.001	.86	
v	.98	.003	.37	
a	.05	<.001	.95	
Ter	.20	.001	.82	

Group effects were also partially due to faster *Ter*. *Ter* represents all parts of the RT that are not involved in the decision-making process. In the context of a mental rotation task, this would include the time spent encoding the stimulus, rotating the stimulus, and preparing/executing a motor response. Given evidence for fine motor control deficits (Kaiser, Schoemaker, Albaret, & Geuze, 2015; Rommelse et al., 2009), and lack of evidence for visual stimulus encoding exceptionalities, a true temporal advantage in *Ter* for youth with ADHD seems unlikely. Instead, the shorter *Ter* might best be understood as the result of prematurely *discontinuing* the mental rotation of images. Such an incompletely rotated image would be expected to compromise the quality of the evidence on which decisions are based and would reduce the signal strength of the decisional process. Thus, the incomplete rotation of images would also contribute to slow drift rate in ADHD, over and above the task non-specific slower drift rate that is already expected. It bears mentioning that faster *Ter* in children with ADHD is not uncommon (Karalunas, Geurts, Konrad, Bender, & Nigg, 2014) and could also potentially be an artifact of a “trade-off” effect between correlated DM parameters. That is, slow drift rates in ADHD may induce faster *Ter* estimates because they impact RT in opposing directions. Nevertheless, the absence of a Rotation × ADHD interaction for *Ter* suggests the absence of a specific ADHD-related deficit in mental rotation abilities.

Interestingly, there was a significant Rotation × ADHD interaction in which increases in boundary separation between small and large rotations were less pronounced in children with ADHD. Similar inflexibility has also been noted in a contextual cueing paradigm (Weigard & Huang-Pollock, 2014), as well as in a paradigm in which speed/accuracy trade-off was manipulated (Mulder et al., 2010). Boundary inflexibility has been linked to hypoactivation in the striatum (Forstmann et al., 2008; Ivanoff, Branning, & Marois, 2008), which is among the most highly implicated brain regions in ADHD (Cubillo, Halari, Smith, Taylor, & Rubia, 2012; Sonuga-Barke, Cortese, Fairchild, & Stringaris, 2016). Here, and despite trial-by-trial feedback, children with ADHD continued to make more errors than non-ADHD controls, suggesting that they had difficulty using the corrective feedback and experience to strategically modify their behavior to improve performance. This in turn likely led to a general and somewhat less efficient strategy of indiscriminately increasing boundary separation or caution in an effort to reduce error rates.

As would be expected with time on task, across both diagnostic groups, there were main effects of Block on drift rate, boundary separation, and *Ter*, in which drift rate and *Ter* became faster and boundary separation narrowed over time. Previous research examining practice effects on speeded RT tasks have found that practice-related reductions in RT are due to a combination of changes to all three primary parameters (Dutilh, Vandekerckhove, Tuerlinckx, & Wagenmakers, 2009). When stimuli are repeated over time (as in the case of the current study), drift rate and *Ter* become faster (Dutilh, Krypotos, & Wagenmakers, 2011) and participants who narrow their boundaries during the course of an experiment (i.e., requiring less evidence to make decisions) also show greater reductions in RT (Dutilh et al., 2009). Finally, a significant Block × Rotation interaction was also found, in which

