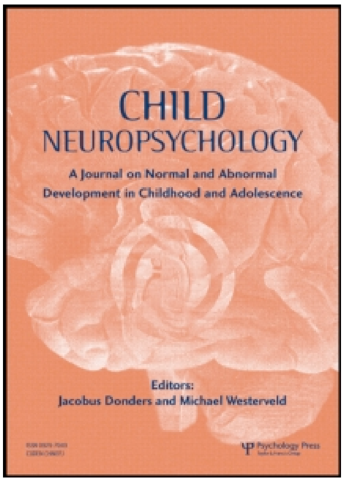

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Cognitive-Motivational Deficits In ADHD: Development of a Classification System

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Cognitive-motivational deficits In ADHD: Development of a classification system

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The classification systems developed so far to detect attention deficit/hyperactivity disorder (ADHD) do not have high sensitivity and specificity. We have developed a classification system based on several neuropsychological tests that measure cognitive-motivational functions that are specifically impaired in ADHD children. A total of 240 (120 ADHD children and 120 healthy controls) children in the age range of 6–9 years and 32 Oppositional Defiant Disorder (ODD) children (aged 9 years) participated in the study. Stop-Signal, Task-Switching, Attentional Network, and Choice Delay tests were administered to all the participants. Receiver operating characteristic (ROC) analysis indicated that percentage choice of long-delay reward best classified the ADHD children from healthy controls. Single parameters were not helpful in making a differential classification of ADHD with ODD. Multinominal logistic regression (MLR) was performed with multiple parameters (data fusion) that produced improved overall classification accuracy. A combination of stop-signal reaction time, posterror-slowing, mean delay, switch cost, and percentage choice of long-delay reward produced an overall classification accuracy of 97.8%; with internal validation, the overall accuracy was 92.2%. Combining parameters from different tests of control functions not only enabled us to accurately classify ADHD children from healthy controls but also in making a differential classification with ODD. These results have implications for the theories of ADHD.

***Keywords*:** ADHD; ODD; Stop-Signal test; Task-Switching test; Choice Delay test.

INTRODUCTION

Attention Deficit/Hyperactivity Disorder (ADHD) and Oppositional Defiant Disorder (ODD) are common childhood-onset disorders with prominent disturbances of attention and their diagnosis is problematic due to symptomatic overlap (Teicher, Ito, Glod, & Barber, 1996). Differential classification of ADHD is complicated by the prevalence of comorbid conditions and the use of subjective reports (structured parent-teacher interview/parent or teacher-completed behavior rating scales). These subjective measures are more helpful in screening for the symptoms than in differential classification.

In addition, there is an evolving awareness that ADHD as currently behaviorally-defined in the *Diagnostic and Statistical Manual of Mental Disorders,* 4th edition (*DSM-IV*: American Psychiatric Association [APA], 1994) is heterogeneous in etiology. Widely

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varying opinions regarding the validity of current views of the disorder confuse attempts to bring uniformity to the discussion. Hence, there is a need for a function-based definition of ADHD based on neuropsychological impairments. Such a definition has much to offer to ADHD diagnosis (Stefanatos & Baron, 2007). Therefore, in the present study we evaluated the efficiency of specifically chosen neuropsychological tests in the classification of ADHD children, ODD children, and healthy controls. This classification approach would help to advance the legitimacy of an objective function-based definition of "attention disorder" that may be more etiologically homogeneous.

Ozonoff and Jensen (1999) compared several aspects of neuropsychological functions in ADHD children with other clinical groups and argued that ADHD children may have a particular neuropsychological profile, and thus careful use of neuropsychological tests is warranted for this population. Classification approaches to ADHD have examined the efficiency of neuropsychological tests in classifying ADHD from healthy controls (Barkley & Grodzinsky, 1994; Doyle, Bierderman, Seidman, Weber, & Faraone, 2000; Perugini et al., 2000). The efficacy of an instrument for classification of ADHD is determined by its ability to distinguish ADHD children from both normal controls and other potentially comorbid clinical groups. To our knowledge, very few studies have evaluated the classification efficiency of neuropsychological tests in differential classification of ADHD children from other clinical groups (Riccio, Reynolds, & Lowe, 2001; Sharma, Perachio, Newcorn, Sharma & Halperin, 1995). For example, Sharma et al. examined the classification performance using CPT measuring inattention and impulsivity and actigraph measures to differentiate ADHD, non-ADHD (including ODD, anxiety disorder, and affective disorder), and healthy controls. They found that Continuous Performance Test (CPT) measures were less helpful in classification compared to the actigraph measure.

