Basic Impairments in Regulating the Speed-Accuracy Tradeoff Predict Symptoms of Attention-Deficit/Hyperactivity Disorder

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Background: Attention-deficit/hyperactivity disorder (ADHD) is characterized by poor optimization of behavior in the face of changing demands. Theoretical accounts of ADHD have often focused on higher-order cognitive processes and typically assume that basic processes are unaffected. It is an open question whether this is indeed the case.

Method: We explored basic cognitive processing in 25 subjects with ADHD and 30 typically developing children and adolescents with a perceptual decision-making paradigm. We investigated whether individuals with ADHD were able to balance the speed and accuracy of decisions.

Results: We found impairments in the optimization of the speed-accuracy tradeoff. Furthermore, these impairments were directly related to the hyperactive and impulsive symptoms that characterize the ADHD-phenotype.

Conclusions: These data suggest that impairments in basic cognitive processing are central to the disorder. This calls into question conceptualizations of ADHD as a "higher-order" deficit, as such simple decision processes are at the core of almost every paradigm used in ADHD research.

Key Words: ADHD, drift-diffusion model, hyperactivity, optimization, perceptual decision-making, speed-accuracy tradeoff

Attention-deficit/hyperactivity disorder (ADHD) is a common child neuropsychiatric disorder. It has a great impact on affected individuals and their families, because individuals with ADHD have trouble adapting their behavior appropriately to social and environmental demands. For example, children with ADHD might have trouble waiting their turn in conversation or staying in their seat in the classroom (impulsive symptoms), or they might have trouble focusing on the task at hand and become distracted easily (inattentive symptoms). Such symptoms can be conceptualized as poor adaptation of behavior to social or environmental demands and have often been attributed to deficits in higher-order cognitive processes. Indeed, functional imaging studies have shown changes in brain activity on tasks that tap these processes (1–4 for review). However, these studies have one thing in common: they use paradigms where subjects respond differentially to different classes of stimuli. As such, these tasks require the subject to make a perceptual decision in choosing the most appropriate course of action. One example is the go/no-go paradigm, where one stimulus requires a button-press as soon as possible, whereas another requires the suppression of that same button press. A basic assumption of these paradigms is that children with ADHD are capable of making such basic perceptual decisions as well as typically developing children. It is an open question whether this is indeed the case. If children with ADHD are impaired in balancing the speed and accuracy with which they make such decisions, this will affect their behavior. For example, a child that decides prematurely that his friend has finished talking, might blurt out a response too quickly.

Decision-making processes can be described with the drift-diffusion model (DDM) (e.g., 5–10). This model conceptualizes decision-making as the accumulation of sensory information over time toward a decision threshold (Figure 1) (6,11 for review): the sensory evidence builds toward a decision until the threshold is reached, at which point the decision is made. One particularly useful property of this model is that it simultaneously accounts for response time (RT) and accuracy (8,12–15). A second useful property is that studies from both humans and nonhuman primates have shown neural correlates of the components of the model, demonstrating that it has ecological validity in addition to theoretical appeal (16–24). In addition to integrating RT and accuracy data into a single model, the DDM permits the decomposing of data into parameters that are related to decision-making and those that are related to sensory or motor processing. Each parameter has a unique effect on behavior, and subjects are required to adjust the parameters of the model to comply with task demands (14). The rate of drift toward a decision threshold depends on the difficulty of the decision at hand, but subjects can adapt the decision threshold to favor speed or accuracy.

