Archival Report

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Memory for Action Rules and Reaction Time Variability in Attention-Deficit/Hyperactivity Disorder

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BACKGROUND: Patients with attention-deficit/hyperactivity disorder (ADHD) exhibit increased reaction time (RT) variability. This finding is consistent across various choice RT tasks and is considered a core ADHD phenotype, often interpreted as expressing occasional attention lapses. This study explores the selective contribution of perceptual and working memory (WM) processes to increased RT variability in ADHD.

METHODS: Low and high WM demands were manipulated in a battery of choice RT tasks administered to two groups of college students (subjects with ADHD vs. healthy control subjects).

RESULTS: Ex-Gaussian distribution fitting revealed an increased rate of exceptionally slow RTs (i.e., higher τ values) in subjects with ADHD under all conditions. These group differences interacted with WM demands, showing the largest group differences when WM processing was most demanding ($\eta_p^2 = .32$). Under demanding WM conditions, evidence accumulation modeling demonstrated that increased RT variability in ADHD is not associated with either momentary or constant deficits in perceptual processing of the target. Rather, results favored a model associating increased RT variability in ADHD with reduced rate of WM retrieval.

CONCLUSIONS: These results suggest a pivotal contribution for the retrieval of action rules from WM to increased RT variability in ADHD.

Keywords: Attention-deficit/hyperactivity disorder, Decision making, Evidence accumulation modeling, Executive functions, Ex-Gaussian distribution, Intraindividual variability, Working memory

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Attention-deficit/hyperactivity disorder (ADHD) involves symptoms of inattentiveness, impulsivity, and hyperactivity (1). It is well established that subjects with ADHD exhibit increased reaction time (RT) variability (2–4) seen across tasks (2–4), ADHD subtypes (5–7), and age populations (8,9). Administration of stimulant medication was found to reduce RT variability among adults with ADHD (10–13). Furthermore, this symptom was found to be related to genetic factors (14–17). These findings have led researchers to suggest that RT variability is a core phenotype of the disorder (3,4).

Studies have demonstrated that increased RT variability in ADHD is mostly due to increased rates of exceptionally slow RTs (indicated in the heaviness of the long RT distribution tail) (7,18–27). A prevalent explanation is that increased rate of exceptionally slow RTs in ADHD reflects attentional lapses, or momentary failures in goal-directed processing (4,15,18,20,25,28–30). However, "lapses of attention" can relate to both working memory (WM) retrieval and perceptual processing, as "attention" refers to the sum of mental resources allocated to all task-relevant processing, including perception (31,32) and WM retrieval (33–36), and it is unclear which one of them is critical.

Studies have found a strong negative correlation between WM abilities and the rate of exceptionally slow RTs in both healthy subjects (37–40) and subjects with ADHD (2,18,24). Additionally, manipulations of WM demands were found to selectively and causally influence the rate of exceptionally slow RTs (41). WM is a system devoted to maintaining and updating rapidly changing information in a purposeful, goal-directed manner (42,43). In choice RT tasks, the retrieval of novel stimulus-response mappings is suggested to involve WM (41,44). WM deficits among individuals with ADHD are well documented (3,24,45), making it reasonable to assume that these deficits can affect the retrieval of stimulus-response rules in choice RT tasks, leading to increased rates of exceptionally slow RTs.

Increased RT variability in ADHD has also been found in tasks low in WM demand (3,4). Under these conditions, the source of increased RT variability in ADHD is most likely linked to a deficit in other, more elementary, cognitive mechanisms, such as perceptual processing. Perceptual processing has been extensively studied in the context of choice RT tasks (46–49), wherein participants are required to attend to a stimulus and classify it into a predetermined set of alternatives. Failures in attending to the stimulus (e.g., as a result of lapses of attention, mind-wandering) would manifest in degraded perceptual processing, leading to

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Table 1. Characteristics of Participants

	ADHD Group (n = 28)	HC Group (n = 28)	t Tests
Male/Female	15/13	9/19	
Age, Years	24.96 (2.03)	23.96 (1.87)	$t_{54} = 1.92$, $p = .06$
Intelligence			
University entrance scores	649.60 (56.22)	668.93 (30.36)	$t_{54} = 1.6$, ns
Raven's accuracy rate	.73 (.17)	.69 (.13)	$t_{54} = 1.66$, ns
Vocabulary accuracy rate	.74 (.11)	.76 (.09)	$t_{54} = .74$, ns
CAARS			
Inattentiveness	23.22 (3.76)	9.6 (4.3)	$t_{52} = 12.41$, $p < .001$
Hyperactivity	21.3 (5.3)	12.74 (4.99)	$t_{52} = 6.07$, $p < .001$
Impulsivity	17.14 (5.87)	9.33 (5.75)	$t_{52} = 5.32$, $p < .001$
ADHD index	17.63 (2.42)	6.85 (3.38)	$t_{52} = 13.47$, $p < .001$

Values are presented as mean (SD).

