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Beyond interference control impairment in ADHD: Evidence from increased intraindividual variability in the color-stroop test

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The present study investigates intraindividual variability (IIV) in the Color-Stroop test and in a simple reaction time (SRT) task. Performance level and variability in reaction times (RTs)—quantified with different measures such as individual standard deviation (ISD) and coefficient of variation (ICV), as well as ex-Gaussian parameters (*mu, sigma, tau*)—were analyzed in 24 children with attention deficit/hyperactivity disorder (ADHD) and 24 typically developing children (TDC). Children with ADHD and TDC presented equivalent Color-Stroop interference effects when mean RTs were considered, and the two groups did not differ in the SRT task. Interestingly, compared to TDC, children with ADHD were more variable in their responses, showing increased ISD and ICV in the Color-Stroop interference condition and in the SRT task. Moreover, children with ADHD exhibited higher *tau* values—that is, more frequent abnormally long RTs—in the Color-Stroop interference condition than did the TDC, but comparable *tau* values in the SRT, suggesting more variable responses. These results speak in favor of a general deficit in more basic and central processes that only secondarily may affect the efficiency of inhibitory processes in children with ADHD. Overall the present findings confirm the role of IIV as a cornerstone in the ADHD cognitive profile and support the search for fine-grained analysis of performance fluctuations.

Keywords: ADHD; Intraindividual variability; Inhibition; Color-Stroop test; Response time distributions.

Attention deficit/hyperactivity disorder (ADHD) is a complex pervasive developmental disorder, diagnosed in approximately 2%–16% of school-aged children (Rader, McCauley, & Callen, 2009) and characterized by age-inappropriate levels of inattention, hyperactivity,

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and impulsivity (American Psychiatric Association [APA], 2000). Behavioral and cognitive difficulties have been attributed to neuropsychological deficits in executive functions such as attentional regulation, response inhibition, and working memory (Barkley, 1997a; Barkley, Grodzinsky, & DuPaul, 1992; Pennington & Ozonoff, 1996; Sergeant, Geurts, & Oosterlaan, 2002).

Despite the actual debate concerning centrality of inhibition and/or broad executive function processes as a causal model of ADHD (Castellanos, Sonuga-Barkes, Milham, & Tannock, 2006; Scheres et al., 2004; Sergeant, 2005; Sergeant et al., 2002; Willcutt, Doyle, Nigg, Faraone, & Pennington, 2005), the neurocognitive view of ADHD considers inhibitory processes as a core deficit in ADHD that secondarily disrupts other executive function processes (Barkley, 1997b; Pennington & Ozonoff, 1996). In particular, children with ADHD are supposed to be particularly affected in the different dimensions of inhibition (see de Ribaupierre, Borella, & Delaloye, 2003; Nigg, 2000) such as inhibition of prepotent responses, stopping of ongoing responses, and interference control (Barkley, 1997a).

Among the cognitive paradigms used to quantify interference control deficits in children with ADHD, the Color-Stroop test is one of the most frequently used tests (Barkley et al., 1992; Frazier, Demaree, & Youngstrom, 2004; Hervey, Epstein, & Curry, 2004; Homack & Riccio, 2004; Lansbergen, Kenemans, & van Engeland, 2007; Pocklington & Mayberry, 2006; Schwartz & Verhaeghen, 2008; Van Mourik et al., 2009). It consists of visually presenting the participants with color names displayed in an incongruent color (e.g., the word "red" written in blue). Participants are instructed to name the color in which the word is written as fast and accurately as possible (Cohen, Dunbar, & McClelland, 1990). Complying with the task's instructions implies the ability to inhibit the prepotent reading response—reading the color name—and to favor the appropriate but nondominant naming response—color in which the word is written. The relative decrease in performance (slower response times or decrease in accuracy) associated with naming the color of incongruent color names, as compared to a control condition with neutral features, is referred to as the "Stroop interference effect" and reflects the cognitive effort involved in interference control.

Most of the studies that examined the Color-Stroop test in the context of ADHD literature referred to Golden's (1978) paper version, a variant of the Color-Stroop word test (Stroop, 1935). To date, some meta-analyses have examined the Stroop interference effect in children with ADHD (as examples, see Homack & Riccio, 2004; Van Mourik et al., 2009). Homack and Riccio reported children with ADHD to be more sensitive to interference than typically developing children (TDC), as shown by a large interference effect size. In contrast, the meta-analysis by Van Mourik et al. (2009) showed that children with ADHD are not more vulnerable to interference than TDC. This latter pattern of findings was also confirmed by the recent study by Williams, Strauss, Hultsch, and Tannock (2007).

Therefore, empirical evidence regarding the deficit in interference control in children with ADHD measured by the Color-Stroop test is not a very reliable finding. When these divergent findings are more closely considered, it appears that several methods were used to quantify the Stroop interference effect: the number of words named correctly, the time to complete a given number of stimuli (which obviously includes errors as well), the number of items named in a given time frame (i.e., 45 seconds in Golden's formula), or the response latency per item in milliseconds. Moreover, it is worth mentioning that the majority of studies used a card version in which several trials were presented on the same card and, still more importantly, did not include a baseline control condition (Lansberger et al., 2007). When individual differences in baseline performance are controlled for, by computing a ratio or a relative ratio, rather than merely considering raw response times or errors in the incongruent condition, children with ADHD no longer appear to present a specific deficit in interference control (for meta-analyses, see Schwartz & Verhaeghen, 2008; Van Mourik et al., 2009). Therefore, it is possible that the deficit highlighted by some authors in the Color-Stroop test for children with ADHD could reflect individual differences in stimuli naming (Tannock, Martinussen, & Frijters, 2000) and be linked to an inappropriate type of measurement (Lansberger et al., 2007), rather than a deficit in interference control.

One of the aims of the present study was thus to assess interference control in children with ADHD and TDC using the Color-Stroop paradigm. In particular, a computerized item-by-item version of this task was used to allow for fine-grained performance analysis of reaction times (RTs); it might help detect behavioral differences in interference control between children with ADHC and TDC children in ways that would not be possible with the most commonly used paper versions. Indeed, recording item-by-item RTs in milliseconds offers an advantage in terms of test sensitivity (Christiansen & Oades, 2009), in particular because it allows examining RTs for correct responses only instead of mixing erroneous and correct responses. Such a procedure also allows mixing trials of the different conditions instead of grouping them by condition. To our knowledge, in all the few studies that used chronometric Color-Stroop tasks, children with ADHD did not appear to be more sensitive to interference than controls (e.g., Albrecht et al., 2008; Carter, Krener, Chaderjian, Northcutt, & Wolfe, 1995; Christiansen & Oades, 2009; Jourdan Moser, Cutini, Weber, & Schroeter, 2009).

Nonetheless, independently of the task version used, those divergent results on the Stroop interference effect in ADHD are based on mean performance levels. As suggested by Nesselroade (1991), individual systematic variations in short-term behavior (that is, moment-to-moment [item-by-item] fluctuations in task performance) provide additional, complementary information that is potentially masked by analyses based on mean performance levels.