One important aspect of optimizing behavior in response to environmental demands involves the speed-accuracy tradeoff (12,15,25–29): errors are more likely when information is noisier, meaning more time is required to reach a correct decision. Trading speed for accuracy (slowing down) is useful in contexts where errors are costly, but accuracy can be sacrificed to gain speed if correct responses have greater value than errors. The DDM provides a mechanism to conceptualize the speed-accuracy tradeoff by flexibly adapting the decision threshold. When the decision threshold is low, responses are fast, but more errors are made. When the threshold is high, more time is taken to collect evidence, thus increasing the chance of a correct decision (Figure 1). As such, flexible adaptation of the decision threshold is crucial to adapting behavior in response to environmental demands. Because subjects with ADHD have difficulty adapting their behavior in response to environmental demands and are prone to impulsiveness, we hypothesized that this might arise from a basic inability to adapt the decision thresh-

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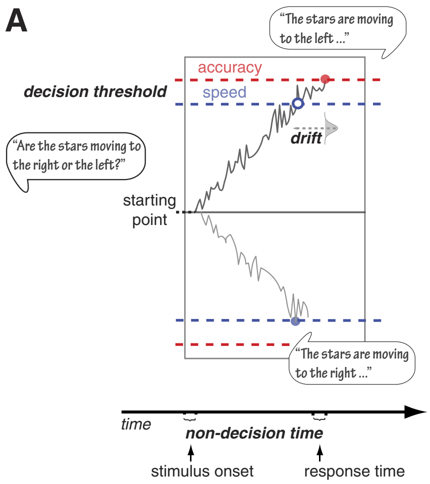

Figure 1. Schematic representation of the drift-diffusion model. **(A)** This model assumes that dichotomous decisions are based on the accumulation of noisy evidence over time to a fixed threshold (decision threshold). As the process is noisy, there is variability in the time to reach threshold, leading to variable response times and possibly incorrect choices. "Drift rate" represents the average amount of evidence accumulated/time unit. "Non-decision time" is the time for processes other then the decision process, such as stimulus encoding and motor responses. **(B)** The drift-diffusion model provides a model for the speed-accuracy tradeoff: when the decision threshold is low, responses are fast but involve a higher risk of an incorrect choice (open blue circle). When the decision threshold is higher, more time is used to collect evidence, increasing the chance of a correct choice (solid red circle). As such, flexible adaptation of the decision threshold is crucial in optimizing speed and accuracy in response to environmental demands.

old. This inability could manifest itself as a tendency to make impulsive and speedy decisions, behavior that is associated with ADHD at a phenotypic level.

We investigated this hypothesis with a basic perceptual decision-making task, where either accuracy or speed was stressed in the instructions. Specifically, we hypothesized that subjects with ADHD would display an overall preference for speed over accuracy, reflected by a lower decision threshold when accuracy was stressed. Furthermore, we hypothesized that subjects with ADHD would show a smaller speed-accuracy tradeoff across levels of accuracy emphasis, reflecting an inability to optimize performance in response to changing task demands. This smaller adjustment in the speed-accuracy tradeoff should be reflected in the difference between decision thresholds in task conditions where either speed or accuracy was emphasized. Finally, we hypothesized that if optimizing behavior at this basic cognitive level is indeed central to ADHD, then these deficits should correlate with symptoms of the disorder.

Thirty typically developing children and adolescents and 25 subjects with ADHD performed a perceptual decision-making task, where accuracy was stressed in one condition and speed was stressed in another (Figure 2). We used a child-friendly version of a random-dot motion task, embedded in a computer game. Subjects were told that a small red rocket was lost in space and that they needed to bring the rocket back home to earth safely, by following the "stars." Stars were depicted as a cloud of randomly moving dots on a screen (12,15,16,30,31). Subjects were to decide whether they were moving to the left or to the right. In "accuracy" sessions, subjects were instructed that they would earn points for being as accurate as possible. In "speed" sessions, they were instructed to respond as quickly as possible and that they would receive more points for being faster. To examine whether differences between groups were specific to the speed-accuracy tradeoff or whether other components of the decision process were also affected, we manipulated difficulty by changing the number of coherently moving "stars" across five difficulty levels.