ADHD, attention-deficit/hyperactivity disorder; CAARS, Conners' Adult ADHD Rating Scales; HC, healthy control; ns, not significant.

lower quality of perceptual information on which to base the final decision. Correspondingly, neuroimaging studies found decreased activity in sensory brain regions of subjects with ADHD during the performance of choice RT tasks (29,30). Additionally, subjects with ADHD were found to make perceptual decisions based on lower signal-to-noise ratios compared with healthy control (HC) subjects (23,50–55).

In this study, we aim to develop a computational theory exploring the contribution of perceptual processing (identification/classification of the target) and WM retrieval (i.e., selecting the response associated with the target) to increased RT variability in ADHD. Toward this aim, we administered a battery of choice RT tasks to a group of college undergraduates either with ADHD or with no current or past psychiatric disorders. The choice RT tasks were performed under low and high WM retrieval demands. First, we use ex-Gaussian modeling to analyze differences between ADHD and HC participants in the shapes of the choice RT distributions. Ex-Gaussian distribution fitting was reported to successfully estimate different aspects in the RT probability density function [see Figure 1 for an explanation of the ex-Gaussian distribution (56,57)], and studies found that increased RT variability in ADHD is specifically due to changes in the heaviness of the right-RT distribution tail [i.e., indexed by the τ parameter (7,18–27)]. Next, we use evidence accumulation modeling to identify the cognitive mechanisms that might underlie the group differences observed in the former ex-Gaussian analysis. In contrast to previous investigations using evidence accumulation modeling, we use a two-stage decision model that allows us to disentangle perceptual and WM processing components.

METHODS AND MATERIALS

Participants

Participants were 56 college students (Table 1), either with ADHD or with no clinical disorder. Participants with ADHD were asked to provide a history of ADHD diagnosis performed by a clinical psychologist or psychiatrist. The diagnosis was confirmed with a structured clinical interview for DSM-IV, including confirmation of the diagnosis with collateral contact when available. Participants completed a computerized version of the Conners' Adult ADHD Rating Scales (58) to measure symptom severity,[1] Raven's Advanced Progressive Matrices Test[2] (59,60), and a Hebrew vocabulary test (61,62), to detect any possible general fluid or crystallized intelligence group differences. No group differences in these factors were found (Table 1). See Supplement 1 for further details.

Procedure

A battery of choice reaction tasks (shape/letter/digit classification) was used. In each task, participants were asked to follow a set of stimulus-response rules, classifying stimuli using manual key-press responses. The three tasks were performed across four factorial conditions of set size (two-choice vs. six-choice) and mapping (arbitrary vs. nonarbitrary). Set size indicated the number of stimulus-response rules (Figure 2). Mapping indicated whether the stimulus-response rules were 1) novel, thus needing to be maintained in WM (arbitrary mapping) (Figure 2A, B), or 2) based on familiar knowledge assumed to be well represented in long-term memory, thus placing little (or no) demand on WM (nonarbitrary mapping) (Figure 2C, D) (41,42,44,63).

WM load was assumed to change with the number of arbitrary rules. That is, WM load was considered to be low in the two-choice arbitrary condition (i.e., two arbitrary rules were used) and to increase in the six-choice arbitrary condition (i.e., six arbitrary rules were used). The two-choice and six-choice nonarbitrary conditions controlled for the effect of set size, regardless of WM load. Thus, the interaction of mapping × set size was assumed to reflect WM load (41) (Supplement 1).

RESULTS

Choice Task Performance

Ex-Gaussian parameters were estimated for each participant, at each condition. Repeated measures analyses of variance

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[1] Two questioners (one in the ADHD group, one in the HC group) were corrupted because of computer malfunction and were omitted from this analysis.

[2] Because of time constraints and because our primary interest was in group differences in contrast to assessments of full scale IQ scores, we administered half of the Raven's Advanced Progressive Matrices Test (i.e., 18 odd items).