There is indeed converging evidence that children with ADHD present a large item-by-item intraindividual variability (IIV), also called "inconsistency," in RTs compared to controls (Borella, Chicherio, Re, Sensini, & Cornoldi, 2011; Castellanos & Tannock, 2002; Kunsti, Oosterlaan, & Stevenson, 2001; Leth-Steensen, Elbaz, & Douglas, 2000; Steger et al., 2001). For instance, Klein, Wendling, Huettner, Ruder, and Peper (2006) showed across a variety of neuropsychological tests—continuous performance test, go/no-go, stop signal, and *n*-back tasks—that IIV reliably contributed to discriminate between children with ADHD and controls. The increased behavioral IIV found in this population is presumably linked to dysfunctions of fronto-striatal-cerebellar circuits and altered dopaminergic modulation (Castellanos & Tannock, 2002; Krain & Castellanos, 2006) and, more generally, to compromised central nervous system integrity (MacDonald, Nyberg, & Bäckman, 2006). As a consequence, increased RT IIV has been hypothesized to be one of the potential markers of underlying neuropsychological deficits related to ADHD (e.g., Castellanos et al., 2006; Borella et al., 2011).

A second aim of the present study was, thus, to examine the patterns of IIV in order to provide information with respect to interference control deficit in ADHD that may potentially be masked by the analyses based on mean RTs (Castellanos et al., 2006). This was possible using a computerized version of the Color-Stroop task, to assess trial-to-trial variability. To our knowledge, only Christiansen and Oades (2009) have analyzed IIV in RTs in the Color-Stroop task. Their results showed no difference in the mean interference effect but significantly greater IIV in children with ADHD compared to TDC.

However, Christiansen and Oades used only a traditional measure of IIV, the individual standard deviation (ISD). The ISD is the measure most widely used to quantify IIV, and it is calculated as the standard deviation across trials of the same task for a given individual. Because it has been shown to be linked to the individual mean level across trials, some researchers used other measures to control for the level of performance, such as the individual coefficient of variation (ICV), which is calculated by dividing the ISD by individual mean (IM). Those indices of IIV assume response times to be normally distributed, whereas RT distributions are often positively skewed. Moreover, a greater proportion of extremely slow responses can lead to a larger size of the tail of the RT distribution and may have a strong influence on the values of the individual mean and ISD (i.e., higher values). Therefore, other researchers have suggested alternative approaches such as fitting ex-Gaussian functions—a convolution of an exponential function and a Gaussian one—to item-by-item RT data to describe more precisely the shape of individual RT distributions (see Ratcliff, 1979).

In fitting the ex-Gaussian distribution, three parameters representing different parts of the curve are obtained: *mu* (μ) and *sigma* (σ) representing the mean and standard deviation of the normal (or Gaussian) component, respectively, as well as *tau* (τ), representing both the mean and standard deviation of the exponential (or ex-Gaussian) component (see Figure 1). In terms of the ex-Gaussian distribution, its mean is given by ($\mu+\tau$) and its variance by ($\sigma^2+\tau^2$).

It has been demonstrated that the ex-Gaussian distribution provides a better statistical fit to RT data than the Gaussian distribution does, and that its parameters may capture important aspects of human cognition (see Heathcote, Popiel, & Mewhort, 1991; Spieler, Balota, & Faust, 1996, 2000). In particular, these parameters might be linked to different processes at play in the task, particularly useful in characterizing the nature of increasingly large performance variability in impaired states and pathological conditions such as ADHD. Leth-Steensen et al. (2000) found that children with ADHD, who were slower (higher mean, IM) and more variable (larger intraindividual standard deviation [ISD]) in their RTs, were highly discrepant from controls in the ex-Gaussian parameter *tau*, but not in *mu* or *sigma*. This pattern served as evidence in support of the hypothesis that children with ADHD demonstrated greater performance variability as a result of abnormally long RTs on some but not all trials, producing a greater positive skew reflected in *tau* in the RT distribution. Additionally, greater values of *tau* combined with similar values of *mu* and *sigma*, further proved to be a more specific performance pattern for identifying children with ADHD than an index of general slowing, reflecting a variety of unspecified difficulties with basic cognitive processes. Indeed, it has been argued that periodic excessively long RTs are a consequence of transient periods of inefficient or nonoptimal processes. These trials have been hypothesized to reflect occasions where children with ADHD demonstrate lapses in attention (see also Douglas, 1999).

While Leth-Steensen et al. (2000) quantified IIV associated with RTs in a relatively simple choice response task (i.e., a discrimination task), which imposes a minimal demand on response control, Hervey et al. (2006) administered another task involving higher demands on response control (i.e., a Go/No-Go task). The authors consistently found children with ADHD to differ from controls with respect to the size of the distribution tail (elevated *tau*). They observed additionally that children with ADHD exhibited larger *sigma* values than controls, which suggests that more variable responses were produced in all trials throughout the task. Further, children with ADHD presented smaller *mu* values, indicating that they, at times, responded more quickly than controls. The divergence in results

