Impairment of Executive Functions in Boys with Attention Deficit/Hyperactivity Disorder

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IMPAIRMENT OF EXECUTIVE FUNCTIONS IN BOYS WITH ATTENTION DEFICIT/HYPERACTIVITY DISORDER

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The main aim of the present study is to compare the efficiency of executive control processes in 24 boys with attention deficit/hyperactivity disorder (ADHD) and 58 normal controls of similar age (between 8 and 11 years). Three reaction time (RT) paradigms were utilized: a dual task that requires coordination of two tasks responses, a shift task that makes it necessary to disengage attention from one task and engage into another one, and a stimulus-response spatial compatibility task that requires participants to inhibit a prepotent response. Another purpose of the study is to examine whether Barkley’s (1997) executive dysfunction or Sergeant et al.’s (1999) resource allocation/arousal model best account for the behavioral deficits associated with ADHD. Examination of raw RT data showed significantly poorer performance in ADHD children with respect to age-matched controls on both the higher-level cognitive functions of executive control and on lower-level abilities (e.g., speed of processing) of all tasks of this study. However, using proportional transformations of raw RT data, we could demonstrate that, in addition to differences in processing speed, also executive control processes were significantly impaired in children with ADHD.

Keywords: ADD/ADHD, monitoring processes, divided attention, response inhibition, task switching, frontal lobe dysfunction

INTRODUCTION

Attention deficit/hyperactivity disorder (ADHD), as defined in the fourth edition of the Diagnostic and Statistical Manual of Mental Disorders (DSM-IV; American Psychiatric Association, 1994), is the most common psychiatric disorder of childhood, affecting approximately 3%–5% of the school-age population. The clinical diagnosis of ADHD, is based on developmentally inappropriate behaviors within three symptom domains: inattention, impulsive behavior, and hyperactivity.

This research was funded by my parents: Cav. Giuseppe Fuggetta and Gatto Lidia, and is dedicated to their memory. The author is grateful for the collaboration of Sandro Conforto and Manolo Venturin, who programmed the software Neuropsychological Investigator, utilized for the presentation of stimuli, recording the responses, and filtering the recorded raw data of tasks employed in this study. I wish to thank Julia Burst and Antonella Santarossa for their help in collecting the data in Germany and Italy, respectively. I thank Carlo Alberto Marzi, Joseph Di Duro, Sergio Morra, and Carlo Umiltà for their suggestions and helping with earlier versions of this manuscript.

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Recent extensive reviews of studies that examined the etiology of ADHD suggest that both neurological and genetic factors are involved. These studies have documented abnormalities in well-defined neuroanatomical networks and neurochemical pathways (see, e.g., reviews in Swanson, Castellanos, Murias, Castellanos & Tannock, 2002; LaHoste, & Kennedy, 1998). These abnormalities involve networks subserving executive control and alerting and include right frontal striatal circuits, particularly the interconnections between the caudate and the orbitofrontal and dorsolateral cortices (Castellanos et al., 1996; Filipek et al., 1997).

The evidence mentioned above is consistent with the hypothesis that frontal lobe deficits represent the neural substrate of ADHD symptoms, which have been attributed to impairment of the higher-level cognitive functions of self-regulation or executive control (Barkley, 1997; Douglas, 1983, 1988; Logan & Cowan, 1984; Schachar & Logan, 1990; Schachar, Tannock, Marriott, & Logan, 1995; Wu, Anderson, & Castiello, 2002).

The focus of current research is to examine efficiency of executive functions (EFs) in children with ADHD compared with controls. In essence, EFs (also termed control functions, control processes, or executive processes) include the abilities that enable individuals to maintain an appropriate problem-solving set for attaining future goals, and involve developing and implementing an approach to performing a task that is not habitually performed (Mahone et al., 2002).

Control processes play a role in a number of rather dissimilar tasks and cognitive activities (see review in Shallice, 1994), but it is generally accepted that executive processes are characterized by common properties: they require attention, consist of a series of unitary operations, are limited by short-term storage capacity, and are easily adapted and modified (Umiltà & Stablum, 1998).

Tasks used to measure EFs, such as the Wisconsin Card Sorting Test, Tower of London task, Tower of Hanoi task, Stroop task, Trail-Making Test-B, Go-no-go task, Stop-signal task, have very different performance demands and have shown impaired performance in ADHD children with respect to controls (Barkley & Grodzinsky, 1994; Carte, Nigg, & Hinshaw, 1996; Casey et al., 1997; Doyle et al., 2000; Grodzinsky & Diamond, 1992; Nigg, Blaskey, Huang-Pollock, & Rappley, 2002; Pennington & Ozonoff, 1996; Weyandt & Willis, 1994; Wu et al., 2002).

In spite of several research studies that have demonstrated that children with ADHD display impaired EF abilities in different tasks as compared to matched controls, there has been little attempt to isolate the specific difficulties that ADHD children display on such tasks (Bayliss & Roodenrys, 2000). Note that they often tap multiple EFs and may also require nonexecutive processes for successful performance. In addition, EF tasks are poorly specified theoretically (Pennington & Ozonoff, 1996). Thus, it is necessary to establish conceptual and theoretical clarity in the study of executive functions and to develop sensitive and specific measure instruments (Denckla, 1996; Morris, 1996) that can eliminate the effect caused by difference in lower-level abilities (e.g., speed of responding), (Wu et al., 2002).

The general aim of the present study was to examine the hypotheses of less efficient executive functioning in ADHD children in comparison to matched controls. We expected a discrepancy in the magnitude of executive control processes activated with the EF tasks employed in the present study across the two children groups.

In order to correlate the relevant issue to research on control processes, that EF tasks may tap non-EF (Denckla, 1996; Pennington & Ozonoff, 1996), and can not isolate the effect caused by difference in lower-level abilities in the assessment of control processes.
On the contrary, in the present study we utilized three RT tasks that enabled component analyses. To circumvent and control for the potentially confounding influence of groups overall differences in processing speed on indexes of executive functioning, we analyzed the data using proportional transformations of raw RTs, as previously used by research studies investigating age-related differences in response latencies (e.g., Christ, Whrte, Mandernach, & Keys, 2001; Hartley & Kieley, 1995).