Neuropsychological tests, particularly frontal/executive tests used in previous studies, have not resulted in good classification of ADHD children from the healthy controls (Barkley & Grodzinsky, 1994; Doyle et al., 2000; Perugini et al., 2000). For example, Perugini et al. explored the predictive power of Conners' Continuous Performance Test (CCPT) and other frontal/executive tests that measure cognitive functions like interference control, working memory, and mental set shifting to classify ADHD children and healthy controls. Performance was significantly different between children with ADHD and healthy controls on only CCPT and not on the frontal executive tests. The battery approach moderately increased the overall predictive power of neuropsychological tests but still failed to detect a large percentage of ADHD children. The neuropsychological test battery used by Doyle et al. has also shown limited utility for the classification of ADHD with healthy controls.

In addition to neuropsychological tests, commercial CPTs such as Gordon Diagnostic System (GDS; Gordon, 1983), Test of Variable of Attention (TOVA; Greenberg, 1996), and Intermediate Visual and Auditory CPT (Sandford, 1995) have been used to examine the classification performance between ADHD and healthy controls (Greenberg & Waldman, 1993; Rielly, Cunningham, Richards, Elbard, & Mahoney, 1999). High rates of false negatives (20%–37% or higher) and limited ability to discriminate between ADHD and other disorders were observed (Greenberg & Waldman). Rielly et al. used the GDS CPT and obtained poor classification performance in children with a history of language disorders for the presence of ADHD. Other studies also found that CPTs have been inconsistent in differentiating ADHD from other clinical groups (Riccio et al., 2001).

A possible reason for the limited efficiency of the neuropsychological tests and CPTs used in previous studies is that these tests were not able to capture the mechanisms that are specifically implicated in the pathology of ADHD. Impairment in cognitive functions like interference control (Seidman, Biederman, Faraone, Weber, & Oullette, 1997), working memory (Barnett, Maruff, & Vance, 2009), mental set shifting (van Goozen et al., 2004), and sustained attention (Swab-Barneveld et al., 2000) are also characteristics of ODD. Recent studies have shown that ADHD children show a specific neuropsychological profile (Ozonoff & Jensen, 1999). Given the specific nature of a neuropsychological profile in ADHD children, we argue that neuropsychological tests that measure cognitive functions specifically impaired in ADHD children would be helpful in differentiating ADHD from ODD children. There is substantial evidence to show that ADHD children have specific deficits in cognitive processes like response inhibition, error monitoring, task-switching/attentional disengagement, selection, conflict monitoring, and motivational style (Barkley, 1997; Cepeda, Cepeda, & Kramer, 2000; Gupta & Kar, 2010; Gupta, Kar, & Thapa, 2006; Rabbitt, 1968; Schachar et al., 2004; Sonuga-Barke, Dalen, & Remington, 2003). For example, behavioral inhibition measured using the stop-signal test showed significant differences between ADHD and normal children (Barkley). This observation is further strengthened by other studies that have controlled for comorbid symptoms like ODD/conduct disorders (CD; Schachar, Mota, Logan, Tannock, & Klim, 2000). Solanto et al. (2001) used the stop-signal and choice delay tests and obtained 90% accuracy in classifying ADHD children and healthy controls. Schachar et al. (2004) found less Posterror Slowing (PES) with ADHD children, and error monitoring performance was not correlated with the symptoms associated with reading disability (RD), ODD/CD, or anxious behaviors. Cepeda et al. found deficiencies in disengagement from one task and preparation for a subsequent task with ADHD children and not with ODD/CD children. ADHD children also show impairment in the alerting and executive control networks of attention (Wang, Sui, Wang, & Fan, 2004). Additionally, ADHD children also show delay aversion, that is, motivation to escape or avoid delay, resulting in preference for small immediate over longer delayed rewards (Sonuga-Barke, 2002). We also found that while these functions did not change between 6–9 years in ADHD children, they improved in age-matched healthy controls (Gupta & Kar, 2009; Gupta, Kar, & Srinivasan, 2009), making them suitable for classification of ADHD (Gupta & Kar, 2009).

Most of the studies have shown that the stop-signal test is a good test to measure response inhibition and error monitoring (Schachar et al., 2004). The task-switching, attentional network, and choice delay tests are good tests to measure control processes like attentional disengagement, selection, conflict monitoring, and motivational style, respectively, in ADHD children. In addition, large group differences between ADHD children and healthy controls were found with these tests (see Gupta et al., 2006, for review). Previous studies have reported that these tests could be sensitive in measuring specific cognitive-motivational deficits in ADHD children (Barkley, 1997; Cepeda et al., 2000; Rabbitt, 1968; Schachar et al., 2004; Sonuga-Barke et al., 2003).