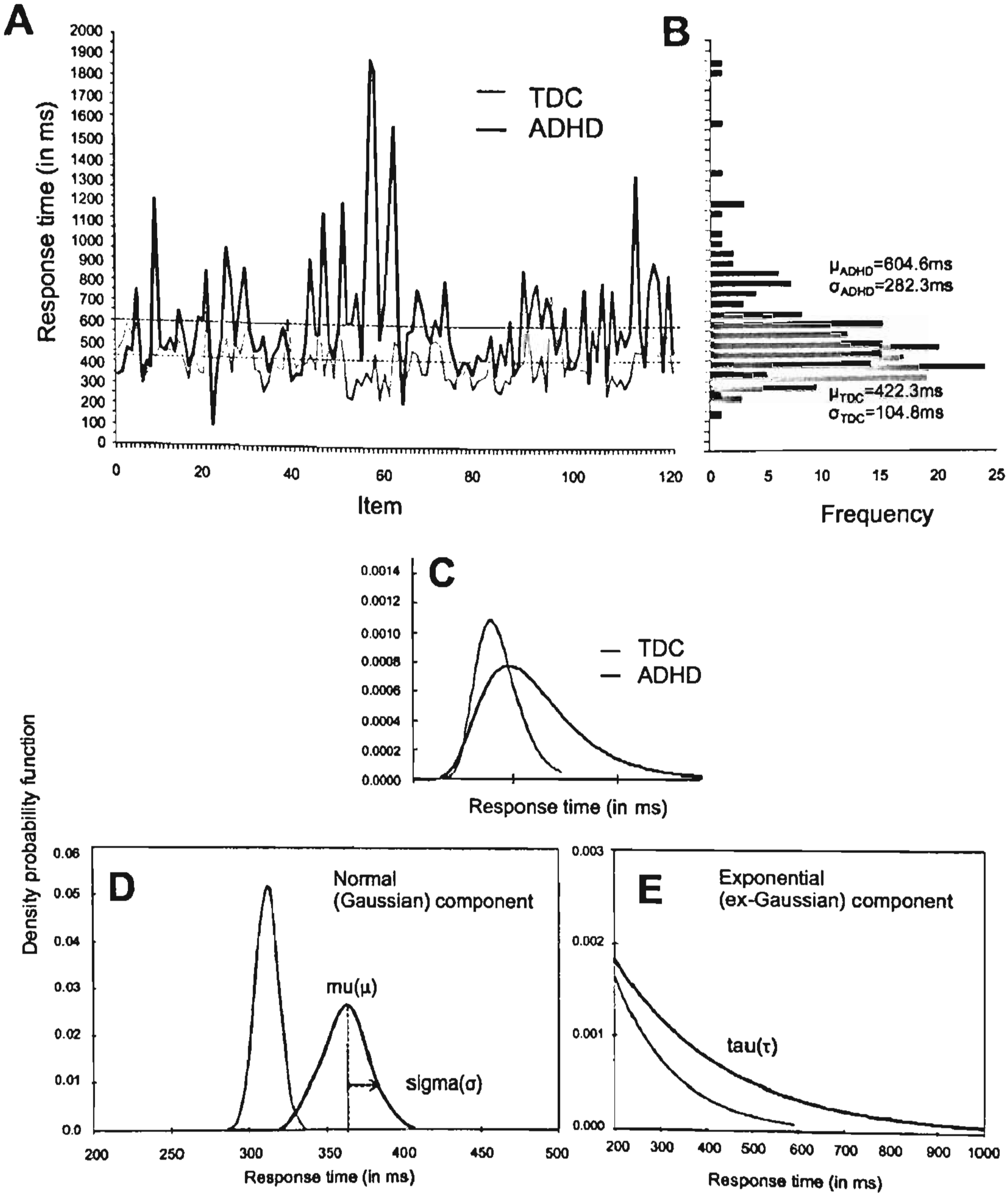

Figure 1 Illustration of the ex-Gaussian distribution: (A) Trajectories of individual responses across 120 items in the SRT (Simple Reaction Time) task from one child with ADHD (dark line) and one TDC (gray line) and (B) their corresponding individual RT distributions. The ex-Gaussian parameters (*mu*, *sigma*, and *tau*) are derived by decomposing (C) each observed RT distribution into (D) its normal (or Gaussian) component and (E) its exponential (or ex-Gaussian) component.

Note. μ = individual mean; σ = individual standard deviation (ISD); TDC = typically developing children; *Mu*(μ) = parameter from the ex-Gaussian analysis reflecting the mean of the Gaussian (or normal) component of the RT distribution; *sigma*(σ) = parameter from the ex-Gaussian analysis reflecting the standard deviation of the Gaussian (or normal) component; *tau*(τ) = parameter from the ex-Gaussian analysis reflecting the mean and the standard deviation of the ex-Gaussian (or exponential) component.

can probably be attributed to differences in the tasks. Indeed, the discrimination task used by Leth-Steensen et al. (2000) seems to produce slower overall response times compared to a Go/No-Go task. Also, the Go/No-Go task with no warning cues and rapid presentation of stimuli clearly primes impulsive responses. To further determine whether these inconsistencies were due to a difference in the degree of response control required by the tasks used in these two studies, Vaurio, Simmonds, and Mostofsky (2009) presented to children with ADHD and controls two variants of the Go/No-Go task but varying in their complexity (or cognitive demands). The authors observed a higher *tau* value (exponential/ex-Gaussian component) and a higher *sigma* value (the normal/Gaussian component) in children with ADHD as compared to controls, independent of the task version. These results are consistent with those from Hervey et al. (2006) in which a similar Go/No-Go task involving high demands on response control was used.

Overall, these findings suggest that when the task requires relatively little response control, increases in IIV are mainly due to intermittent slow responses. When the requirement for response control is higher, IIV is larger throughout the entire RT distribution (that is in slow as well as in fast responses). This could reflect inefficiency in mechanisms critical to engage a state of preparedness to respond. Therefore, Vaurio et al. (2009) concluded that both impaired response preparation and intermittent lapses in attention contributed to increasing variability in performance in children with ADHD. These findings could not have been detected using conventional RT analyses. The ex-Gaussian approach seems therefore to go above and beyond conventional statistical approaches, which focus on the analyses of central tendency measures.

Despite promising results, only a few other studies applied ex-Gaussian function analyses to RT data of children with ADHD (Buzy, Medoff, & Schweitzer, 2009; Geurts et al., 2008; Hervey et al., 2006; Vaurio et al., 2009); we might therefore further our understanding of inhibitory deficits in children with ADHD by isolating more specifically the IIV associated with RTs.

To our knowledge, the present study is the first one to analyze IIV in children with ADHD in a task that measures more specifically the dimension of interference control (e.g., Nigg, 2000)—that is, the Color-Stroop task. Indeed, the Stop signal and Go/No-Go tasks are the most commonly used in ADHD but refer to a different aspect of inhibition (see Nigg, 2000). These tasks measure the inhibition of a dominant motor response rather than that of a preponderant verbal response as in the Color-Stroop.

In summary, the present study aims to examine IIV in ADHD using a computerized version of the Color-Stroop test. As mentioned previously, not all studies have used a control condition; it is therefore difficult to decide whether potential difficulties in the interference task are really due to a deficit in inhibition or, more simply, to a deficit in a more basic mechanism such as processing speed. It is therefore important to assess whether IIV is larger in an interference condition than in a control one.

Furthermore, to examine the generalizability of IIV in children with ADHD and TDC, it also appeared important to use an independent task that did not involve the same content domain (verbal) as the Color-Stroop task itself. Therefore, a simple reaction times (SRT) task, often used to examine IIV (e.g., Borella et al., 2011), in which participants had simply to react to the appearance of target stimuli and that imposed a minimal demand on response control, was used. The use of both tasks should indeed allow us to determine whether children with ADHD compared to TDC are (a) impaired in interference control processes, as classically found in the literature, or (b) characterized by a deficit in lower and more central mechanisms of information processing such as processing speed, assessed by the SRT task as an independent measure, in which case it could not be considered to be a difficulty specific to the control of interference. Both the mean level and the variability of performance (RTs) will be analyzed. Furthermore, to provide convergent and complementary results about the role of IIV in interference control in the Color-Stroop test, different indices of IIV in RTs will be considered: the classical indices of ISD and ICV but also the ex-Gaussian parameters *mu, sigma*, and *tau*.

With respect to mean performance level, and in conformity with the meta-analysis by van Mourik, Oosterlaan, and Sergeant (2005), we expected children with ADHD not to differ from TDC. The mean interference effect should also be similar in the two groups. However, children with ADHD should present a larger IIV in the Color-Stroop task, compared to TDC; that is, they should produce slower and more variable responses than TDC, indexed by larger ISD and ICV (e.g., Christiansen & Oades, 2009). With respect to ex-Gaussian analyses (e.g., Hervey et al. 2006; Vaurio et al., 2009), children with ADHD should show higher values of *tau*, reflecting a greater frequency of extremely long RTs, whereas they should not differ from TDC with respect to the *mu* value (mean level of performance); we will examine whether they would also present a larger value for *sigma* (variance). If children with ADHD are more variable than TDC, as we believe and has been assumed in the literature, they should also exhibit higher levels of IIV in the SRT. This would show that processing is altogether less robust in this population; processing robustness has been associated with neural information-processing fidelity (e.g., Li, Huxhold, & Schmiedek, 2004).