The three EF tasks we employed were: a dual-task paradigm, which requires coordination of different responses; a shift paradigm, which makes it necessary to disengage attention from one task and engage into another one; and a stimulus-response spatial-compatibility task, which requires participants to inhibit a predominant compatible response and to generate an incompatible response.

Previously, dual-task, shift-task, and spatial-compatibility task paradigms were employed to assess cognitive performance in ADHD children Carlson, Pelham, Swanson, & Wanger, 1991; Cepeda, Cepeda, & Kramer, 2000; Del Pino & Alison, 1996; Kramer, Cepeda, & Cepeda, 2001; Yong-Liang et al., 2000). This limited previous work makes a study of each of three factors timely.

Carlson et al. (1991), used the dual task technique to examine divided attention in methylphenidate and placebo ADHD boys. In the single-task (ST) condition, in which the two tasks did not overlap in time, nonmedicated ADHD children responded slowly to the primary task, which consisted of single-digit-number addition problems presented on a computer screen, and slowly to the secondary task, which consisted of pushing a foot pedal as quickly as possible upon hearing a computer-generated tone presented before or after each arithmetic problem. In the dual-task (DT) condition, in which the two tasks did overlap in time, the placebo group showed greater decrements in arithmetic accuracy compared to ST condition to maintain speed on the secondary task. On the contrary, medicated ADHD participants maintained accuracy on the primary task and sacrificed speed in the secondary task by slowing down RTs. These findings provided evidence that ADHD children fail to allocate their available cognitive resources to the primary task and demonstrated the treatment efficacy of methylphenidate in reallocation of existing cognitive resources from a secondary task to the primary task (Carlson et al., 1991).

Del Pino and Alison (1996) tested ADHD and control children with dual task utilizing finger tapping and nursery rhyme recitation. The results indicated that there were no significant differences in children with ADHD and nonclinical children in overall tapping rate, number of verbal errors, or verbal output if the two tasks were continuous and highly structured, demonstrating the children’s ability to divide and allocate attention. However, when tasks were required in non-sequential order, ADHD children demonstrated difficulty to reallocate their attention to the actual task (Del Pino & Alison, 1996).

Cepeda et al. (2000) and Kramer at al. (2001) examined the control processes involved in task set inhibition and preparation to perform a new task with on-and-off-medicated ADHD children and non-ADHD children. The paradigm involves switching between two different tasks, deciding how many numbers were presented on a computer screen and discriminating the value of a number presented on the screen. The children also performed single-task control conditions. ADHD children showed substantially larger switch costs than non-ADHD children. However, when on medication, the ADHD’s switch performance was equivalent to control children (Cepeda et al., 2000). Comparing the task-switching performance in ADHD children while on and off medication, it was demonstrated that methylphenidate enhanced the children’s ability to rapidly and accurately inhibit inappropriate task procedures and to prepare for a new task (Kramer et al., 2001).
Yong-Liang at al. (2000) examined spatial S-R compatibility task on event-related potentials (ERPs) in boys with and without ADHD. Children were instructed to squeeze one of two dynamometers as accurately and as fast as possible in response to a left- or right-pointing arrow presented on a computer screen. The black or blue color of the arrow determined whether the response was to be compatible (e.g., right arrow with right-hand response) or incompatible (e.g., right arrow with left-hand response), respectively. At the performance level, ADHD children made fewer correct responses than control children, but were not slower or more inaccurate in the incompatible condition than the controls. Regarding the ERP activity, cognitive group differences were found. The ADHD group had longer N1 latency and larger condition effect on the frontal N2, which would be related to either the detection or the inhibition of an inappropriate tendency to respond and reflect a greater frontal involvement for the correct responses. These results suggested an inhibitory regulation problem in ADHD children (Yong-Liang et al., 2000).

With respect to the past efforts that have evaluated the performance of ADHD children on the dual task, shift task, and spatial S-R compatibility task separately, in this work the three measures were studied in one sample, to examine the degree of association among tasks within the EF construct. We aimed to clarify whether the three tasks tap distinctive or common aspects of control and monitoring processing, to prove that specific deficits in control processing are related to symptoms of ADHD.

Two main approaches have been developed to account for the behavioral deficits of ADHD. The executive dysfunction theory of ADHD put forward by Barkley (1997) proposes that poor behavioral inhibition is the core deficit of ADHD, which produces secondary deficits in executive abilities. It includes deficits in inhibiting prepotent responses, i.e., a response that is associated with reinforcement; interrupting ongoing response, which allows for a delay in the decision to continue responding; and controlling interference, i.e., protecting a response from cancellation by competing responses. This theory helps to unify the evidence pointing to the attentional and inhibitory processing deficits identified for ADHD children. In congruence with Barkley’s model, Pennington and Ozonoff (1996) concluded that children with ADHD have deficits in motor inhibition.

The resource allocation/arousal model of ADHD (Sergeant, 2000; Sergeant, Oosterlaan, & Vander Meere, 1999) offers an alternative explanation: an optimal state of arousal and activation is a prerequisite to prepare for motor action and meet the demands of the task to be performed. This model suggests that children with ADHD have specific problems with the output stage of information processing, and the cause that selectively affects motor organization in ADHD is a decreased state of activation with an inability to allocate and to maintain an optimal state of arousal (Sergeant et al., 1999; Sergeant, 2000). Therefore, according to Sergeant et al.’s (1999) model, those with ADHD primarily suffer from suboptimal energetic stages; they have problems in utilizing attentional capabilities in an optimal manner, rather than real attentional or executive deficits.