Methods and Materials

Participants

Fifty-seven children participated in the study, including 25 children with ADHD. Two control subjects were excluded from the analyses due to poor performance on the task, because more than two-thirds of their choices constituted fast guesses (impulsive choices based on a guess or caused by a distraction). Demographic information is listed in Table S1 in Supplement 1. Subjects with ADHD were matched to typically developing control subjects, for age, Tanner stage, gender, IQ, hand preference, and socioeconomic status (years of parental education). Subjects were recruited through the Department of Child and Adolescent Psychiatry at the University Medical Center Utrecht in the Netherlands (children with ADHD) and local schools (typically developing control subjects). The procedure was approved by the Medical Ethical Review Board at the University Medical Center Utrecht, and informed consent was obtained from a parent for each child as well as assent from the subject. Children with major physical or neurological illness, learning disabilities, or IQ < 70 were excluded from participating. The IQ was assessed with the Wechsler Intelligence Scale for Children II, Wechsler Intelligence Scale for Children—Revised, or Wechsler Adult Intelligence Scale. Subjects with ADHD were required to have a clinical diagnosis for ADHD from our department as well as meet criteria for ADHD according to the Diagnostic Interview Schedule for Children, parent version (DISC-P). Control subjects were excluded if they met criteria for any diagnosis on DISC-P or if any first-degree relative had been diagnosed with a psychiatric disorder.

Teacher ratings were collected with the Teacher Rating Form when possible (32). These were available for 20 subjects with ADHD and 20 control subjects. Nineteen subjects with ADHD were receiving short-acting medication and were asked to discontinue treatment for a minimum of 24 hours before participating in the study.

Paradigm

To manipulate the speed-accuracy trade-off we used a version of the random-dots motion paradigm (e.g., 12,14–16,18,30,31,33).

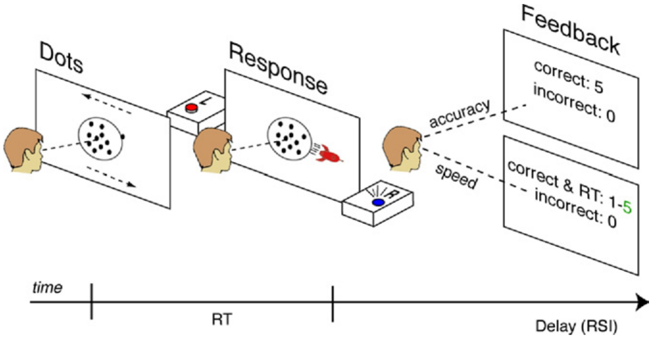

Figure 2. Random-dot motion task. Subjects were instructed to indicate the direction of an array of randomly moving dots by a button press. The motion stimulus stayed on until a button was pressed. After the response, feedback showing the number of points earned was given. During accuracy sessions, subjects earned five points for each correct choice. During speed sessions, subjects earned between one and five points, depending on the speed of their response. To stress the importance of speed, 5-point rewards were displayed in a green font and accompanied by a special winning bleep. RT, response time.

Subjects were instructed to maintain fixation on the middle of the screen (at 60-cm distance) and to decide the direction of motion of a cloud of randomly moving white dots. They indicated their decision at any time during motion-viewing with a button press. Task difficulty was manipulated by manipulating the percentage of coherently moving dots, where the task was harder for trials with fewer coherently moving dots. For the current study we developed a child-friendly version of the task, where the paradigm was embedded in a simple game where children showed a rocket the way home (Supplement 1).

Prepractice Session

To become familiar with the task, subjects practiced during the first set of task instructions. Ten practice trials were displayed with relatively easy coherence levels (12.8%, 25.6%, and 51.2% coherently moving dots). If performance was poorer than 60% correct, more trials were displayed until performance reached at least 60% correct trials.

Practice Session and Difficulty Levels

After the prepractice session, subjects performed 80 practice trials to estimate their individual discrimination threshold. Two randomly interleaved adaptive staircases were used to estimate the 82% performance level (34). The first staircase started at a high motion coherence level (80%), and the second staircase started at very low motion coherence level (5%). On the basis of the estimated discrimination threshold, a Weibull function was used to determine the proportion of coherently moving dots for each difficulty level. For each subject, the proportion of coherently moving dots was obtained corresponding to performance levels of 50%, 63%, 71%, 95%, and 99% correct choices. These five difficulty levels were then used in the experimental “accuracy” and “speed” sessions (Figure S1 in Supplement 1).