METHOD AND MATERIALS

Participants

Twenty-four children with attention deficit/hyperactivity disorder (ADHD) and 24 typically developing children (TDC), aged 9 to 12 years, participated in the study. ADHD participants, all of whom attended normal schools, were recruited through referrals from Italian university-based ADHD clinics. The control group was formed with children who attended the same schools as the ADHD children and came from the same socioeconomic background.

Patients' diagnoses were established by qualified psychiatrists or clinical psychologists following indications in the Diagnostic and Statistical Manual of Mental Disorders, Text Revision (*DSM-IV-TR*; APA, 2000). The diagnosis of children with ADHD was based on the fact that they were beyond the cutoff in rating scales for ADHD disorder, either the ADHD rating scale for teachers (Scala per i Disturbi di Attenzione/Iperattività per Insegnanti -SDAI; Cornoldi, Gardinale, Masi, & Pettenò, 1996) or the Conners' Rating Scale—Revised (Conners, 1997). The SDAI scale is a simple scale, similar in organization and scope to those largely used in other countries (e.g., DuPaul, Power, Anastopoulos, & Reid, 1998). It presents the 18 ADHD symptoms (described by *DSM-IV-TR*), whose frequency and intensity must be rated on 4-point scales from 0 to 3. The scale has been validated and standardized for the Italian population and has shown good reliability ($r = .95$; Marzocchi, Re, & Cornoldi, 2010) and test-retest reliability ($r = .80$; Marzocchi & Cornoldi, 2001). The cutoff for considering a child for a possible diagnosis of ADHD is represented by a mean item rating above 1.5.

In order to be included in the ADHD group, clinical interviews with teachers, children, and their parents had to confirm the presence of at least six symptoms either of inattention or hyperactivity both at school and at home. Furthermore, children had to present weaknesses (scores below the normative mean of at least 1.5 standard deviations) in at least two of a series of neuropsychological tests assessing executive functions (see Sinpia's guidelines, 2006).

Written informed consent was obtained from parents or legal guardians. The patients and controls underwent the same screening and diagnostic procedures, interviews, and psychological testing. We excluded children who presented one or more of the following conditions: (a) their Wechsler Intelligence Scale for Children (WISC) IQ score was below 85; (b) they were receiving medication; (c) they had either a previous diagnosis of a learning disability, or, even if not diagnosed, they were identified by teachers as having severe difficulties either in reading or mathematics; (d) they had a history of neurological disorders, sensory problems, motor impairment, or any developmental psychiatric disorder other than ADHD; and (e) they met the *DSM-IV-TR* criteria for major depression, anxiety, bipolar disorder, a psychotic disorder, or a mood disorder.

Children with ADHD and TDC did not differ in terms of mean age, $F(1, 47) = 0.28$, $p = .60$ (ADHD: 9.50 ± 1.32; TDC: 9.29 ± 1.40), gender distributions, $\chi^2(1) = 1.78$, $p = .18$ (ADHD: 20 male, 4 female; TDC: 16 male, 8 female), and IQ, $F(1, 47) = 0.13$, $p = .72$ (ADHD: 100.04 ± 6.87; TDC: 101.83 ± 6.21).

Color-Stroop Test

The computerized Color-Stroop test was adapted from Spieler et al. (1996) and from Fagot, Dirk, Ghisletta, and de Ribaupierre (2009; see also Ludwig, C., Fagot, D., Chicherio, C., & de Ribaupierre, A, 2011). The experiment was piloted using the E-prime software (E-Prime 1.1; Psychology Software Tools, Pittsburgh, PA). The stimuli consisted of four color names (ROSSO—red; BLU—blue; VERDE—green; GIALLO—yellow) written in red, blue, green, or yellow, depending on the condition either congruent (i.e., the word GREEN printed in green) or incongruent (i.e., the word RED printed in green). Additionally, in the neutral condition, four different stimuli (^^^^; ++++; ****; '''') were presented in red, blue, green, or yellow. Stimuli were presented on a 35 cm (14-inch) video graphics array color computer monitor. All stimuli were presented on a black background. The three experimental conditions were distributed over nine blocks of 24 trials each. The order of the blocks and the order of the trials within a block were first randomized and then identical for all participants. Randomization respected two constraints. First, within a block, no more than three consecutive trials belonged to the same condition. Second, negative priming was controlled for, in that the color word of any given item never matched the color of the succeeding item. In each block, there were eight congruent, eight incongruent, and eight neutral trials. In summary, 72 trials per condition were presented, for a total of 216 items in nine blocks. The task started with nine practice trials (three items per condition), with stimuli and timing identical to those of the experimental blocks. In each trial, the following sequence of events occurred: A white fixation point appeared in the center of the computer screen for 1,000 ms. The stimulus appeared in the center of the screen and remained until the onset of the participants' response. Participants were instructed to name the color of each stimulus as quickly and accurately as possible. Voice onset latency was measured via a voice key interfaced with the computer. Afterward, the screen went blank for 800 ms, following the onset of the participants' response. The experimenter recorded the participants' responses on paper. All participants could take a short break after each block of trials.

Simple Reaction Time Task

The computerized Simple Reaction Time (SRT) task was adapted from Hultsch, MacDonald, Hunter, Levy-Bencheton, and Strauss (2000; see also Ludwig et al., 2011).

The experiment was piloted using the E-Prime software (E-Prime 1.1.; Psychology Software Tools, Pittsburgh, PA). The stimuli consisted of a white cross located in one of five positions corresponding to the points of a five-branch invisible star on the center of the computer screen. Distribution of the stimuli on noncentral locations was meant to prevent anticipatory responses. Stimuli were presented on a 35 cm (14-inch) video graphics array color computer monitor. All stimuli were presented on a black background. The SRT task was presented in five blocks of 24 trials each, for a total of 120 items. The order of the blocks and the order of the trials within a block were first randomized, and then identical for all participants. Randomization respected two constraints. Within a block, no more than two consecutive trials belonged to the same position, and no more than two consecutive trials belonged to the same interstimulus interval. The task started with six practice trials, with stimuli and timing identical to those of the experimental blocks. On each trial, the following sequence of events occurred: a white fixation point appeared in the center of the computer screen and the stimuli remained until the onset of the participants' response. Participants were instructed to react as fast as possible to the apparition of the cross (+) after a fixation point (•) had been presented, by pressing with their dominant hand on a button box. Afterward, the screen went blank for a delay between 500 and 1,700 ms, following the onset of the participants' response. The interstimulus interval varied between 500 and 1,700 ms by increments of 300 ms. Response latency was recorded for each trial via a response box, corresponding to the delay between the apparition of the cross and the participant's response. Participants were given the option of taking a short break every 24 trials (i.e., between blocks of trials).