ADHD children are characterized by heterogeneous characteristics (Castellanos, Sonuga-Barke, Milham, & Tannock, 2006) in terms of symptom domains, neuropsychological impairments, and comorbid behavioral problems. Hence, a battery of neuropsychological tests that measure cognitive control functions would help us to understand the cognitive mechanisms that underlie the ADHD pathology and to contribute towards building a comprehensive theory of ADHD. This would also have clinical implications for the formulation of therapeutic strategies for ADHD along with an accurate classification of the disorder.

In addition, it is not clear whether these tests can also accurately classify ODD children. It is important to integrate data from different cognitive-motivational aspects and to evaluate its usefulness in the classification of ADHD children from other neurodevelopmental disorders. Therefore, we integrated stop-signal, task-switching, attentional network, and choice delay tests into a single computerized tool/battery, which can provide the clinician with additional useful information that can be integrated with other diagnostic approaches. A group of pure ODD children without the presence of comorbid ADHD symptoms was included to examine the usefulness of the battery in differential classification of ADHD from ODD children. In addition, we were also interested in identifying the subset of parameters that can accurately classify the three groups. The present study uses Receiver Operating Characteristics (ROC) and Multinomial Logical Regression (MLR) for computing classification accuracies. Given the heterogonous nature of ADHD and results from previous studies (Doyle et al., 2000; Perugini et al., 2000), we hypothesized that a combination of parameters from multiple tests would lead to a more accurate classification of children with ADHD, ODD, and healthy controls compared to a single parameter or test.

METHODS AND MATERIALS

Participants

A total of 240 (120 ADHD combined type and 120 healthy controls) children in the age range of 6–9 years (30 children in each age level in both the ADHD children and healthy control groups) and 32 ODD children in the 9 years age group only participated in the study. Since very few ODD children in the 6–8 years age group were available, only 9-year-old children with ODD were included in the study. Healthy controls were selected from a school.

The patient groups consisted of consecutive unmediated referrals to a child psychiatry outpatient clinic and were referred by consultant psychiatrists. All children in the clinical sample underwent a comprehensive assessment according to the common practice at the clinic as well as *DSM-IV* (American Psychiatric Association, 1994) criteria. A semi-structured interview was conducted by the consultant psychiatrists and the clinical, family, and medical histories were made available to the investigators. The investigator also interviewed the parents with the Hindi version of the Conners' Parent Rating Scale-Revised: Long form (CPRS-R:L; Conners, 2002). Two translators performed the English-to-Hindi translation and two others performed the Hindi-to-English back translation. The translators were not aware of the purpose of the rating scale. ADHD children had ADHD index *T*-scores above 65 and healthy controls had ADHD index *T*-score below 65 on the CPRS-R:L. Twenty percent of the ADHD children had a comorbid diagnosis of ODD. All the children were intellectually normal and scored in the range of 50–95 percentiles on Colored Progressive Matrices (CPM), indicating average to above average level of intellectual functions (Raven, Raven, & Court, 1998). All the participants had normal or corrected-to-normal vision. Ethical approval was obtained for the present study and written informed consent was obtained from the parents.

Neurocognitive Tests

Stop-Signal Test. In the Stop-Signal Test (SST; Schachar et al., 2004), the primary, or "go" task involved discrimination between an "X" or an "O" presented in the center of a computer screen for 1000 ms. The go stimulus was followed by a blank screen for 2000 ms. A green circle indicated to the participants not to respond in some trials (25% of the total trials). The session consisted of four blocks of 40 trials each. We used a dynamic tracking procedure to set the timing of the circle (stop-signal delay) (Logan, 1994). Eight parameters were obtained from this test: meangoRT, mean RT for the first correct go response immediately following an error trial (Error+1RT), PES, mean delay, stop-signal reaction time (SSRT), total error, omission error, and commission error. The latency of the unobserved stop process (SSRT) was calculated by subtracting mean delay (at which the participants inhibit 50% of the time) from mean go reaction time. To measure error monitoring, the trials in which a stop signal was presented but the participant failed to stop were identified. PES was calculated by subtracting the mean go RT from Error + 1RT.

Attentional Network Test. The Attentional Network Test (ANT; Rueda et al., 2004) was employed to examine the alerting, orienting, and executive networks in children. Each child completed a 30- minute session of the child version of the ANT. The target array was a drawing of either a single yellow fish or a horizontal row of five yellow fish, presented above or below fixation, over a blue-green background. The participants had to respond whether the central fish pointed to the left or right by pressing the left or right arrow key, respectively. The ANT consisted of 24 practice trials and three experimental blocks of 48 trials each. There were 12 conditions with three target types (congruent, incongruent, and neutral) and four cues (no cue, central cue, double cue, and spatial cue). Five parameters were measured from this test (alerting effect, orienting effect, conflict effect, grand mean reaction time [GMRT], and total error). The alerting score was obtained by subtracting the median RT for double cue from median RT for the no-cue condition and the orienting score by subtracting the median RT for spatial cue from the RT for central cue. The conflict score was obtained by subtracting the congruent RTs from the incongruent RTs across all the cue conditions.