Another purpose of the present study was to contrast the executive dysfunction and resource allocation/arousal models described to elucidate and clarify the nature of behavioral deficits associated with ADHD. In detail, we examined which of the two models better accounts for the performance obtained from the ADHD children in the three tasks employed in this study. The three tasks tested the performance of children in situations that enable the dissociation of changes in resource and arousal with changes in the need for executive processes.
METHODS

Participants

The study was conducted in Italy and Germany. Two groups of children, ranging in age from 8 to 11 years, participated. The first group consisted of 24 children diagnosed with ADHD. The second group consisted of 58 control children. Thirteen diagnosed ADHD German children came from a specialized childhood disorders neurological center in Maulbronn and from the Institute of Medical Psychology and Behavioral Neurobiology of Tübingen. Eleven ADHD Italian children came from a children’s neuropsychiatry service in Monselice (Padova), an ADHD diagnostic and treatment study in Mestre (Venezia), and “La nostra Famiglia” rehabilitation Institute in Treviso. The control group of children was recruited from local schools in the two countries. Thirty German children were recruited from a Tübingen elementary school, whereas the 28 Italian children were recruited from an elementary school in Montebelluna (Treviso).

The 24 children in the ADHD group were all boys, ranging in age from 8 years, 7 months to 11 years, 3 months (mean 118.21 months, SD 9.20 months). The clinical children were considered for the study based on four criteria. First, children were recruited if they were formally diagnosed with ADHD by a health-care professional (i.e., a physician, psychiatrist, pediatrician and/or psychologist) using the DSM-IV (American Psychiatric Association on 1994) criteria for ADHD combined type (i.e., met criteria for both the hyperactive/impulsive axis and inattentive axis). The diagnoses were confirmed across doctors.

Second, participants in this group had a significant score on both impulsivity-hyperactivity and ADHD factors. These factors were assessed through the completion by parents of the Conners’ Parent Questionnaire (CPRS; Conners, 1989, 1997), which is a well-researched standardized rating scale that assesses behavioral difficulties and attention problems at home. The CPRS Short Form consists of 27 items. Parents respond to a 4-point Likert scale indicating severity of a particular behavior.

Third, the children in the ADHD group had no syndromes of childhood psychopathology other than ADHD based on the DSM-IV and through the completion by parents of the DSM-IV screener (Hartman et al., 2001). The screener contains seven scales: ADHD, oppositional defiant disorder (ODD), conduct disorder (CD), anxiety, depression, pervasive developmental disorder (PDD), and schizophrenia. Items were rated on a scale from 0 to 3. Scores on the ADHD scales were above the 95th percentile. Scores on all other scales were below the 50th percentile.

Finally, these participants had an IQ > 85 as assessed with Raven’s Colored Matrices (Raven, 1956, 1995). The screening measured general intellectual ability to reduce the confounding impact of low IQ on tasks’ performance of this study.

Children with ADHD were admitted to the study only if they met diagnostic criteria for ADHD (Combined Type) according to the Conners’ Parent Questionnaire. The rate of return for the parent questionnaires was 81%. Of the parent forms returned, 92% scored greater than 1.5 standard deviations above the mean (i.e., equal to or greater than the 93rd percentile) on both the impulsivity-hyperactivity and ADHD factors. This requirement resulted in the loss of 8 children from the original sample, bringing the final sample size to 24. All boys in the ADHD group were required to discontinue stimulant medication (e.g., methylphenidate) at least 24 h prior to testing. Of the 24 children in the ADHD group, 7 German children were reported to be taking stimulant medication, and 17 were not.
The control group of participants consisted of 58 children, all boys, ranging in age from 8 years, 10 months to 11 years, 4 months (mean 116.97 months, SD 8.44 months). Children qualified as suitable only if they satisfied inclusion criteria similar to those of the clinical group. First, there was an absence of other syndromes of childhood psychopathology assessed on the completion by a parent of the DSM-IV screener (Hartman et al., 2001). The inclusion criterion in the control group of children was a score below the 50th percentile on all scales of DSM-IV. Second, none met diagnostic criteria for ADHD on the completion of the Conners’ Parent Questionnaire (Conners, 1989, 1997). And last, these participants had an IQ > 85 as assessed with Raven’s Colored Matrices (Raven, 1956, 1995), to reduce the confounding impact of low IQ on task’s performance.

The return rate for the Conner’s Parent Questionnaire was 75%. About 3% of questionnaires scored greater than 1.5 standard deviations above the mean on both the impulsivity-hyperactivity and ADHD factors. These criteria resulted in the loss of 22 children from the original sample, bringing the final sample size to 58.

Age and a measure of IQ were obtained from each child as matching variables between the two groups. Two independent sample t-tests showed that controls and ADHD children did not differ significantly for age and IQ variables (age in months: 118.21 vs. 116.97; IQ score: 98.6 vs. 101.3, for ADHD and control children, respectively). All boys were right-handed, had normal or corrected-to-normal vision, and were unaware of the purposes of the study.

**Measures and Procedures**

Written consent was obtained from the parents before the children participated in the study. Participants performed the three RT tasks (i.e., dual task, switch task, and spatial stimulus-response compatibility task) in one 50-min testing session. Two brief breaks of 5 min each were inserted between tasks. The order of presentation of the three tasks was counterbalanced across participants. Children were tested by one examiner individually in a noiseless room with an ambient light on. They were seated in front of the computer screen at a viewing distance of about 40 cm.

**Apparatus**

All testing was performed with an IBM-PC computer, endowed with an AMD K6 at 233 Mhz CPU, with 64 MB of memory, a Matrox MGA-G100 AGP video card with 4 MB of video RAM, and a 16-bit sound card. The screen resolution was of 800 × 600 pixels with 24 bits of color, 60 Hz of screen refresh, in a 14-inch color monitor.

Presentation of stimuli and recording of RTs were controlled by an unpublished software called Neuropsychological Investigator. Two keyboard keys were used for response execution. The “A” key was located to the left of the body midline and was operated by the left index finger. The “L” key was located to the right of the body midline and was operated by the right index finger. The two keys were highlighted, with two sticky labels with a black cross symbol over the “A” key and a black dot over the “L” key, respectively. Participants were instructed to locate the two response keys before the beginning of task, and to fixate only the computer screen during each task’s execution.

The instructions of all tasks stressed the importance to respond as quickly and as accurately as possible following the appearance of the stimulus. RTs were recorded from
stimulus onset to response execution. A feedback tone (300 ms) informed the participant about accuracy of the response at the end of each trial, with a high tone for a correct response and a low tone for a wrong response.

Executive Function Tasks

**Dual task.** A paradigm that has proven to be very useful to study a specific executive component is a variant of the dual-task paradigm developed by Umiltá, Nicoletti, Simion, Tagliabue, and Bagnara (1992).