Tasks Reliability

Reliability estimates were computed on mean correct RTs separately for both children with ADHD and TDC, using the split half method (odd-even) with the Spearman-Brown correction. The Color-Stroop Interference (ADHD: incongruent stimuli, $r = .97$; neutral stimuli, $r = .99$; TDC: incongruent stimuli, $r = .99$; neutral stimuli, $r = .99$) and the Simple Reaction Time (ADHD: $r = .99$; TDC: $r = .97$) tasks provided very good reliability.

Procedure

All tasks were administered individually in one session. After participants were informed of the purpose of the investigation, the SRT task and the Color-Stroop test were administered. The order of the tasks was fixed starting with the SRT and then the Color-Stroop task. On average, the session lasted about one hour.

RESULTS

Design of the Analyses

After examining the reliability of the measures of interest at the group level, analyses were performed to first test the group effect on mean RT performance (a) in the Color-Stroop interference effect, focusing on incongruent and neutral conditions, and (b) in the SRT task. Additionally, as concerns the Color-Stroop test, an index of interference was also computed to control for individual differences in baseline performance: The interference index was based on the relative difference between RTs in the incongruent and RTs in the "signs" neutral condition, that is: (RTs incongruent – RTs neutral)/RTs neutral (see Borella, Delaloye, Lecerf, Renaud, & de Ribaupierre, 2009). Although mean levels of performance were not the primary outcome of interest, those analyses provide a descriptive context within which group differences in performance variability (i.e., IIV in RTs) can be interpreted.

Second, analyses considering traditional indices to quantify IIV in RTs were conducted for the two tasks. In particular, the (a) intraindividual standard deviations (ISD), (b) intraindividual standard deviations computed for the 25% fastest responses (lower quartile, fast-ISD) and the 25% slowest (highest quartile, slow-ISD), and (c) intraindividual coefficients of variation (ICV) were computed.

Third, and finally, to describe more precisely the shape of the individual RT distribution and to better characterize the nature of increased IIV in children with ADHD, ex-Gaussian parameters were estimated using the statistical package quantile maximum probability estimator (QMPE) (Cousineau, Brown, & Heathcote, 2004; Heathcote, Brown, & Mewhort, 2002). The QMPE package outputs an exit code (e.g., information about convergence properties, Hessian singularity) indicating whether the estimated solution is acceptable. Acceptable exit codes are defined in the QMPE manual (e.g. Cousineau et al., 2004). In the present sample, distributions for ADHD and TDC were acceptable for all experimental conditions and tasks, indicating that ex-Gaussian distributions provide a good fit to the Color-Stroop data. Therefore, we used all estimated ex-Gaussian parameters from cases with acceptable exit codes.

For the Color-Stroop and SRT tasks, only correct response latencies were considered for all analyses. Extremely fast responses—RTs below 150 ms for the SRT task and below 200 ms for the Color-Stroop test—were discarded as implausible (e.g., Fagot et al., 2009). With respect to latencies in the Color-Stroop task, all RTs associated with errors were eliminated to exclude voice-key errors (in which the voice key was triggered by a false start, either stutter or extraneous noise) and intrusion errors (in which the participant responded to the incorrect dimension of the stimulus, such as reading the word instead of naming the color).

Descriptive statistics of mean performance levels and performance variability for the measures of interest are presented in Table 1.

Color-Stroop Interference Effect

To analyze the interference effect, a mixed design 2 × 2 analysis of variance (ANOVA) was conducted on average RTs with Group (children with ADHD, TDC) as the between-subjects factor and Condition (incongruent condition vs. neutral condition) as the repeated measures.

Results demonstrated a nonsignificant main effect of Group, $F(1, 46) = 2.90$, $\eta_p^2 = .06$, $p = .09$. The main effect of Condition (interference effect) was significant, $F(1, 46) = 76.90$, $\eta_p^2 = .63$, $p < .001$, indicating that incongruent stimuli were associated with longer latencies as compared to neutral stimuli. The Group × Condition interaction was not significant, $F(1, 46) = 1.00$, $\eta_p^2 = .02$, $p = .32$.

With respect to the interference index (i.e., relative difference between mean RTs in the incongruent and mean RTs in the neutral conditions), one ANOVA with Group (children with ADHD, TDC) as the between-subjects factor was conducted.

Results showed that the main effect of Group was not significant, $F(1, 46) = 2.50$, $\eta_p^2 = .05$, $p = .12$, indicating that children with ADHD and TDC did not differ.

Table 1 Performance Level and Variability in the Color-Stroop and Simple Reaction Time Tasks for Typical Developing Children (TDC) and Children with ADHD.

	TDC (n = 24)	ADHD (n = 24)
Color-Stroop Interference task		
IM RT		
Neutral	847.6 ± 51.0	1034.0 ± 72.4
Incongruent	1086.1 ± 79.8	1223.5 ± 69.4
Interference index[a]	0.27 ± 0.03	0.20 ± 0.03
ISD RT		
Neutral	207.5 ± 33.3	398.2 ± 84.8
Incongruent	264.5 ± 37.1	400.0 ± 60.2
ICV RT		
Neutral	0.22 ± 0.02	0.34 ± 0.03
Incongruent	0.23 ± 0.02	0.31 ± 0.02
Simple Reaction Time task		
IM RT	415.1 ± 17.4	437.4 ± 18.0
ISD RT	109.7 ± 8.2	170.8 ± 25.9
ICV RT	0.26 ± 0.01	0.37 ± 0.03

Note. RT = reaction times; IM = individual mean; ISD = individual standard deviation; ICV = individual coefficient of variation. Mean ± standard error.

[a]Index calculated on the basis of response times as follows: ([RT incongruent condition - RT control condition] / RT control condition).

IIV Traditional Indices

Separate mixed-design 2 × 2 ANOVAs were conducted with Group (children with ADHD, TDC) as the between-subjects factor and Condition (incongruent vs. neutral stimuli) as the repeated measures on ISD, fast ISD-slow ISD, and ICV (see Figure 2).

With respect to analyses of ISD, the main effect of Group was significant, $F(1, 46) = 4.20$, $\eta_p^2 = .08$, $p < .05$, indicating that children with ADHD were more variable than TDC (see Table 1). In contrast, the main effect of Condition (or interference) and the Group × Condition interaction were not significant, $F(1, 46) = 2.30$, $\eta_p^2 = .05$, $p = .14$ and $F(1, 46) = 2.10$, $\eta_p^2 = .04$, $p = .16$, respectively.

When interference effect was examined on the fast-ISD, only a main effect of Condition was found, $F(1, 46) = 37.30$, $\eta_p^2 = .45$, $p < .001$: Incongruent stimuli were associated with more variable responses than neutral stimuli for the fastest RTs in both groups, which evidenced an effect of interference. The main effect of Group and the Group × Condition interaction were not reliable (for both, $F < 1$).

Conversely, a significant main effect of Group was found on the slow-ISD, $F(1, 46) = 7.50$, $\eta_p^2 = .14$, $p < .01$, with children with ADHD being more variable in their responses, specifically in the slower tail of the individual RT distributions (see Figure 2) than the controls. The main effect of Condition (interference effect) and the Group × Condition interaction were not reliable (for both, $F < 1$).