Task-Switching Test. In the Task-Switching test (TST), the stimuli were either a single digit (1 or 3) or three digits (111 or 333) presented at fixation. On each trial either the cue, "What number?" or the cue "How many?" appeared above the target stimulus. Participants were required to switch between two different tasks based on the cue that appeared above the target stimulus: Discriminating the value of a number or deciding how many numbers were present. Stimuli stayed on the screen until response was made (Cepeda et al., 2000). Feedback (100 Hz tone) was given whenever participants made an error. A practice session of 75 trials preceded the experimental session consisting of 200 trials. Task-Switching was measured by computing the switch costs, the difference in the overall reaction times of switch and nonswitch trials. In addition, we also calculated the number of errors committed in switch trials (STE) and nonswitch trials (NSTE), total error, and mean reaction time on posterror trials (PERT).

Choice Delay Test. The Choice Delay Test (CDT; Solanto et al., 2001) involved choosing between a small reward (1 point) delivered after a short delay (1 second) or a large reward (6 points) delivered after a long delay (20 seconds). A practice session with five trials preceded the experimental session that consisted of 30 trials. The percentage choice of long-delay reward (%LDR) was measured.

Procedure

All four tests were run on a laptop computer. The participants were seated at a distance of 60 cm and responded using a keyboard or mouse. After CPM was administered, all four tests were administered in random order to all the children. The whole test session lasted between 80–90 minutes with frequent breaks. Clear instructions and a practice session were given before for all tests.

Data Analysis

ROC was used to measure classification performance (sensitivity and specificity) for all the measures. Sensitivity denotes the proportion of accurately diagnosed individuals and specificity refers to the proportion of healthy individuals diagnosed accurately as having no impairment. A ROC curve is obtained by computing the sensitivity and specificity of a binary classifier by varying a decision or discrimination threshold. We report the best sensitivity-specificity based on the ROC curve for each binary classification. MLR is capable of classifying more than two categories and we use MLR to classify ADHD, ODD, and healthy controls.

ROC analysis was performed with all the children as well as with the 9-year-olds from all the three groups. With 19 parameters, the number of all the subsets of parameters was enormously large. As a first step, we performed ROC analysis for each parameter separately and for each pair of groups to investigate the effectiveness of individual parameters, in classifying the two groups (ADHD children and healthy controls; ADHD and ODD children; ODD children and healthy controls) to minimize the computations. Based on the ROC analysis, we identified a set of six parameters (SSRT, PES, Mean Delay, Switch Costs, %LDR, and GMRT). Given our goal of identifying the optimal subset of parameters for classification, we performed MLR analysis with all possible combinations of only those six parameters selected based on the initial ROC analysis.

RESULTS

ADHD and Healthy Controls

A correlation between intelligence and cognitive parameters showed that none of the measures were significantly related to intelligence (all *r*s $< .12$, *ns*) in the total sample, except PES, $r = -.12$, $p < .05$. ADHD children ($M = 7.78$ years, $SD = 1.13$) and healthy controls ($M = 7.80$ years, $SD = 1.10$) did not differ on age, $F(1, 58) = 0.620$, $p > .05$, and intellectual ability, $F(1, 58) = 2.24$, $p > .05$. The two groups differed on *DSM-IV T*-score of ADHD on CPRS-R:L, $F(1, 232) = 11191.75$, $p < .001$.

The effect size of all the 19 measures ranged between .008–.75. Effect size for six parameters, percentage choice of large delay reward; switch costs; posterror slowing; mean delay; grand mean reaction time, and stop-signal reaction time (.402–.752) was higher compared to the rest of the parameters (.008–.353). Here we are interested in determining the classification performance of the three groups and only results relevant to classification accuracy of the three groups are presented and discussed (see Gupta & Kar, 2009 for details on group differences).

ROC analysis was performed for each parameter for each group and across all age groups to determine the effectiveness of individual parameters to distinguish between ADHD and healthy controls. Figure 1 contains examples of ROC curves of SSRT and PES of one age group (6 years old children). Sensitivity and specificity values were computed for each parameter and are shown in Table 1. Overall, classification accuracy across all age groups was largest for %LDR. Other effective parameters included PES, GMRT, and SSRT. Sensitivity (78.3%–96.7%) and specificity (86.7%–94.2%) were highest for these four parameters.