In the current study the primary task is a speeded dual-choice form-discrimination task. The secondary task is an unspeeded color-discrimination task. There are two experimental conditions: the single-task condition (ST), in which only the primary task has to be performed, and the dual-task condition (DT), in which the primary task is performed together with the secondary task. All the participants during the execution of the first part of the task performed the ST condition, in which they had to discriminate the digits 2 and 5. Responses were emitted by pressing, as fast and as accurately as possible the “black cross” or “black dot” keys representing “2” and “5” stimuli, respectively. In the DT condition during the second part of the task they had first to respond to 2 or 5 by pressing one of the two keys, and then tell aloud and without time pressure the color of the stimulus (red or green). The participant was instructed to emit the response to the primary task (R1) as fast as possible, whereas there was no time pressure for emitting the response to secondary task (R2).

This dual-task paradigm differs from the standard one in some important aspects. The R1 and the R2 are emitted to different characteristics of the same stimulus (i.e., shape and color), rather than to two different stimuli. The fact that information is simultaneously available in performing the two tasks renders it necessary to make a decision about the order of the two responses.

**Stimuli.** The stimuli were the numbers 2 and 5. They could be red or green on a black background and were presented at the center of the screen. Their size was 4 degrees and 52 minutes (width) × 7 degrees and 35 minutes (height) of visual angle. Figure 1 shows an example of how the two stimuli were presented one after another.

**Procedure.** The stimuli were presented according to a quasi-random sequence, with the constraints that there was an equal number of 2s and 5s and an equal number of red or green digits, with no more than three consecutive identical stimuli. Every trial

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**Figure 1** Sequence of two stimuli in the dual-task. The primary speeded task to be executed in both ST and DT conditions, was a form task. The unspeeded secondary task to be executed in DT condition only, was a color task.
began with the onset of the stimulus displayed for 2,000 ms and followed by a blank screen. The response-stimulus interval (RSI) was 3,000 ms. Participants completed the trial a single session divided into two conditions (ST and DT), with blocks of 40 trials each and a 5-min rest in between. Both blocks were preceded by a practice block of 12 stimuli.

**Shift task.** The task-switching paradigm involves the performance of two tasks not simultaneously but with some alternation. In one condition (i.e., the nonswitch baseline, or repetition condition), the same task is repeated a number of times. In the other condition (i.e., the switch, or alternation condition), participants switch from one task to another. The basic phenomenon of task shifting is that when one is engaged in two speeded tasks, it is faster to respond to a repetition condition than to a switch condition.

In this study we utilized the “alternating runs” experimental paradigm (Rogers & Monsell, 1995), in which each block includes trials of both repeated and switch conditions arranged in sequences of two items of the same block. This allows one to compare “shift” and “nonshift” items within the same block of stimuli. In this way, the task changes predictably every two trials, and participants were instructed accordingly.

**Stimuli.** The stimuli were the numbers 1, 8, or 0 presented at the center of the screen in red, green, or white on black background. Their size was 4 degrees and 52 minutes (width) × 7 degrees and 35 minutes (height) in visual angle on screen. There were two tasks: a shape discrimination task (Task A), in which white “1” or “8” was shown, and a color discrimination task (Task B), in which a “0” in green or red was shown. Figure 2 depicts an example of the sequence of four stimuli.

**Procedure.** The stimuli were presented according to a quasi-random sequence, with the constraint that there was an equal number of 1 or 8, an equal number of red or green stimuli, an equal number of trials that required Task A or Task B, and an equal number

![Figure 2](image-url) Two sequences of two trials employed in the shift-task. The “A1” and “A2” stimuli belonged to Task A (form), while “B1” and “B2” stimuli belonged to Task B (color). The “A2” stimulus is an example of non-switch (repeated) trial, while the “B1” stimulus is an example of switch trial, which requires performing a different task with respect to the preceding trial.
of trials that required a same or different responses to the preceding trial, with no more than three consecutive same or different responses. Every trial began with the onset of the stimulus, which came until a response was executed by pressing one of the two response keys. The Response-stimulus interval (RSI), 600 ms was constant for all the blocks.

We collected data from the participants in a single session subdivided in two blocks of 64 trials each, with a regular alternation of the two tasks every two items (i.e., AABBAABBAA ... ) in the same block of stimuli, according to “alternating runs” paradigm (Rogers & Monsell, 1995). There was a 5-min rest between the two experimental blocks, with the first experimental block preceded by a 40 stimuli practice block. Participants were informed that the two tasks alternated every two stimuli.

In Task A the “black cross” or “black dot” keys were to be pressed in response to “1” or “8,” respectively. In Task B, the “black cross” or “black dot” keys were to be pressed in response to the “red” or “green” stimuli, respectively.

**Spatial stimulus-response compatibility task.** The spatial stimulus-response (S-R) compatibility depends on the processing of spatial information and occurs when the spatial position of the stimulus signals the spatial position of the correct response (e.g., see review in Umiltà & Nicoletti, 1990). In the spatial S-R compatibility task, stimulus position is task relevant, because the value of the imperative stimulus in the spatial dimension determines the value of the response in the same dimension (Tagliaabue, Zorzi, Umiltà, & Bassignani, 2000).

Two experimental conditions are employed in the spatial S-R compatibility paradigm. In the compatible-pairings condition, participants are instructed to press the response key in the same side of the stimulus onset (i.e., left-side key when the stimulus appears to the left of fixation). In the incompatible-pairings condition, participants are instructed to respond by pressing a key in the opposite side of the stimulus onset (i.e., right-side key when the stimulus appears to the left of fixation and vice versa).

**Stimuli.** The visual display included a white 0 of 4 degrees and 52 minutes (width) × 7 degrees and 35 minutes (height) in visual angle, at 9 degrees and 39 minutes to the left or right side from the center of a white fixation cross of 4 degrees and 52 minutes (width) × 4 degrees and 52 minutes (height). Figure 3 shows an example of a trial of the S-R spatial-compatibility task.