Results on ICV showed a significant main effect of Group, $F(1, 46) = 8.70$, $\eta_p^2 = .16$, $p < .01$: Children with ADHD produced more variable responses than did TDC (see Table 1). The main effect of Condition ($F = 1.40$, $\eta_p^2 = .03$, $p = .24$) and the Group × Condition interaction ($F = 2.40$, $\eta_p^2 = .05$, $p = .13$) were not significant.

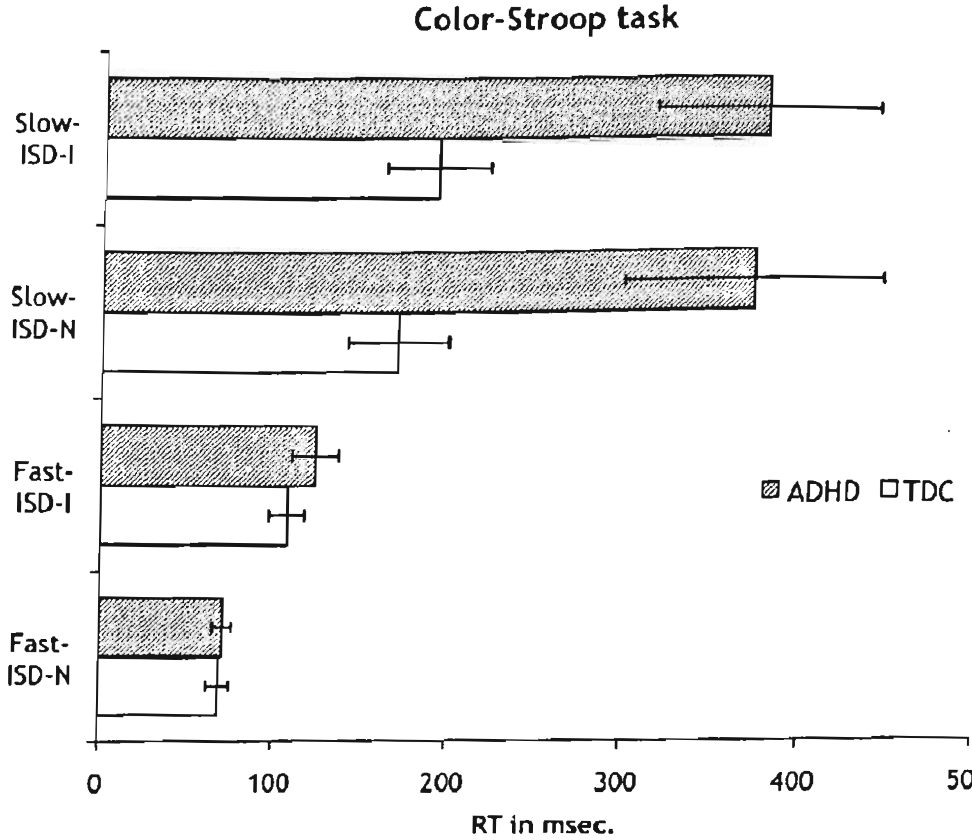

Figure 2 Color-Stroop interference task: Variability of performance for children with ADHD and typically developing children. Error bars represent one standard error.
Note. TDC: typically developing children; ISD: individual standard deviation; Fast-ISD: ISD of the lower quartile for RTs; Slow-ISD: ISD of the upper quartile for RTs; I: incongruent stimuli; N: neutral stimuli. Error bars represent one standard error.

IIV: Ex-Gaussian Analyses

Separate mixed-design 2 × 2 ANOVAs were conducted on *mu, sigma,* and *tau* parameters with Group (children with ADHD, TDC) as the between-subjects factor and Condition (incongruent vs. control conditions) as the repeated measures to analyze the interference effect.

Analyses on parameter *mu* revealed a significant main effect of Condition, $F(1, 46) = 91.1$, $\eta_p^2 = .70$, $p < .001$, which indicated higher values in the *mu* parameter that represents central tendency of RT for the Gaussian component of the distribution (i.e., slower mean RTs) for incongruent stimuli as compared to neutral stimuli. The main effect of Group, $F(1, 46) = 3.64$, $\eta_p^2 = .09$, $p = .06$, as well as the Group × Condition interaction, $F(1, 46) = 2.43$, $\eta_p^2 = .03$, $p = .28$, were not significant.

Results for the parameter *sigma* demonstrated a significant main effect of Condition (or interference), $F(1, 46) = 16.18$, $\eta_p^2 = .29$, $p < .001$. Higher values were found for incongruent than for neutral stimuli in the parameter representing the standard deviation for the normal component of the distribution. This indicates overall larger variability for RTs associated with incongruent stimuli as compared to RTs associated with neutral stimuli. The main effect of Group and the Group × Condition interaction were not significant (for both, $F < 1$).

In contrast, as concerns the *tau* parameter, results evidenced a significant main effect of Group, $F(1, 46) = 4.98$, $\eta_p^2 = .11$, $p < .05$, which indicates higher values in the *tau* parameter representing the mean and standard deviation for the ex-Gaussian component of the distribution for children with ADHD than for TDC (see Figure 3). This means that, as compared to TDC, children with ADHD produced more variable responses specifically in the longer tail of the RT distribution, suggesting a higher frequency of long RTs. The main effect of Condition and the Group × Condition interaction were not significant, respectively, $F(1, 46) = 2.26$, $\eta_p^2 = .03$, $p = .14$, and $F(1, 46) = 2.31$, $\eta_p^2 = .03$, $p = .14$.