Accuracy Sessions

In the two accuracy sessions, subjects were instructed to be as accurate as possible to show the rocket the way home. Subjects earned five points for each correct answer and zero points for each incorrect answer. Subjects performed two sessions of 125 trials each, resulting in a total of 250 trials, with 50 trials/difficulty level. Difficulty levels were randomly distributed over each session.

Speed Sessions

The two accuracy sessions were followed by the two speed sessions. Here, subjects were instructed to respond as quickly as possible. Subjects could earn between one and five points for a correct choice, where five points were awarded for the fastest responses, and one point was awarded for the slowest responses. No points were given for incorrect choices. For each subject, fast and slow responses were defined with the RT-distribution for each difficulty level obtained in the accuracy sessions. For each coherence-sample a γ function was fit to the RT data (8,35). From this distribution, RTs at the 20th, 40th, 60th, and 80th percentiles were calculated. In the speed version of the task, subjects could earn five points for RTs that fell within the first 20th percentile, four points for RTs between the 20th and 40th percentile, and so forth. When RT fell above the 80th percentile, subjects earned one point. An individual reward scheme was used to ensure that each subject had equal likelihood of maximizing scores within the speed session and that the score of 5 points was within the capability of each subject. To stress the importance of speed, five-point rewards were displayed in a green font and accompanied by a special winning-bleep. Subjects performed two blocks of 125 speed trials, resulting in a total of 50 trials/difficulty level. Difficulty levels were randomly distributed over each session.

End of the Experiment

The game ended with a feedback display showing total scores and a picture of the rocket on earth, accompanied by the text “Thank you, we are back home!” Total task duration was a maximum of 25 min (depending on time taken for breaks).

Behavioral Analyses

The DDM assumes that, for each dichotomous choice, sensory evidence accumulates in favor of one or the other alternative. When this accumulation of evidence reaches a threshold value (decision threshold), the choice is made (Figure 1). The speed-accuracy tradeoff is controlled by the height of the decision threshold that can be estimated by fitting the DDM to the data while permitting the decision threshold to vary between speed and accuracy conditions. However, speed and accuracy might also be affected by other parameters, such as difficulty (14,26,36): in this task, the coherence of the motion stimulus reflects decision difficulty, meaning that drift-rate (the speed at which evidence accumulates [Figure 1]) is likely to covary with coherence of the motion stimulus (12,14). Furthermore, the speed of the motor response could theoretically differ between speed and accuracy conditions. As such, we allowed three parameters of the model to fluctuate within subjects across conditions: decision threshold, drift-rate, and nondecision time (which includes the motor response). We used the Diffusion Model Analysis Toolbox to fit the DDM to the individual data and to determine the model with the best trade-off between fit quality and model complexity (37,38) (Supplement 1).

Statistical Analyses

Group differences were investigated with the SPSS statistical package (version 16.0, SPSS, Chicago, Illinois). Summary data of accuracy, speed, and total points scored (Figure 3) were analyzed with a mixed-model analysis of variance (ANOVA), with speed-accuracy tradeoff (two levels) and difficulty (five levels) as within-subject factors and group (ADHD vs. control) as a between-subject factor. Performance data were corrected for fast guesses before being entered in the ANOVA (Supplement 1). The DDM parameters (decision threshold, nondecision time, and drift rate) were analyzed with a mixed-model ANOVA. Constrained DDM parameters, vari-