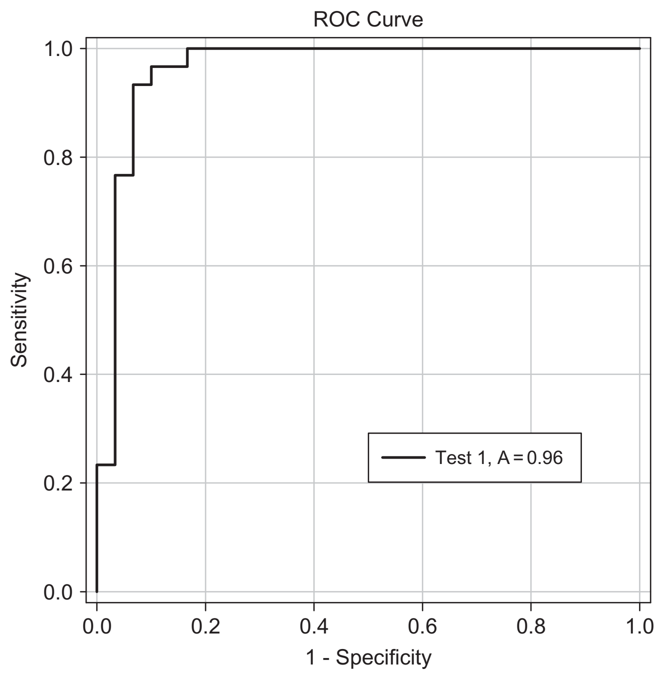
ADHD, ODD Children, and Healthy Controls

All three groups consisted of 9-year-old children. The groups were not significantly different with respect to age, $F(2, 89) = 0.017$, $p > .05$, and intellectual ability, $F(2, 89) = 0.316$, $p > .05$. The ADHD *DSM-IV T*-score on CPRS:R-L was significantly more for ADHD children ($M = 80.8$, $SD = 2.48$) compared to healthy controls ($M = 44$, $SD = 1.32$), $F(1, 89) = 4721.5$, $p < .001$, and ODD children ($M = 43$, $SD = 1.10$), $F(1, 89) = 117.0$, $p < .001$. The ODD *DSM-IV T*-score on CPRS:R-L was significantly more for ODD children ($M = 83.4$, $SD = 2.09$) compared to ADHD children ($M = 51.8$, $SD = 11.1$), $F(1, 89) = 26.7$, $p < .001$, and healthy controls ($M = 45.8$, $SD = 0.66$), $F(1, 89) = 31.7$, $p < .001$.

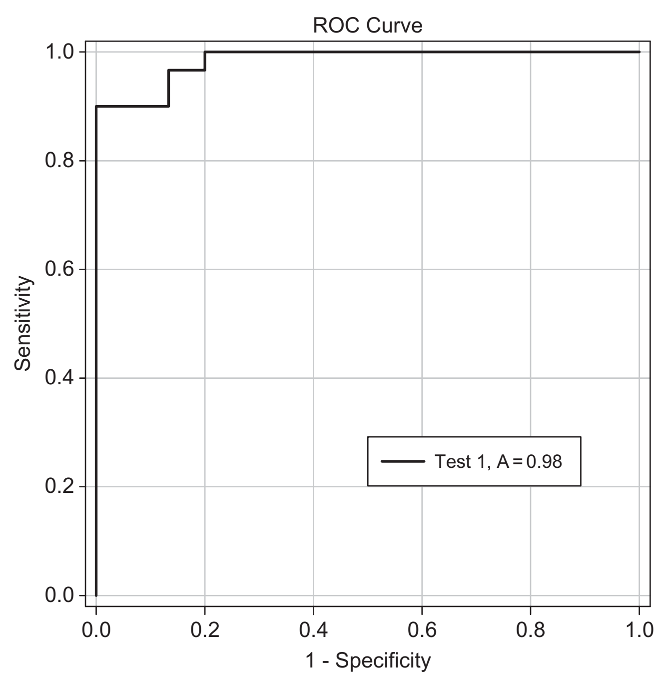
The ROC analysis indicated that the classification performance of the six parameters—%LDR, Switch Costs, SSRT, PES, Mean Delay, and GMRT—was much higher compared to the other parameters for classification with each pair of the three groups. For example, when comparisons were made between children with ADHD and ODD, then the sensitivity of each of the six parameters was in the range of 80%–100% and specificity was 78%–96%. The %LDR was the most sensitive parameter in accurately classifying ADHD and healthy controls (95.4%). PES was the most sensitive parameter for classification between ADHD and ODD (96%). For classification between ODD children and healthy controls, the SC was the most sensitive parameter (84.3%).