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**Figure 3** Stimulus sequence of a trial in the stimulus-response spatial compatibility task. Panel “A” represents the central fixation cross. Panel “B” shows a stimulus presented on the right of fixation. In the case of compatible pairings the participant was required to press the right key while in the case of incompatible pairings the participant had to press the left key.
Procedure. The stimuli appeared according to a quasi-random sequence, with the constraints that there were an equal number of left or right imperative stimuli with no more than three consecutive same-side presentations. Every trial began with the central fixation cross, which stayed on the screen for 1000 ms, followed by 100 ms of free screen, and the subsequent onset of the stimuli shown till each participant answered by pressing of a response key. Response-stimulus interval (RSI) was 1500 ms. Participants completed the trial in a single session subdivided into two blocks (corresponding S-R pairings and non-corresponding S-R pairings) of 40 trials each, with a 5-min rest in between. Both blocks were preceded by a practice block of 12 stimuli.

All participants first performed the compatible stimulus-response (CSR) condition, in which they were instructed to fixate the fixation cross and to respond with the left key if the stimulus was presented on the left side and with the right key if the stimulus was presented on the right side. At the end of CSR condition, after a rest time of about 5 minutes, participants performed the incompatible stimulus-response (ISR) condition, in which they were required to press the right key to the stimulus on the left side and the left key if the stimulus was presented on the right side. The left key to press was the “black cross,” whereas the right key to press was the “black dot.”

RESULTS

Raw reaction times filtering criteria

A semiautomatic filtering operation of raw RTs recorded from each trial of tasks was carried out by an unpublished software called Neuropsychological Investigator. Correct responses were divided from errors and subjected to two filtering criteria: an absolute filtering criterion and a relative filtering criterion. To remove anticipations or retardations in correct response times of participants, the absolute criterion excluded, for each subject, correct responses in which RTs less than 150 ms and RTs greater than 3000 ms occurred. Because of variability in response rates within group, the relative criterion eliminated, for each subject, RTs that were less or more than two standard deviations from the mean of each task’s experimental condition. Table 1 shows the means and standard deviations percentage of correct RT trials eliminated as a function of group and task.

For each of the three tasks, the mean of eliminated correct RT data were submitted to one-way analyses of variance (ANOVA) to test for intergroup differences in percentage of eliminated trials. The ANOVAs for percentage of eliminated trials was not significant between the two groups on each task, respectively, [F(1,80) < 1ns (see Table 1). Data analyses were performed using Statistical Package for Social Sciences (SPSS) program, Version 11.01.

Table 1 Means and standard deviations of percentage eliminated correct RTs as a function of group and task.

<table>
<thead>
<tr>
<th>Task</th>
<th>ADHD</th>
<th>Normal control</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>M</td>
<td>SD</td>
</tr>
<tr>
<td>Dual task</td>
<td>5.83</td>
<td>1.72</td>
</tr>
<tr>
<td>Shift task</td>
<td>5.00</td>
<td>2.32</td>
</tr>
<tr>
<td>Spatial-compatibility task</td>
<td>4.95</td>
<td>1.63</td>
</tr>
</tbody>
</table>
Tasks data statistical analyses plan

The remaining correct RT data were submitted to statistical analysis from two perspectives: raw response latencies and proportionally transformed response latencies. Error rates were also examined. Table 3 shows means and standard deviations for each of these variables.

To compare performance between ADHD and matched control children on each executive task of this study, we first examined performance using raw RT data and accuracy error rates data. Thus, for each executive task of this study, the mean correct raw RT data, and accuracy error rates data were submitted to two analyses of variance (ANOVAs) with repeated measures. Both ANOVAs had one between-subjects factor, Group (ADHDs and controls), and one within-subjects factor, condition of trials (Control and Executive). Post-hoc comparisons for all significant Condition × Group interactions were performed with the paired \( t \)-test adjusted for multiple comparisons with Bonferroni method.

In order to determine whether the expected raw RT differences between the clinical and control groups for high-order tasks was caused by differential efficiency of control process or by the more general differences in speed of processing, we calculated for each participant the percentage of slowdown to perform the high-order task conditions, with respect to the participant’s performance in the complementary baseline control task conditions.

More precisely, in the case of dual task, we calculated for each subject the RTs ratio between the DT cost and the performance in ST condition: \((DT – ST)/ST\). In the shift task we calculated, for each subject the RTs ratio between the shift cost and the performance in nonshift trials condition: \((shift trials – nonshift trials)/nonshift trials\). And finally, in the stimulus response spatial compatibility task, we calculated for each subject the RTs ratio between the response interference effect and the performance in compatible S-R pairings condition: \((incompatible S-R pairings–compatible S-R pairings)/compatible S-R pairings\).

For each of the three executive tasks, one-way analyses of variance (ANOVA) was used as a parametric approach to test for intergroup differences in executive functioning in the dependent measure of raw RT data proportional transformation score.

Preliminary Statistical Analysis

To check the multidimensional nature of executive functions assessed through the measures used in the study and to examine the relationships between various executive measures of tasks proportional transformation scores, standard Pearson correlation was used.

Table 2 shows the correlation coefficients between the two groups of children and all tasks measures of executive functioning: the dual task, the shift task, and the spatial compatibility proportional scores. We found a modest but significant degree of association between each paradigm index of executive functioning and the group variable, indicating that a reliable relation exists between the groups and predictor tasks. On the other hand, there were low correlation coefficients evident within the three measures of cognitive control processes, suggesting that the EF measures were relatively independent of one another, and tapped different and individual functional components of the EF construct.
Executive Function Tasks

Dual task. Analyses performed to compare the performance of ADHD with respect to normal control children, revealed the following statically significant main effects and interaction:

The Group main effect for RTs, $F(1, 80) = 16.235, p < .001$, but not for error rates, $F < 1$, show that the overall RTs were 150 ms longer for ADHDs than for control children in general (802 vs. 652 ms, respectively; (see Table 3).

Table 2 Correlations among diagnostic group of children and executive function measures.