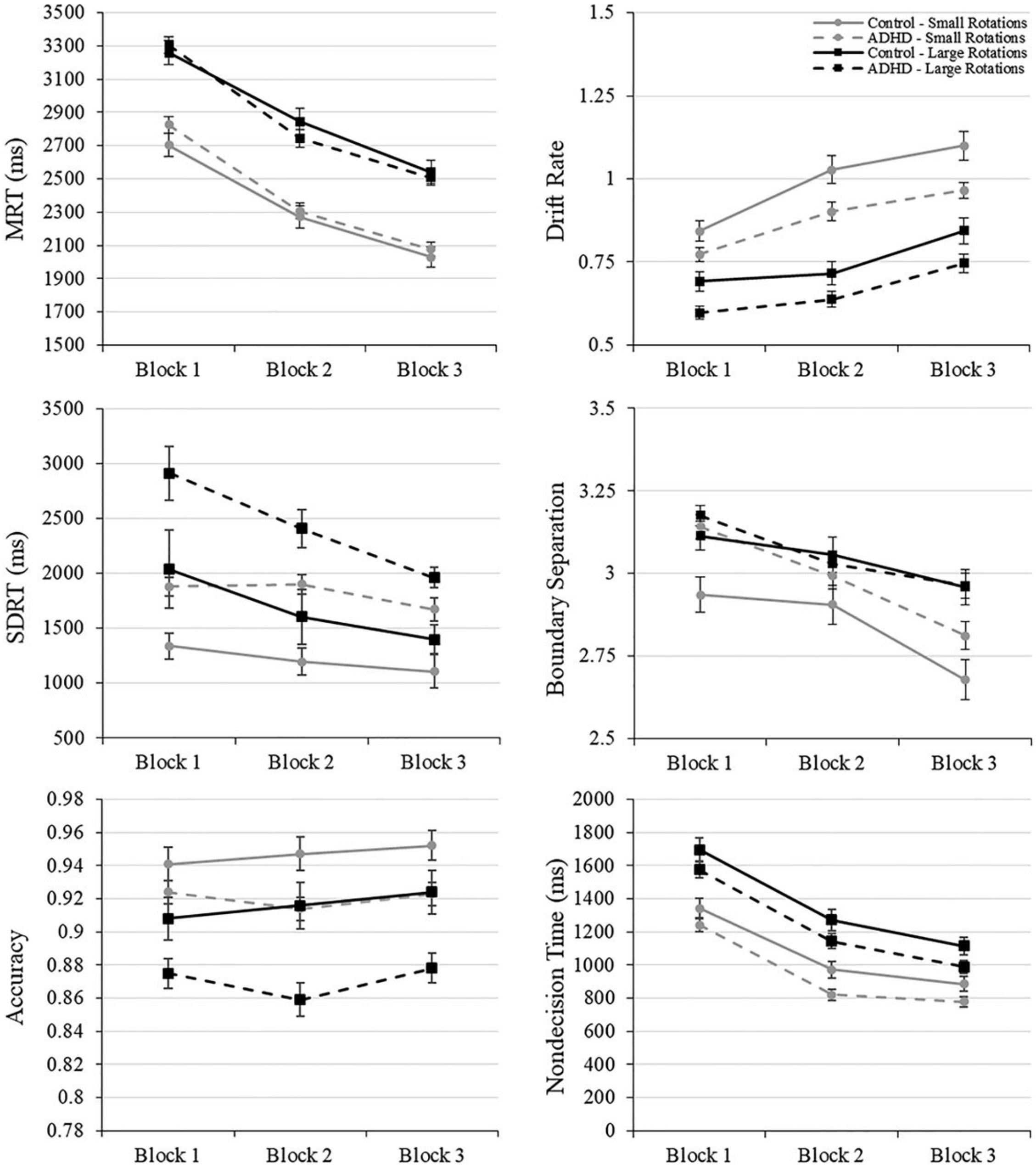

Fig. 2. Plots of MRT, SDRT, accuracy, drift rate, boundary separation, and nondecision time (*Ter*) by group, block, and rotation. Black line = large rotations; Grey lines = small rotations; Dotted line = ADHD; Solid line = Controls.

there were greater increases in drift rate, greater decreases in boundary separation, and smaller decreases in nondecision time for small *versus* large rotations, which may reflect the automatization of the rotation process. Prior studies using mental rotation tasks attribute the disappearance of angle effects on RT with extended practice to an apparent switch from the slow/algorithmic rotation strategy to a more rapid one based on memory retrieval (Kail, 1986; Provost et al., 2013).

Decades of research have documented the presence of performance deficits among children with ADHD on a wide range of neuropsychological tasks including, but not limited to, tasks of visuospatial cognition, timing, WM, inhibitory control, and sustained attention (Castellanos & Tannock, 2002; Frazier, Demaree, & Youngstrom, 2004; Martinussen et al., 2005; Schoechlin & Engel, 2005; Willcutt et al., 2005). The DM results reported here provide clearer evidence of intact rotational abilities in ADHD than is currently available in the literature, and our work contributes to mounting evidence that slow drift rate provides a more parsimonious explanation for cognitive weaknesses in ADHD across domains (Huang-Pollock et al., 2012; Karalunas et al., 2014; Merkt et al., 2013; Metin et al., 2013; Salum, Sonuga-Barke, et al., 2014; Shapiro & Huang-Pollock, 2019; Weigard & Huang-Pollock, 2017).

These empirical advances also bear important implications for process-oriented clinical assessment, in which the separate

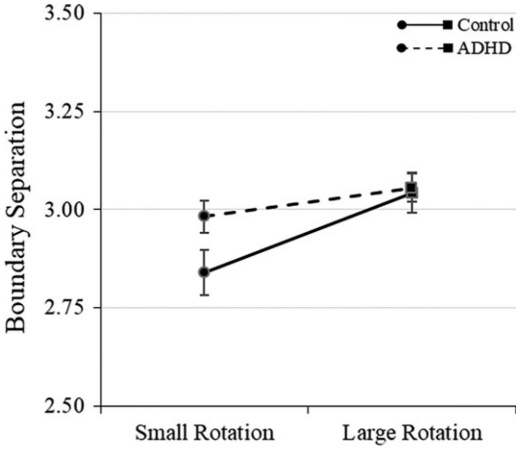

Fig. 3. Boundary separation by ADHD status and stimulus rotation. Dotted line = ADHD; Solid line = Controls.