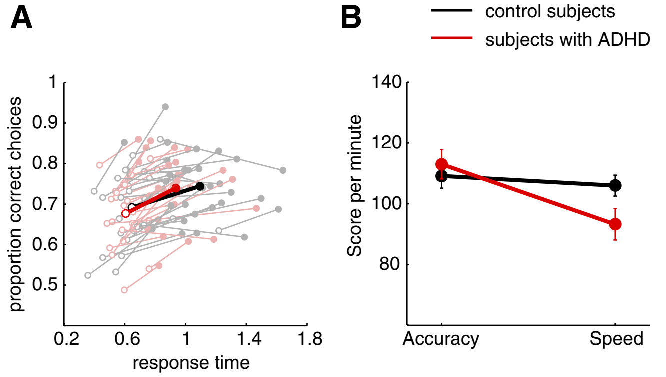

Figure 3. Speed-accuracy tradeoff and reward rate. **(A)** The speed-accuracy tradeoff between accuracy and speed sessions. Each data-point represents mean response time vs. mean proportion of correct choices for accuracy (solid dots) and speed sessions (open dots). The dim lines show data for individual subjects, whereas bright lines indicate group means. Subjects with attention-deficit/hyperactivity disorder (ADHD) (red) have faster responses than control subjects (black) in accuracy sessions but are equally fast in the speed sessions. **(B)** Average (SEM) points scored/min (reward rate) on accuracy and speed sessions. Subjects with ADHD (red) had reward rates similar to control subjects (black) in accuracy sessions but lower reward rates in speed sessions.

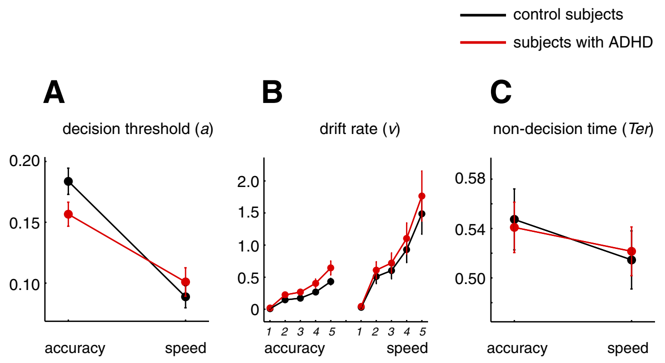

Figure 4. Differences between subjects with attention-deficit/hyperactivity disorder (ADHD) (red) and healthy control subjects (black) on the three main parameters of the drift-diffusion model for accuracy and speed sessions. Data-points represent means (SEM). **(A)** Decision threshold is a measure of regulation of the speed-accuracy tradeoff. Compared with control subjects, subjects with ADHD showed a lower decision threshold on accuracy sessions but not speed sessions. This indicates a smaller adjustment of the speed-accuracy tradeoff for subjects with ADHD, possibly because of impaired regulation of the decision threshold. **(B)** Drift-rate represents the accumulation of sensory information/unit time (quality of the stimulus). Drift rates covaried with the motion coherence, with larger drifts-rates for stronger coherence (easier trials). For each motion-strength, drift rates were significantly larger in speed sessions than in accuracy sessions, indicating faster processing of sensory information when speed is required. There were no differences in drift-rate between subjects with ADHD and control subjects. **(C)** Nondecision time represents time involved in processes other then the decision process (e.g., encoding and motor processes). Nondecision times were lower for all subjects in the speed version of the task. There were no differences between groups.

ability in nondecision time (s_z), variability in starting point (s_t), and variability in drift rate (η) were compared between groups with two-sampled *t* tests. Finally, a regression analysis was run to test whether changes in decision parameters could predict ADHD symptoms, as assessed by the DISC-P. For this purpose we calculated the difference between accuracy and speed sessions for each main parameter. These values together with the variability parameters (s_z, s_t, and η) were entered as independent variables in the two separate regression analyses with cumulative DISC symptom-scores (for inattentiveness or hyperactivity/impulsivity, respectively) as the dependent variable. These results were corroborated by repeating the analyses with teacher ratings of inattentive and hyperactive/impulsive symptoms as the dependent variable.

Results

Speed-Accuracy Tradeoff

Most subjects had fewer correct choices and faster RTs for speed than accuracy sessions, reflecting the speed-accuracy tradeoff [$F(1,53) > 60.7$, $p < .0001$] (Figure 3A). Furthermore, most subjects made more errors and responded more slowly when choices were more difficult [$F(1,53) > 21.5$, $p < .0001$]. For RT, there was a group × session interaction, where subjects with ADHD were faster than control subjects on accuracy but not speed sessions [$F(1,53) = 8.5$, $p = .005$]. There were no differences between groups in the proportion of correct choices made for both accuracy and speed sessions ($p > .5$). In sum, all subjects showed the speed-accuracy tradeoff to some degree. However, subjects with ADHD showed a preference for speed, even in the accuracy sessions.