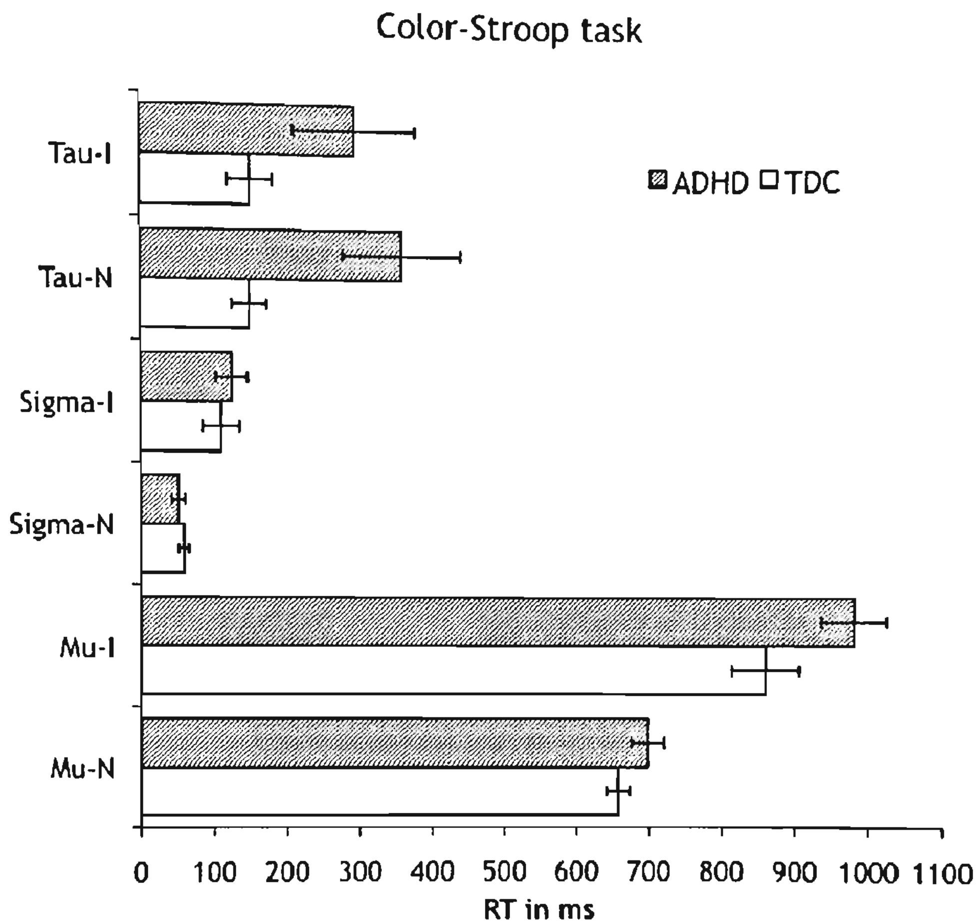

Figure 3 Color-Stroop interference task: Ex-Gaussian parameters from individual RT distributions for children with ADHD and typically developing children. Error bars represent one standard error.
Note. TDC: typically developing children; Mu: mean of the normal component of the individual RT distribution; Sigma: standard deviation of the normal component of the individual RT distribution; Tau: the mean and standard deviation of the exponential component of the RT distribution; I: incongruent stimuli; N: neutral stimuli. Error bars represent one standard error.

SRT Task

The one-way ANOVA conducted to investigate group differences on mean RTs did not show any significant effect ($F < 1$), which indicated that children with ADHD reacted equally fast to the stimuli as compared to TDC (see Table 1).

IIV Traditional Indices

The main effect of Group was significant for ISD, $F(1, 47) = 5.10$, $\eta_p^2 = .10$, $p < .05$, showing that children with ADHD were more variable in their responses than were TDC in the SRT task.

Additionally, the main effect of Group was significant for both fast-ISD, $F(1, 47) = 4.60$, $\eta_p^2 = .09$, $p < .05$, and slow-ISD, $F(1, 47) =. 4.1$, $\eta_p^2 = .08$, $p < .05$, indicating that children with ADHD were globally more variable in their responses (see Figure 4).

The main effect of Group was also significant for ICV, $F(1, 47) = 9.70$, $\eta_p^2 = .18$, $p < .01$, which confirmed that children with ADHD were more variable in their responses than were TDC (see Table 1).

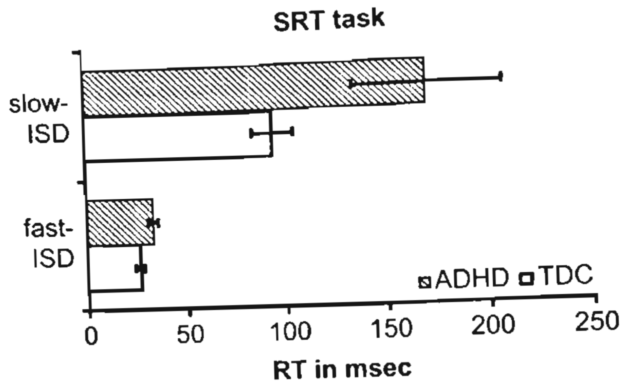

Figure 4 Simple reaction time task: Variability of performance for children with ADHD and typically developing children. Error bars represent one standard error.
Note. SRT task: Simple Reaction Time task, TDC: typically developing children; ISD: individual standard deviation; Fast-ISD: ISD of the lower quartile for RTs; Slow-ISD: ISD of the upper quartile for RTs. Error bars represent one standard error.

IIV: Ex-Gaussian Analyses

One-way ANOVAs were conducted on *mu, sigma,* and *tau* parameters in the SRT task. Results showed that the main effect of Group was not significant for the *tau* parameter, $F(1, 47) = 3.2$, $\eta_p^2 = .06$, $p = .08$, and for the *mu* and the *sigma* ones (for both, $F < 1$) (see Figure 5).

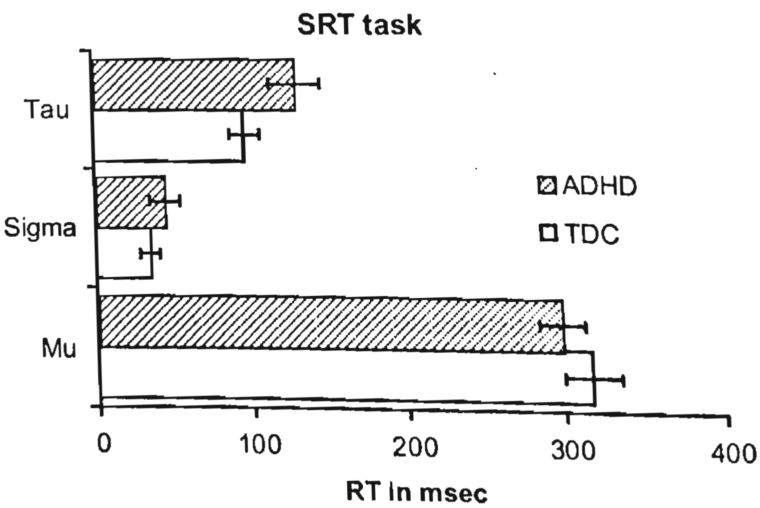

Figure 5 Simple reaction time task: Ex-Gaussian parameters from individual RT distributions for children with ADHD and typically developing children. Error bars represent one standard error.
Note. SRT task: Simple Reaction Time task; TDC: typically developing children; Mu: mean of the normal component of the individual RT distribution; Sigma: standard deviation of the normal component of the individual RT distribution; Tau: the mean and standard deviation of the exponential component of the RT distribution. Error bars represent one standard error.

DISCUSSION

Mixed results are reported in the literature with regard to the deficit of interference control in the Stroop-Color task in children with ADHD as compared to control populations (Homack & Riccio, 2004; Lansberger et al., 2007; Schwartz & Verhaeghen, 2008; Van Mourik et al., 2009). One of the aims of the present study was, therefore, to assess further interference control in children with ADHD and in typically developing children (TDC) in an item-by-item computerized Color-Stroop test. Such a task format allows for a finer grain of analysis than the often-used manual presentation in which items have to be grouped by condition. In particular, this format makes it possible to focus on correct responses only and, more importantly for our present purpose, to study intraindividual variability (IIV) or inconsistency. Study of IIV presents the interest to provide a more complete representation of the distribution of responses than a central tendency such as the mean or the median. Moreover, intraindividual variability has been associated with processing robustness and, when large, has been interpreted to reflect lapses in attentional control.