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<thead>
<tr>
<th>Diagnostic Group of Children</th>
<th>Dual Task Proportional Score</th>
<th>Shift Task Proportional Score</th>
<th>Spatial Compatibility Proportional Score</th>
</tr>
</thead>
<tbody>
<tr>
<td>Diagnostic group of children</td>
<td>1.000</td>
<td>-.295**</td>
<td>-.311**</td>
</tr>
<tr>
<td>Dual task proportional score</td>
<td>1.000</td>
<td>.003</td>
<td>.192</td>
</tr>
<tr>
<td>Shift task proportional score</td>
<td>1.000</td>
<td>.042</td>
<td></td>
</tr>
<tr>
<td>Spatial compatibility proportional score</td>
<td>1.000</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

*p < 0.01. *p < 0.05, (two-tailed).

Table 3 Means and standard deviations of raw scores, error rates, and proportional scores as a function of group and task.

<table>
<thead>
<tr>
<th>Task</th>
<th>ADHD</th>
<th>Normal control</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>$M$</td>
<td>$SD$</td>
</tr>
<tr>
<td><strong>Dual task</strong></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>
| Single task trials raw score (ms) | 661.6 | 176.9 | 566.7 | 96.7 
| Dual task trials raw score (ms) | 943.1 | 267.0 | 737.7 | 158.2 |
| Single task trials error rate (%) | 5.62 | 4.31 | 4.91 | 5.09 |
| Dual task trials error rate (%) | 4.69 | 4.19 | 3.84 | 3.08 |
| Dual task proportional score (%) | 43.35 | 22.18 | 30.33 | 18.22 |
| **Shift task**                |     |      |     |      |
| Repeated trials raw score (ms) | 705.9 | 144.9 | 632.8 | 122.6 |
| Shift trials raw score (ms) | 893.4 | 178.9 | 766.1 | 144.9 |
| Repeated trials error rate (%) | 4.30 | 5.01 | 3.21 | 3.73 |
| Shift trials error rate (%) | 7.68 | 4.90 | 6.28 | 4.95 |
| Shift task proportional score (%) | 27.14 | 11.28 | 21.55 | 11.49 |
| **Spatial compatibility task** |     |      |     |      |
| Compatible trials raw score (ms) | 491.2 | 168.6 | 400.7 | 67.1 |
| Incompatible trials (ms) | 684.9 | 251.9 | 502.7 | 84.7 |
| Compatible trials error rate (%) | 4.89 | 5.78 | 3.28 | 4.73 |
| Incompatible trials error rate (%) | 9.58 | 8.55 | 6.42 | 5.60 |
| Spatial compatibility proportional score (%) | 40.32 | 25.63 | 26.42 | 16.43 |
The Condition main effect (ST and DT) was significant for RTs, \( F(1, 80) = 253.517, p < .001 \), but not for error rates, \( F < 1 \), showing that RTs in ST condition were 226 ms faster than in DT (614 vs. 840 ms, respectively, (i.e., dual-task cost).

Results of the interaction Group \( \times \) Condition was also significant for RTs, \( F(1, 80) = 15.094, p < .001 \), but not for errors, \( F < 1 \). Post-hoc comparison showed a significant difference in RTs between the two groups of children in ST condition of 95 ms and in DT condition of 205 ms, respectively. The RTs dual-task cost was greater for the ADHD group than for the control group (281 vs. 171 ms, respectively).

The ADHDs, who had the slowest overall RTs (802 ms), also showed the largest discrepancy between the baseline control condition and high order executive condition (281 ms). On the other side, the matched control children, who have the faster responders (652 ms), showed the smallest dual-task cost (171 ms). To circumvent and control for the potentially confounding influence of groups overall differences in processing speed on raw RT index of executive functioning, we analyzed the data using proportional transformations of raw RTs.

The DT proportional transformation score was greater for the ADHD group than for the control group (43.35% vs. 30.33%, respectively), and was significant, \( F(1, 80) = 7.612, p < .01 \) (see Table 3).

Taken together, these results suggest that processing speed differences may have contributed to the longer response latencies in ADHDs; but it does not appear that the discrepancy between RTs in the ST and DT conditions was attributable to general slowing. Instead, the executive control effect was proportionally larger for ADHD children compared with normal control children, suggesting greater difficulty in planning and coordinating of two tasks responses.

**Shift task.** Analyses performed to compare the performance of ADHD with respect to normal control children revealed the following statistically significant main effects and interaction:

The Group main effect for RTs, \( F(1, 80) = 8.936, p < .01 \), but not for error rates, \( F < 2 \), showed that the overall RTs, were 100 ms longer for ADHDs than for control children (800 vs. 700 ms, respectively; (see Table 3).

The Condition main effect was significant for RTs, \( F(1, 80) = 319.045, p < .001 \), showing that RT in switch trials was significant greater than in nonswitch trials (830 vs. 669 ms). So was the error rate, \( F(1, 80) = 47.395, p < .001 \) (6.98% vs. 3.75%, respectively; (i.e., shift-task cost).

Results of Group \( \times \) Condition interaction was significant for RTs, \( F(1, 80) = 9.137, p < .01 \), but not for errors, \( F < 1 \). Post-hoc comparison showed a significant difference in RTs between the two groups of children in nonswitch trial conditions of 73 ms and in shift trial conditions of 127 ms, respectively. A significant difference between shift and non shift trial conditions (i.e., shift-task cost) for each of the two groups was found. The shift-task cost was greater for the ADHD group than for the control group (188 vs. 133 ms, respectively).

The ADHDs, who had the slowest overall RTs (800 ms), also showed the largest shift-task cost on this paradigm (188 ms). On the other side, the matched control children, who had the faster responders (700 ms), showed the smallest discrepancy between the baseline control condition and high order executive condition of trials on the shift task (133 ms). To circumvent and control for the potentially confounding influence of groups overall differences in processing speed on raw RT index of executive functioning, we need to analyze the data using proportional transformations of raw RTs.
The shift-task proportional transformation score was significant, $F (1, 80) = 4.063$, $p < .05$, being greater for the ADHD group than for the control group (27.14 vs. 21.55%, respectively; (see Table 3).

Taken together, these results suggest that processing speed differences may have contributed to the slower response latencies in ADHDs; but it does not appear that the discrepancy between RTs in the nonshift and shift trial conditions was attributable to general slowing. Instead, the executive control effect was proportionally larger for ADHD children compared with normal control children, suggesting greater difficulty in disengaging from one task and switching attention to another task.