Optimizing the Speed-Accuracy Tradeoff

Subjects with ADHD scored fewer points/min than control subjects in the speed sessions, as reflected by a group × session interaction [$F(1,53) = 12.3$, $p = .001$] (Figure 3B). This lower rate of reward suggests that they might have failed to optimize the speed-accuracy tradeoff. If so, this should be reflected by a smaller difference in decision threshold between speed and accuracy sessions. To investigate this, we fitted the DDM to the data of each individual subject and tested for differences in decision threshold, reflecting the speed-accuracy tradeoff, and drift rate, reflecting difficulty. We further tested for differences in nondecision time to assess group differences in other, nondecision processes.

All subjects had lower decision thresholds for speed than accuracy sessions [$F(1,53) = 216.6$, $p < .001$] (Figure 4, Table 1). An interaction between "group" and "session" showed that subjects with ADHD had lower decision thresholds than control subjects in accuracy sessions but higher decision thresholds in speed sessions [$F(1,53) = 14.7$, $p < .001$]. This interaction was suggestive of smaller speed-accuracy tradeoffs for subjects with ADHD compared with control subjects (Figure 4A). To explore this further, we determined the individual speed-accuracy tradeoff of each subject, by calculating the difference between the height of the decision threshold for the accuracy and speed sessions. Subjects with ADHD had a smaller speed-accuracy tradeoff than typically developing control subjects [$t(53) = 3.8$, $p < .0001$] (Table 1).

Overall, subjects had higher drift rates and shorter nondecision times in speed than accuracy sessions [$F(1,53) = 23.7$, $p < .001$; $F(1,53) = 8.3$, $p < .005$]. There were no group differences or interaction effects for drift rate or nondecision time. These data suggest

Table 1. Parameter Values of DDM for Typically Developing Control Subjects and Subjects with ADHD

		Control Subjects (n = 30)			ADHD (n = 25)		
DDM Parameter		Accuracy	Speed	Difference	Accuracy	Speed	Difference
Decision Threshold	*a*	.184 (.06)	.089 (.05)	.095 (.04)[a]	.157 (.05)	.101 (.06)	.056 (.04)[a]
Drift Rate							
Difficulty level 1	*v*1	.007 (.06)	.031 (.07)	−.023 (.04)	.022 (.06)	.046 (.07)	−.025 (.03)
Difficulty level 2	*v*2	.146 (.10)	.509 (.60)	−.362 (.60)	.226 (.18)	.610 (.66)	−.384 (.53)
Difficulty level 3	*v*3	.174 (.11)	.604 (.71)	−.430 (.71)	.266 (.21)	.722 (.78)	−.456 (.62)
Difficulty level 4	*v*4	.269 (.17)	.928 (1.08)	−.659 (1.09)	.404 (.33)	1.103 (1.21)	−.700 (.96)
Difficulty level 5	*v*5	.432 (.28)	1.489 (1.74)	−1.057 (1.74)	.644 (.55)	1.765 (1.95)	−1.121 (1.54)
Nondecision Time	T_{er}	.547 (.14)	.515 (.13)	.033 (.07)	.541 (.10)	.522 (.10)	.019 (.06)

Values given are mean (SD). Values for drift rates are shown for each difficulty level with difficulty decreasing from Level 1 to 5.
DDM, drift-diffusion model.
[a] Reflects a significant difference in the shift of decision threshold *a* (speed-accuracy tradeoff) between control subjects and subjects with attention-deficit/hyperactivity disorder (ADHD), $p < .0001$.

that subjects with ADHD do not optimize the speed-accuracy tradeoff to the same degree as control subjects (Supplement 1).