contributions of different psychological processes to task completion are quantified (e.g., seminal work by Larry Jacoby in the field of memory; Jacoby, 1991). As two descriptors of a single response, RT and accuracy are produced simultaneously and are non-independent. However, the standard in the field is to select one or the other for analysis, even if they yield important interpretive differences. For example, in some situations, an individual may intentionally sacrifice accuracy for speed. In others, the mean RT for an individual or group may not be significantly slower than another, as was the case in the present study, but the shape of the RT distribution could clearly show a pattern of frequent long RTs that is characteristic of children with ADHD (Antonini, Narad, Langberg, & Epstein, 2013). So, separately considering RT and accuracy leads to at best an incomplete understanding of performance, and at worst, erroneous interpretations of data.

Although clinicians often “eyeball,” or informally take differences in speed/accuracy/skew into consideration during interpretation, the DM provides an empirically supported method of integrating all of these descriptors into a single set of psychologically meaningful metrics. It has also shown promise in discriminating clinical populations beyond ADHD, including anxiety (White, Skokin, Carlos, & Weaver, 2016), depression (Pe, Vandekerckhove, & Kuppens, 2013), and schizophrenia (Moustafa et al., 2015). Currently, the lack of nationally representative normative data for DM parameters on commonly administered tests prevents clinicians in the field from personally adopting such an approach (Galloway-Long, Shapiro, & Huang-Pollock, 2016), but establishing these norms while developing future commercial tasks holds promise for enhancing clinical utility.

Among the many strengths of the current study was the use of a visuospatial task that does not use traditional alphanumeric stimuli, which could have been a confound given the well-documented academic difficulties among children with ADHD, including in this sample (Arnold, Hodgkins, Kahle, Madhoo, & Kewley, 2020; Frazier, Youngstrom, Glutting, & Watkins, 2007). There are of course limitations as well. First, although the mental rotation task is among the most widely accepted tests of visuospatial cognition and has been previously evaluated with evidence accumulation models (Larsen, 2014; Provost & Heathcote, 2015), it does not capture all elements of spatial cognition. Future studies are encouraged to evaluate the generalizability of our findings by applying the DM to other spatial processes such as perspective taking, spatial memory, or other forms of mental transformation (e.g., 3-dimensional rotation, mental folding, brittle transformations) (Bayliss, Jarrold, Baddeley, Gunn, & Leigh, 2005; Kozhevnikov & Hegarty, 2001; Moreau, 2013; Resnick & Shipley, 2013; Rump & McNamara, 2013).

Second, despite its advantages over traditional statistical methods, the DM is optimized for binary decision tasks with a mean RT of approximately 1500 ms. However, this is unlikely to have impacted the reliability of our results, as the model’s use has been validated in tasks with average RTs of over 7000 ms (Lerche & Voss, 2017). Third, there were too few trials to calculate DM parameters on all angular rotations, leading to the choice to use two broader classifications of rotation angles. It is likely that some of the interactions with rotation may have been different had greater trial numbers been included. And finally, it bears mentioning that a common argument within the diffusion modeling literature is that because trial condition cannot be anticipated, and stimulus properties that inform processing adjustments are not identified until after evidence accumulation has begun, only the model parameter representing stimulus difficulty (i.e., drift rate) can change across manipulations on a trial-by-trial basis (Ratcliff, 1978). Thus, our findings for the influence of rotation on boundary separation or *Ter* might be questioned. However, in this particular task, stimuli are actively rotated before the onset of the accumulation stage, such that knowledge of rotation angle could theoretically be used to determine the appropriate level of caution for each trial (Larsen, 2014). Likewise, since a significant portion of *Ter* is rotation time, which necessarily varies by angular discrepancy, trial-by-trial differences are to be expected.

CONCLUSION

Performance on speeded reaction time tasks among children with ADHD is often marked by slow, variable, and inaccurate responding. Despite evidence for spatial difficulties in ADHD, and the importance of spatial cognition in general, this remains an understudied domain. In a mental rotation task, we found no evidence of a specific deficit in visuospatial cognition. However, there was evidence of ADHD-related slower drift rates, faster nondecision times, as well as ADHD-related difficulty adjusting response thresholds with changes in rotation.

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CONFLICTS OF INTEREST

There are no conflicts of interest declared.

SUPPLEMENTARY MATERIAL

To view supplementary material for this article, please visit https://doi.org/10.1017/S1355617720001198

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