The above results suggest that different parameters might be effective in classifying different groups. Given our objective of finding the subset of parameters that could accurately classify all three groups, we performed MLR analysis with all possible combinations of six chosen parameters (SSRT, PES, Mean Delay, Switch Costs, %LDR, and GMRT). The classification accuracy obtained for a selective subset of parameters is presented in Table 2. Classification performance with individual parameters was poor (64%–72%) compared to that with a combination of parameters. As more parameters were combined, overall percentage of correct classification increased (Table 2). We found that a subset of three parameters: PES, MD, and %LDR gives an overall classification performance just above 90%. A subset of five parameters SSRT, PES, Mean Delay, Switch Costs, and %LDR, $\chi^2 = (5, n = 92) = 186.4$, $p < .001$, significantly predicted the individual's group membership and produced an overall classification accuracy of 97.8%, with 93.3%, 100%, and 100% for healthy controls, ADHD, and ODD children, respectively. Other subsets of parameters produced lower overall classification performance.

To validate our results with our own data set of 9-year-old children with ADHD, ODD, and healthy controls, the data sets were divided into two parts: a training set and testing set (46 children in each set). Half of the participants from each of the three groups were randomly selected for computing the MLR coefficients and the other half were tested



(a)



(b)

Figure 1 An example of ROC curves of (a) SSRT and (b) PES of 6-year-old group.

Table 1 Sensitivity and Specificity of all the Parameters for the Classification of ADHD Children from Healthy Controls in Each Age Level.

		Sensitivity (%)					Specificity (%)				
		Age					Age				
Tests	Outcome Parameters	6	7	8	9	6–9	6	7	8	9	6–9
CDT	%LDR	100	100	96	93	96.7	100	100	93	96	94.2
ADT	Switch Costs	100	100	90	96	85.5	90	70	93	70	87.5
	PERT	50	43.3	60	60	47.5	50	43.3	63.3	90	55.0
	Total Error	66.6	56.6	66.6	63.3	72.5	73.3	53.3	73.3	76.6	44.2
	STE	63.3	63.3	73.3	63.3	68.3	73.3	53.3	56.6	63.3	44.2
	NSTE	63.3	50	63.3	63.3	69.2	60	56.6	56.6	66.6	41.7
SST	SSRT	93.3	100	93.3	93.3	78.3	93.3	66.6	83.3	86.6	86.7
	Mean Delay	90	96.6	96	96	87.5	86.6	83.3	86	83	89.2
	PES	100	100	100	100	90.8	80	73	90	93	89.2
	MeangoRT	83.3	63.3	76.6	80	68.3	83.3	70	73.3	73.3	70.8
	Error+1RT	60	40	53.3	60	55.5	53.3	60	66.6	73.3	59.2
	Total Error	80	80	80	86.6	75.8	70	83.3	76.6	90	85.8
	Omission Error	50	56.6	76.6	66.6	37.5	53.3	56.6	56.6	66.6	79.2
	Commission Error	76.6	83.3	73.3	80	80.8	76.6	93.3	86.6	73.3	80.0
ANT	GMRT	100	96.6	93.3	93.3	88.3	83.3	96.6	90	86.6	93.3
	Alerting Effect	50	66.6	60	66.6	55.8	60	66.6	60	70	53.3
	Orienting Effect	53.3	73.3	63.3	76.6	57.5	50	50	60	60	59.2
	Conflict Effect	70	70	53.3	60	55.8	66.6	66.6	53.3	60	69.2
	Total Error	76.6	66.6	66.6	70.0	62.5	66.6	70.0	50.0	63.3	68.3

Note. CDT: Choice Delay Test; TST: Task-Switching Test; SST: Stop-Signal Test; ANT: Attentional Network Test; %LDR: Percentage choice of long-delay reward; PERT: Posterror Reaction Time; STE: Switch Trial Error; NSTE: Nonswitch Trial Error; SSRT: Stop-Signal Reaction Time; PES: Posterror Slowing; GMRT: Grand Mean Reaction Time.

Table 2 Classification Accuracy of Few Single and Combined Parameters of the Four Tests for the Classification of the ADHD, ODD children, and Healthy Controls.

	Groups (% Correct Classification)			
Outcome Parameters	ADHD (9 Years)	ODD (9 Years)	Healthy Controls (9 years)	Overall % Correct Classification
SSRT	93.3	100	0	65.2
LDR	80	59.4	76.7	71.7
SSRT & PES	100	56.3	60.0	71.7
PES & Switch Costs	96.7	78.1	86.7	87.0
SSRT, PES, & GMRT	100	68.8	66.7	78.3
PES, Mean Delay, & LDR	100	90.6	83.3	91.3
SSRT, PES, Mean Delay, & GMRT	100	78.1	73.3	83.7
PES, Mean Delay, Switch Costs, & LDR	100	93.8	90.0	94.6
SSRT, PES, Mean Delay, Switch Costs, & LDR	100	100	93.3	97.8
SSRT, PES, Mean Delay, Switch Costs, & GMRT	100	93.8	90.0	94.6
SSRT, PES, Mean Delay, Switch Costs, LDR, & GMRT	100	96.9	93.3	96.7

Table 3 Confusion Matrix of the Three Groups of Children after Internal Validation.