However, subjects with ADHD made faster decisions than control subjects during accuracy sessions. As such, one hypothesis could be that subjects with ADHD are closer to a physical RT limit, resulting in a floor effect for RT in the speed sessions. Accordingly, lower speed-accuracy tradeoffs for subjects with ADHD might reflect this physical RT limit. We addressed this by determining the RT-windows for scoring points individually: the highest points were awarded for RTs within the fastest 20% from the accuracy session (Methods and Materials). Even very fast responses were therefore well within the capacity of the subjects. Furthermore, the RT windows (20th percentile—fastest RT) were not narrower for subjects with ADHD than for control subjects [$F(1,53) = .14, p > .71$]. Finally, we included the RTs from the accuracy sessions as a covariate in the ANOVA to test whether differences in the speed-accuracy tradeoff were dependent on them. This did not change the finding of a group × session interaction for the decision threshold [$F(1,53) = 9.6, p = .003$], suggesting that faster RTs in the accuracy condition did not account for the smaller speed-accuracy tradeoff adjustment for subjects with ADHD. In all, these additional analyses indicate that group differences in optimizing the speed-accuracy tradeoff reflect a difference in adapting the decision threshold rather than a group difference in RT.

Relationship to ADHD Symptoms

To explore whether optimizing behavior at this basic level of perceptual decision-making was related to the ADHD behavioral phenotype, we tested whether differences in decision parameters were related to symptoms of the disorder. Two regression analyses were run: the first included parent ratings of overall inattentive symptoms, and the second included parent ratings of overall hyperactive/impulsive symptoms as the dependent variable. The difference in decision threshold between speed and accuracy sessions (speed-accuracy tradeoff), drift rates (difficulty), and nondecision times were entered as predictors, along with variability-parameters (Methods and Materials). None of the parameters predicted inattentiveness ($p > .58$). However, two parameters predicted the variance in impulsivity/hyperactivity symptoms: speed-accuracy tradeoff ($\beta = -.58; p < .05$), and a parameter reflecting variability in the decision threshold (s_z; regression coefficient $\beta = -.47; p < .05$) (Supplement 1). However, across subjects the variance in s_z was minimal, making this finding less reliable (only 13 of 25 subjects had $s_z > 0$, median approximately 0, variance $= .003$). The negative linear relationship between speed-accuracy tradeoff and impulsivity/hyperactivity symptom scores (corrected for the effects of all other parameters in the DDM) is plotted in Figure 5. This result was corroborated by repeating these analyses with teacher ratings of inattentive and hyperactive/impulsive symptoms as the dependent variables (available for 19 subjects with ADHD). Here again, the speed-accuracy tradeoff predicted hyperactive/impulsive symptoms ($\beta = -.612; p < .05$) but not inattentive symptoms ($p > .05$).

Discussion

We explored basic cognitive processing in ADHD with a perceptual decision-making paradigm. We investigated whether individuals with ADHD were able to balance the speed and accuracy of decisions. We found impairments in this basic regulation that predicted hyperactive and impulsive symptoms.

Interestingly, individuals with ADHD were not impaired on all aspects of task performance (Figure 3): although they showed a preference for speed, they did not make more errors than control subjects in either speed or accuracy sessions. As such, the lower speed-accuracy tradeoff was not problematic in terms of their accuracy: their preference for speed did not result in more mistakes. However, the cost of a poorer speed-accuracy tradeoff became apparent in the speed sessions: although individuals with ADHD were as accurate as control subjects, they scored fewer total points/min. As such, the smaller adaptation of the decision threshold was not optimal in terms of reward maximization. This failure to optimize was not due to an inability to make fast choices in general but rather seemed to be due to a basic maladaptive setting of the decision threshold. The specificity of these impairments in performance underscores the basic level of these findings: it is not cognition in general that is impaired but rather an ability to optimize behavior, even at a basic cognitive level. This does not necessarily imply that it is only bottom-up processes that are involved. Rather, trial-to-trial adaptation of the decision threshold is likely to also involve aspects of top-down control.