**Spatial S-R compatibility task.** Analyses performed to compare the performance of ADHD respect to normal control children showed statistically significant the following main effects and interaction:

The Group main effect for RTs, $F (1, 80) = 20.485$, $p < .001$, and for error rate, $F (1, 80) = 4.341$, $p < .05$; showed that overall RTs were 136 ms longer for ADHDs than for control children (588 vs. 452 ms, respectively). ADHDs were significantly 2.39% less accurate than matched controls (7.24% vs. 4.85%, respectively; (see Table 3).

The pairings condition main effect was significant for RTs, $F (1, 80) = 188.581$, $p < .001$, showing that RTs in incompatible S-R pairings condition were significantly greater than in compatible S-R pairings condition (594 vs. 446 ms). So was the error rate, $F(1, 80) = 21.448$, $p < .001$ (8% vs. 4.08%, respectively; (i.e., spatial-compatibility or response-interference effect).

The Group × Pairing condition was significant for RTs, $F (1, 80) = 18.131$, $p < .001$, but not for errors, $F < 1$: Post-hoc comparison showed a significant difference in RTs between the two groups of children in both S-R compatible and incompatible pairing conditions (91 and 182 ms, respectively). A significant response interference effect was found for each of the two groups. This effect was greater for the ADHD group than for the control group (194 vs. 102 ms, respectively).

The ADHDs, who had the slowest overall RTs (588 ms), also showed the largest discrepancy between the baseline control condition and high order executive condition on this task (194 ms). On the other side, the matched control children, who had the faster overall responders (452 ms), showed the smallest discrepancy between the two conditions of trials on this paradigm (102 ms). To circumvent and control for the potentially confounding influence of groups overall differences in processing speed on spatial compatibility effect, we analyzed the data using proportional transformations of raw RTs.

The difference in the response interference proportional transformation score was significant between the two groups, $F (1, 80) = 8.596$, $p < .01$ (40.32% vs. 26.42%, respectively; (see Table 3).

Finally, these findings suggested that independent from their generalized reduction in the time efficiency in information processing speed, the clinical group of children with respect to matched controls had a proportionally larger inhibitory control impairment, suggesting greater difficulty in inhibiting a prepotent compatible response and generating an incompatible response.

**DISCUSSION**

The main aim of the present study was to verify the hypothesis of various components of EFs impairment in ADHD children with respect to matched controls, shown by poor performance on those executive control processes employed in three RT tasks. The
three tasks were the dual task, switch task, and S-R spatial-compatibility task paradigms. To our knowledge, this is the first study in which the three tasks were studied in one sample.

The low correlation between EF tasks provided supports the possibility that executive functions can be fractionated into more or less independent functional components and is consistent with the conceptualization of executive functioning as a multifaceted construct. In our study, we could demonstrate that the three tasks used tapped separate and individual functional components of executive functioning, and that the impairment of specific components of executive functions can be isolated and examined individually in the ADHD population. Other studies reported low correlations between different tasks thought to measure a different form of inhibition or impulsivity (Olson, Schilling, & Bates, 1999; Scheres et al., 2004). Umiltà & Stablum (1998) suggested an interesting double dissociation between dual-task and shift-task paradigms in closed-head-injury patients.

Specific Executive Deficits Associated with ADHD

A relevant issue to research on EF is to develop sensitive and specific measurement instruments that can eliminate the effect caused by difference in lower-level abilities (e.g., speed of responding; Wu et al., 2002). In this work, tasks were chosen to isolate the effects associated with lower-level activities when a specific higher level of cognitive component was examined.

After controlling for the confound of slow processing speed by transforming our raw RT data into proportional scores, we still demonstrated a discrepancy in the magnitude of the executive control processes effects between the two groups of children. In fact, examination of proportional scores data suggest that effects were larger for ADHD children than for matched controls. The clinical group required significantly more time to coordinate the two task responses in the dual task, more time to disengage attention from one task to another task in the shift task, and more time to inhibit a prepotent compatible response and generate an incompatible response in the spatial S-R compatibility task. Taken together, these findings suggest that, above and beyond differences in processing speed, the clinical group of children showed on each task specific executive deficits in comparison to normal control children.

Dual task

In the dual task, it was shown for all participants that the secondary task caused a slowing in the speed of the primary task (i.e., dual-task cost). To explain this effect Umiltà et al. (1992) invoked Pashler’s notion of a bottleneck (Pashler & Johnston, 1989) and proposed that in the dual-task condition the bottleneck occurs at the decision stage. In particular, they suggested that the decision to perform the two tasks one after the other competes with the decision to execute the first response for access to the same processing stage. This common stage acts as a bottleneck, causing postponement of the response to the primary task and lengthening the RT for this task. In accordance with a postponement model, it was argued that the structure in which the decision stage of two responses are coordinated is the central executive (Baddeley, 1986) that intervenes when is required making action plans and decisions (Umiltà et al., 1992).

In our study, ADHD children showed a significantly greater proportional interference effect in the dual task than the control group, and this suggests greater postponement.
of the response to the primary task in the clinical group than controls (43.35% vs. 30.33%, respectively). When children in the ADHD groups had to perform two tasks in sequence in accordance to test instruction (first R1 and than R2), they took longer in planning the order of the two responses.

These results are in agreement with those obtained by Carlson et al. (1991), which provided evidence that nonmedicated, compared to medicated, ADHD children responded slowly to the primary task when the two tasks did not overlap in time. The authors (Carlson et al., 1991) concluded that ADHD fails to allocate their available cognitive resources to the primary task.

**Shift task.** In the shift task, the results demonstrated that switching between two tasks produces a slowing down (i.e., switch cost) in all participants. A variety of theoretical accounts of task shifting have been proposed (see review in Monsell, Yeung, & Azuma, 2000). One theory considers the RT cost of a task switch as essentially a subtractive measure of the duration control process that occurs with switch trials and not with nonswitch trials (Monsell et al., 2000). In switch trials, executive processes are required that need extra time for loading processing algorithms required for the new task from long-term memory into working memory and for inhibiting of previously used processing algorithms that are no longer appropriate (Cepeda, Cepeda, & Kramer, 2000). The cost in errors of a switch must presumably be attributed to occasional failures to perform this process effectively or completely.