	Diagnostic System's Diagnosis		
Clinician Diagnosis	Healthy Controls	ADHD	ODD
Healthy Controls	95.98%	4.0%	1.32%
ADHD	0%	94.64%	5.3%
ODD	8.75%	5.0%	86.25%

with these coefficients. Only five sets of parameters—SSRT, PES, Mean Delay, Switch Costs, and %LDR—were used for cross-validation as these subsets of parameters most accurately classified the three groups. The validation was performed five times (randomly picking one half for computing regression coefficients and the other half for testing) and the mean overall percentage of correct classification with the testing set was 92.2%, with 95.98%, 94.64%, and 86.25% for healthy controls, ADHD, and ODD children, respectively (see Table 3).

DISCUSSION

The current study was conducted to examine the effectiveness of neuropsychological tests that measure cognitive-motivational deficits specific to ADHD. A prominent aspect of the present study is the inclusion of ODD children to determine the usefulness of cognitive-motivational tests in discriminating between ADHD and ODD children. In addition, the present study has advantages over previous studies in terms of larger sample size, selection of better neuropsychological tests, which measures the specific cognitive-motivational mechanisms underlying the pathology of ADHD, and use of better diagnostic methods like multinomial logistic regression (Doyle et al., 2000; Perugini et al., 2000; Sharma et al., 1995).

Four cognitive tests that measure specific cognitive impairments associated with ADHD were identified based on previous studies and used for classification. Single cognitive tests showed limited discriminating ability (64%) and data fusion with multiple tests improved the overall classification accuracy (97.8%). Consistent with our expectations, a subset of cognitive parameters (SSRT, PES, Mean Delay, Switch Costs, and %LDR) that measure response inhibition, error monitoring, task-switching, and delay aversion was critical for the classification of ADHD with ODD children. These parameters are associated with control functions that are response inhibition, error monitoring, task-switching, and motivational style.

Our results indicated that two tests, the stop-signal test and choice delay test, produced a reasonably good classification performance around 90%. The addition of a task-switching test increased the overall correct classification from 90% to 95%. Hence, we suggest the inclusion of a task-switching test with a stop-signal test and a choice delay test in a classification system/battery to get better classification performances above 95%. The three tests can be completed within 45 minutes and they can be potentially useful as diagnostic tools.

Our results extend the finding of the Solanto et al. (2001) study by showing that SSRT and %LDR together are not only helpful in differentiating ADHD from healthy controls but also helpful in the differential classification from ODD children. The classification performance with ADHD and healthy controls using a choice delay test (Solanto et al.) was lower (70%) than that obtained in the present study (95.4%). The two studies differed in the parameters associated with the long-delay reward. The magnitude of the long-delay reward was six points, given after 20 seconds in our study compared to two points, given after 30 seconds in the earlier study (Solanto et al.). The larger difference between the short- and long-delay reward in our study might have resulted in making the choice delay test more sensitive in our study.

Classification performance was better with the tests used in the present study than previously obtained in other studies (Doyle et al., 2000; Perugini et al., 2000). A possible reason for our better classification results is the inclusion of mostly pure ODD and ADHD children in the present study with only 20% of ADHD children having comorbid ODD. This may have enabled the tests to effectively capture the cognitive impairments specifically associated with ADHD and resulted in better classification. In addition, we have compared age-matched children in our study. Applying tests for each age separately could give a better classification accuracy compared to pooling participants across large age groups. For example, classification accuracy of the %LDR was 95.4% for 6- to 9-year-old children and it increased from 95.4% to 100%, when each age group was examined separately. The lower performance in earlier studies could be due to the large age range used (Perugini et al.). Poor executive functioning among children with ADHD can be viewed as a developmental deficit in ADHD children (Gupta & Kar, 2009). There was no significant improvement in cognitive-motivational processes in ADHD children aged 6–9 years. However, there was significant improvement in performance in these processes in healthy controls between 6–9 years of age (Gupta & Kar, 2009; Gupta et al., 2009). Thus, including a very broad age range may increase the risk of not finding group differences and poor classification due to tests that are either too difficult for ADHD children or too easy for healthy controls (Barkley, 1997).