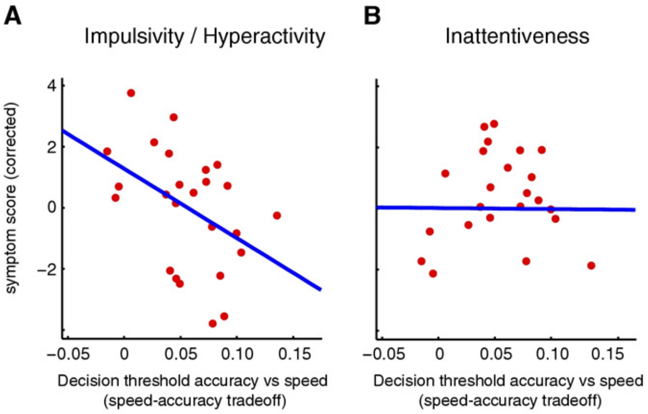

Figure 5. Relationship between the speed-accuracy tradeoff (as reflected by decision threshold) and attention-deficit/hyperactivity disorder (ADHD) symptoms. On the x axis, the ability to flexibly regulate the speed-accuracy tradeoff in response to task demands is reflected by the difference in decision threshold between the accuracy and speed sessions. **(A)** The speed-accuracy tradeoff predicts hyperactive/impulsive symptoms scores on the impulsivity/hyperactivity scale (y axis) but not inattentive symptoms **(B)**. Data are corrected for the effects of other parameters of the drift-diffusion model.

Our findings tie in with findings from neuroimaging studies in ADHD that have stressed the involvement of frontostriatal circuitry in this disorder (39). In ADHD, problems in this circuitry have been linked to a range of cognitive and behavioral problems. Recently, a perceptual decision-making task, similar to the one here, was used to show that striatum is involved in adapting the decision threshold to balance the speed-accuracy tradeoff. When speed is stressed, activity in striatum increases, with the greatest increases for those individuals who adjust their decision threshold most (18,29). These results make it plausible that similar neurobiological mechanisms might underlie problems in optimizing behavior both at the basic level shown here and at the behavioral level of ADHD-symptoms.

There are limitations to our study that need to be acknowledged. First, although subjects with ADHD were either not receiving medication or discontinued treatment 24 hours before participating in the study, most were not stimulant-naive. As such, we cannot rule out that some of the observed changes in the speed-accuracy tradeoff are due to long-term effects of stimulant medication. Second, with larger groups, statistical power would have been greater and our findings would probably have appeared stronger. As such, we cannot be certain that null findings in the present study are not due to low power. However, effect size (partial η^2) for the main effect of session was .803 and .217 for the group × session interaction, indicating that these findings are fairly robust. Third, although subjects who had received a diagnosis of a learning disability were excluded, we did not assess learning impairments directly. Therefore, we cannot rule out that differences in learning ability between groups might have affected our results. Furthermore, although we only included control subjects without a psychiatric diagnosis and without first-degree relatives with a psychiatric diagnosis, we cannot be sure that some of these control subjects will not develop psychiatric symptoms in the future. Finally, we found that a reduced ability to optimize the speed-accuracy tradeoff relates to hyperactive and impulsive symptoms of ADHD but not to attention symptoms. As such, these findings do not present an encompassing explanation of the disorder but merely show that impairments in basic decision processes are involved in it.

In sum, theoretical and experimental accounts of ADHD have typically highlighted higher-order cognitive processes. Such accounts make the assumption that basic perceptual processes are not impaired in this disorder. We reasoned that this might not be the case. Rather, we hypothesized that, if basic cognitive processes such as perceptual decision-making are indeed characterized by problems in optimization, this might be directly tied to the ADHD phenotype. Indeed, we found that the performance of individuals with ADHD on a perceptual decision-making task was characterized by poor optimization of the speed-accuracy tradeoff, where they demonstrated an overall preference for speed. Furthermore, these impairments were directly related to the hyperactive and impulsive symptoms that characterize the ADHD-phenotype. In all, these data show that ADHD is associated with impairments in basic cognitive processing. The relationship with ADHD symptoms suggests that these impairments are central to the disorder. This calls into question conceptualizations of ADHD as a "higher-order" deficit, because basic decision processes are at the core of almost every paradigm used in ADHD research.

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