Our hypothesis, in line with some recent meta-analyses, was that children with ADHD should not be more sensitive to interference when mean performance levels in RTs are considered. In contrast, it was expected that they would exhibit an increased variability in behavioral performance due to dysfunctional regulatory processes producing larger fluctuations in attention or response control (e.g., Tannock, 2003).

To determine whether IIV is specific to a given task and its demands, a classical measure used in the study of IIV, a simple response time task was administered. It was indeed relevant, because the present study aims to select an independent measure of processing speed to better assess the generalizability of IIV in ADHD. Indeed, if increased IIV is a general characteristic of children with ADHD, as we claim, it should show larger fluctuations not only in an interference task such as the Color-Stroop task but also in a task that requires minimal attentional control, such as a simple response time (SRT) task. If, however, increased IIV is specifically due to a deficit in interference control, children with ADHD should exhibit larger fluctuations in the Color-Stroop task only and not in the SRT. It could also be the case, however, that IIV is a general characteristic but varies with the task demands. It would therefore be observed in both types of task but to a greater degree in the interference condition of the Color-Stroop task.

In line with our hypothesis, results showed a similar interference effect in children with ADHD and TDC, as long as the mean performance level was considered. This was true both for the raw RTs, when the incongruent condition was compared to the neutral control one (no Group by Condition interaction in the analysis of variance) and for the interference index, which controls for individual responses in baseline performance. Although contradictory with a number of studies in the field, these results are in line with other studies, which used a computerized version of the Color-Stroop (Alderson, Rapport, & Kofler, 2007; Christiansen & Oades, 2009; Jourdan Moser et al., 2009). Together with a meta-analysis by Van Mourik et al. (2009) and by Schwartz and Verhaeghen (2008), they indicate that group differences in the Color-Stroop interference effect are not as large as suggested by previous studies on ADHD.

It should be noted, however, that the task format may also have played an important role in accounting for these results. The Stroop interference effect, estimated on the basis of RTs, has been shown to be larger in the blocked card-like format than in the item-by-item version in young adults (Kindt, Bierman, & Brosschot, 1996; Salo, Henik, & Robertson, 2001) in typically developing children (Kindt, Bierman, & Brosschot, 1997) and in older adults (Ludwig, Borella, Tettamanti, & de Ribaupierre, 2010). The grouped format might introduce additional distracting cues, making it more difficult to resist interference. It would therefore be of interest for future studies to compare the control of interference in the two task formats in an ADHD sample to clarify such an issue.

In contrast with the mean level, IIV was larger in children with ADHD than in TDC in the Color-Stroop task: the classical IIV indexes, ISD and ICV, were indeed higher independently of the task condition (or type of stimulus). Analyses performed on the upper and lower quartiles of RTs (rather than on the entire range of RTs) showed that children with ADHD produced more frequent extremely long RTs but comparable fast responses suggesting that children with ADHD suffer from intermittent lapses of attention. They did not seem affected when producing fast responses, which would have attested to an impulsive mode of responses (e.g., anticipations) and to impairments in other aspects of attention. When the ex-Gaussian fitting procedure was used, which is more appropriate to describe the shape of individual RT distributions, children with ADHD were found to exhibit higher *tau* but comparable *mu* and *sigma* values, meaning that the distributions of RTs were more skewed in this group. Furthermore, it should be noted that, as was expected, incongruent stimuli were associated with higher levels of fluctuations than neutral stimuli (Spieler et al., 2000). This result indicates that incongruent stimuli indeed require increasing attentional control to meet the task constraints; this increase was, however, similar for both groups (no interaction). Thus, IIV appears altogether larger in children with ADHD independent of the stimulus condition.

With respect to the SRT, group differences were not significant when mean RTs were considered. In contrast, children with ADHD displayed larger fluctuations than did TDC when classical indices of IIV in RTs were examined (ISD and ICV). Thus, a similar pattern of results was obtained in both the Color-Stroop and the SRT tasks, supporting the hypothesis of a deficit primarily in more basic and central information processing for children with ADHD (Castellanos et al., 2006).

Moreover, in the SRT task, ISDs were larger in children with ADHD than in TDC children for both the 25% slowest and the 25% fastest RTs, which points to an overall higher variability throughout the task. These results could indicate not only that children with ADHD have periodic lapses in attention but also that another mechanism may additionally contribute to increasing IIV, such as an impairment in response preparation as suggested by Vaurio et al. (2009). However, the ex-Gaussian analyses did not reveal significant differences between groups in the SRT task and, as such, do not provide sufficiently strong evidence to definitely support this interpretation of the data.

Of course, we have to acknowledge that the clinical sample size was relatively small. Moreover, we did not investigate ADHD subtypes in the present work. Future studies should thus assess whether IIV interference control is influenced by the ADHD comorbidity, and whether the present results are replicated and can be generalized with other clinical samples. For example, our ADHD group also failed in some executive tasks, and because this failure is not present in all children with ADHD (Willcutt et al., 2005), our group could be particularly impaired. Finally, future studies should also consider assessing reading ability with direct and standardized measures rather than only relying on teachers' ratings.

It is noteworthy that our results are in line with other studies, in particular those using an item-by-item presentation and focusing on the mean performance level in the Color-Stroop task (Christiansen & Oades, 2009; Schwartz & Verhaeghen, 2008; Van Mourik et al., 2009) or on IIV in ADHD (e.g., Castellanos & Tannock, 2002; Williams et al., 2007).

In sum, findings on both mean RTs and IIV clearly do not converge with theories suggesting the existence of a specific deficit, in children with ADHD, in the control of interference in the Color-Stroop test. Interference control may, thus, be a less fundamental characteristic of the disorder than previous empirical work led researchers to believe. Nonetheless, the present data are consistent with difficulties involving a self-regulatory deficit or a failure to allocate adequate effort to meet task demands in children with ADHD, as suggested by Douglas (1999); this deficit leads to some extent to the occurrence of a higher number of attentional lapses during the course of information processing, as shown by IIV indices (Douglas, 1999). Even though Douglas argues, in contrast with the present study, that response inhibition is a fundamental characteristic of children with ADHD, the author also suggests that a broad pattern of variability in performance across a wide range of tasks reflects this dysregulation in ADHD. Our findings provide strong and additional support for considering larger IIV in RTs as a cornerstone in the determination of the cognitive profile of ADHD (Castellanos et al., 2006). Together with other researchers (see Castellanos et al., 2006; Sergeant et al., 2002), we also claim that altered performance in inhibitory tasks, and in particular when interference control is considered, is not due to inhibitory processes only. A complementary interpretation could be in terms of a deficit in processing robustness, which could be associated with neural information-processing fidelity (Li et al., 2004) and linked to the dysfunctions of fronto-striatal-cerebellar circuits, which are responsible for most of the disturbed sensorimotor integration and altered dopaminergic modulation (Castellanos & Tannock, 2002; Krain & Castellanos, 2006) that characterize ADHD.

To conclude, from a clinical point of view, the present results highlight the utility of using a computerized version of the Color-Stroop task, which allows estimating more accurately both the mean performance level and the variability in performance. Both aspects of individual performance should be considered more closely in future research of ADHD before interpreting results in favor of a deficient interference control.

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