Our data indicates that single cognitive tests have limited utility, which is consistent with findings from other studies (Barkley & Grodzinsky, 1994; Doyle et al., 2000). Our study extends the findings of Barkley and Grodzinsky by using multiple parameters obtained from a battery of tests. Perugini et al. (2000) found a diagnostic accuracy of 70% with only CCPT and 67% with only digit span test and 77% with the combination of these two tests for ADHD. Similarly, Solanto et al. (2001) found that the classification accuracy of %LDR or SSRT individually was 70%, but together these two parameters correctly classified nearly 90% of children with ADHD. Berlin, Bohlin, Nyberg, and Janols (2004) reported better results with combining the performance on response inhibition, working memory, and emotion regulation.

Simultaneous existence of deficits in both inhibition and motivation control functions in ADHD children found in the present study supports the multiple pathway models of ADHD aetio-pathophysiology (Nigg, Willcut, Doyle, & Sonuga-Barke, 2005; Sergeant, Geurts, Huijbregts, Scheres, & Oosterlaan, 2003; Sonuga-Barke et al., 2003; Willcutt, Doyle, Nigg, Faraone, & Pennington, 2005) and extends its findings by suggesting that other cognitive control functions, like task-switching and error monitoring, are also important in ADHD. Specifically, these pathways involved executive and motivational pathways. The executive function pathway involves a dysregulation of thought and action that is primarily characterized by a core deficit in inhibitory control. This pathway is associated with the meso-cortical branch of the dopamine system projecting to the cortical control centers (e.g., pre-frontal cortex; Sonuga-Barke, 2002). Alternatively, the motivational pathway involves delay aversion, which is a dominant characteristic of the motivational style associated with ADHD. It is linked to the meso-limbic dopamine branch associated with the reward circuits (e.g., nucleus accumbens). Deficits in both processes are thought to give rise to the manifestation of ADHD (Sonuga-Barke et al., 2003). These two pathways give rise to the ADHD diagnosis of the combined subtype. Further studies on the relationship between these processes are needed to understand the etiology of ADHD.

To date, only one study has used logistic regression analysis to explore the utility of tests of executive functions in the classification of children with ADHD (Berlin et al., 2004). Berlin et al. found good classification accuracy between children with and without ADHD with a response inhibition function similar to our study. However, they did not address the issue of differential classification (ADHD vs. ODD). It is to be noted that the present study has successfully identified a specific set of parameters (SSRT, PES, MD, SC, and %LDR), based on neuropsychological tests, that are associated with the inhibitory and motivational mechanisms and offer a potential solution for accurate differential classification of ADHD and ODD in children.

Results of the present study indicated that there are three major underlying processes, for instance, poor inhibitory control, task-switching/attentional disengagement, and delay aversion that are critically involved in the pathology of ADHD. We also found that these three processes do not recover with age in ADHD children compared to healthy controls (Gupta & Kar, 2009; Gupta et al., 2009). Literature on adult ADHD has also found deficits in inhibitory control, task-switching/attentional disengagement, and motivational control (Aron, Dowson, Sahakian, & Robbins, 2003; O'Connell et al., 2009; Oberlin, Alford, & Marrocco, 2005; Plichta et al., 2009; Smith, Taylor, Brammer, Toone, & Rubia, 2006; Tucha et al., 2005). Hence, these control processes should be seen as a constellation showing stable deficits in ADHD children (Gupta & Kar, 2009).

We conclude that a test battery/classification system based on the current study could be useful to a clinician as a supplement to the already existing diagnostic tools. However, further validation is required to see whether the system developed in the present study could give better results than other methods. The present study has some limitations. The ADHD children included in the current study had severe symptoms and combined ADHD subtype. Further studies should include more borderline cases in the sample to further validate the results. It would be worthwhile to investigate if these tests can help to discriminate between different subtypes of ADHD or mild ADHD and at-risk children in a nonclinical sample and ADHD with other neurodevelopmental disorders. In addition, in the present study, only 20% of ADHD children had comorbidity with ODD. Therefore, we were not able to compare the difference in classification accuracy of pure ADHD children from ADHD children having comorbidity with ODD. Future studies can examine the ecological validity of these neuropsychological tests by including more ADHD children with comorbid conditions of ODD and other disorders.

Results of the present study indicate that the classification performance of neurocognitive measures was better compared to the classification performance of CPTs. It is important to directly compare the measures used in the present study with other CPTs with the same sample to further validate the findings of the present study. To minimize administration time, we did not include some of the cognitive tests, such as reaction time variability, in this study. Future studies need to include them to examine their effectiveness in the classification of ADHD and ODD children.

The present study indicates that a battery approach with tests of control functions including response inhibition, error monitoring, task-switching, and motivational style shows considerable promise for the differential classification of ADHD.

Findings of the present study also inform us about the nature of ADHD from a cognitive/functional perspective. Future studies should continue to compare children with ADHD to children with other psychological disorders. Although it is useful to know that children with ADHD differ from healthy controls, it is more relevant to clinicians to be able to distinguish between ADHD and other disorders.

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