In this study, the ADHD children showed a significant greater switch-task proportional score than the control group (27.14% vs. 21.55%, respectively), providing evidence that they are impaired in the ability to disengage from one task and switch attention to another task.

The results of this study are in agreement with previous studies on task switching, which also demonstrated that ADHD children have substantially larger switch costs than nonclinical children or ADHD children on medication (Cepeda et al., 2000; Kramer et al., 2001).

**Spatial S-R compatibility task.** In the spatial S-R compatibility task, the results showed a spatial-compatibility effect. For all participants the response was faster and more accurate when the left or right position of the stimulus corresponded to the left or right position of the response key (corresponding S-R pairings) than when it did not (noncorresponding S-R pairings).

There is converging behavioral and psychophysiological evidence that the spatial stimulus code automatically activates the corresponding response (e.g., De Jong, Liang, & Lauber, 1994; Eimer, 1995; Eimer, Hommel, & Prinz, 1995; Kornblum & Lee, 1995; Proctor, Lu, Wang & Dutta, 1995). Basically, dual-route models (e.g., De Jong et al., 1994; Kornblum, Hasbroucq, & Osman, 1990) maintain that, when the imperative stimulus appears, two routes are activated: the automatic, unconditional (direct) route, independent of stimulus identification; and the conditional (controlled) route, depending on stimulus identification, which activates the correct response. If the unconditional and conditional routes activate the same response (i.e., corresponding S-R pairings), the correct response is quickly executed. If the two routes activate different responses (i.e., noncorresponding S-R pairings), the incorrect direct response must be aborted in favor of the correct one. Therefore execution requires extra time (e.g., Tagliabue et al., 2000).

To perform the correct response in noncorresponding S-R pairings condition, participants had to actively inhibit the response automatically activated on the same side by the appearance of stimulus on screen. This control process required the intervention of the inhibitory capability of subjects.
In the present study, ADHD children showed greater difficulties with respect to matched controls in inhibiting the inappropriate imperative response, automatically activated on the same side to the appearance of the stimulus on screen, in order to perform the contralateral response in compliance with the incompatible task (40.32% vs. 26.42%, respectively). This demonstrates an ADHD deficit for inhibiting strongly environmental triggered responses.

Contrary to the results of this study, Yong-Liang et al. (2000) did not show that ADHD children produced a larger incompatibility effect on response speed with respect to normal boys. It is important to note that Yong-Liang et al. (2000) used a mixed S-R compatibility paradigm, whereas in the present study participants performed in two different blocks, first the compatible S-R condition and then the incompatible S-R condition. We suggest that a mixed S-R compatibility paradigm may have reduced for both groups of children the possibility to maintain an appropriate problem-solving set to predict successfully the task’s condition to perform in consequence to the appearance of stimuli on screen. This may have consequently mitigated in the Yong-Liang et al.’s (2000) study the response-time differences between the two groups of children.

Other studies have demonstrated a deficit of inhibitory control in ADHD children (Bayliss & Roodenrys, 2000; Casey et al., 1997; Grodzinsky & Diamond, 1992; Nigg et al., 2002; Schachar & Logan, 1990). Casey et al. (1997) have used three response-inhibition tasks in ADHD children designed to probe inhibition during three different stages of attentional processing: stimulus selection, with a sensory discrimination task; response selection, with a compatible–incompatible stimulus-response paradigm; and response execution, with a go/no-go task. Significant differences in performance of children with ADHD and non-ADHD volunteers were observed in all three inhibition tasks. These differences were correlated with anatomical measures of frontostriatal circultry (e.g., the region of the prefrontal cortex, caudate, and globus pallidus) found to be abnormal in children with ADHD, in particular those of the right hemisphere, supporting a role of right frontostriatal circuitry in inhibition in ADHD children.

Implications on the Theoretical Models for ADHD

Another purpose of the work was to examine which of the two main approaches developed to explain the behavioral deficits of ADHD better accounts for the performance of the ADHD children in the three tasks employed.

The results of this study confirm both theoretical models proposed in explaining the symptoms of ADHD: Barkley’s (1997) inhibitory processes and executive control deficits model; and Sergeant et al.’s (1999) resource allocation/arousal model.

Consistent with Barkley’s (1997) model of ADHD, the proportional cost transformation measures of dual task, shift task, and spatial S-R compatibility task have revealed a number of different control and monitoring processes deficits in ADHD children with respect to matched controls, independently from their generalized reduction in processing speed. Barkley’s (1997) model proposes that poor behavioral inhibition is the core deficit of ADHD, including deficits in inhibiting predominant responses, interrupting ongoing response, and controlling interference, which produce secondary deficits in executive functioning.

Moreover, consistent with the prediction of Sergeant et al.’s (1999) resource allocation/arousal model, we found poor performance in ADHD children with respect to control children in all task’s conditions, also in those more simple that did require more lower-level
abilities of processing speed. In fact, significant greater raw RTs were obtained in ADHD children with respect to control children in performing the ST condition in the dual-task paradigm (662 vs. 567 ms); in performing nonswitch trials in switch task paradigm (706 vs. 633 ms); and in executing the compatible S-R pairing condition in spatial compatibility paradigm (491 vs. 401 ms). Sergeant et al.’s (1999) model proposes that deficit of ADHD is characterized by a decreased state of activation or arousal, with an inability to allocate and maintain resources.

In summary, in the present study we employed three EF measures that allowed us to control for the confound effect caused by differences in lower-level abilities (e.g., speed of responding; Wu et al., 2002). We demonstrated that, above and beyond differences in processing speed, the clinical group of children showed on each task of this study specific executive function deficits in comparison to normal control children. We conclude that our data are consistent with both classes of models, which can be utilized to clarify and elucidate the nature of behavioral deficits associated with ADHD: Barkley’s (1997) executive dysfunction model, better accounts for the executive process deficits shown by children with ADHD; whereas Sergeant et al.’s (1999) resource allocation/arousal model better represents the processing speed deficits of ADHDs compared with nonclinical children.

REFERENCES


