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Children With ADHD Show Impairments in Multiple Stages of Information Processing in a Stroop Task: An ERP Study

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This study investigated the role of impaired inhibitory control as a factor underlying attention deficit hyperactivity disorder (ADHD). Children with ADHD and typically developing children completed

an animal Stroop task while electroencephalogram (EEG) was recorded. The lateralized readiness potential and event-related brain potentials associated with perceptual and conflict processing were analyzed. Children with ADHD were slower to give correct responses irrespective of congruency, and slower to prepare correct responses in the incongruent condition. This delay could result from enhanced effort allocation at earlier processing stages, indicated by differences in P1, N1, and conflict sustained potential. Results suggest multiple deficits in information processing rather than a specific response inhibition impairment.

Attention deficit hyperactivity disorder (ADHD) is one of the most common child psychiatric disorders, with a prevalence rate of 5–10% in school-age children (American Psychiatric Association, 2000; Polanczyk, Willcutt, Salum, Kieling, & Rohde, 2014). Accumulating evidence indicates that an impairment in executive functions (EFs) could serve as a neuro-cognitive basis of the disorder (e.g., Nigg, Willcutt, Doyle, & Sonuga-Barke, 2005). However, previous findings also suggest that only 35–50% of children with ADHD have EF deficits (Nigg et al., 2005) and the symptom profile in ADHD is highly heterogeneous (Sjöwall, Roth, Lindqvist, & Thorell, 2013). Dysfunctions in other sensory and cognitive processes, for example, in perceptual encoding (Steger, Imhof, Steinhausen, & Brandeis, 2000) and motor preparation (Banaschewski et al., 2008) have also been documented in children with ADHD. The present study aimed to further investigate the existence and nature of potential impairments in inhibitory control—one component of EFs—and in other stages of information processing using event-related brain potentials (ERPs).

Inhibitory control is the ability to successfully respond to a task-relevant dimension while inhibiting inappropriate automatic responses or suppressing interference due to a task-irrelevant dimension (Brydges et al., 2012). There are at least two distinguishable processes that contribute to inhibitory control: interference suppression or stimulus interference control, and response inhibition (Bunge, Dudukovic, Thomason, Vaidya, & Gabrieli, 2002). According to Barkley's (1997) model of ADHD, dysfunction in inhibitory control leads to a secondary disruption of other EF components in ADHD. It is not clear, however, to what extent impaired inhibitory control underlies ADHD, and whether interference control or response inhibition is disrupted, or both (Nigg, 2001; van Mourik, Oosterlaan, & Sergeant, 2005). It is likely that children with ADHD have more severe deficits in response inhibition than in interference suppression (Nigg, 2001), but the majority of previous studies tested only the former subprocess.

The ability to suppress a task-irrelevant dimension is crucial in experimental paradigms such as the Stroop task. In the Color-Word Stroop task, participants are required to name the ink color (task-relevant dimension) in which a color word (task-irrelevant dimension) is printed. If the ink color does not match the meaning of the word, performance deteriorates. However, interference control deficits in ADHD are not consistently found, based on performance in the Stroop task or Stroop-like tasks; the effect size of differences between children with ADHD and typically developing (TD) children strongly depends on the method of calculating the interference score (Lansbergen, Kenemans, & van Engeland, 2007; van Mourik et al., 2005). Nevertheless, other indices reflecting Stroop-like interference might better differentiate TD and ADHD children, such as parameters obtained from reaction time (RT) distributional analysis and various ERP measures investigated in the present study.

ERPs can provide insight into the temporal resolution of cognitive processes occurring before the overt behavioral response. Early ERP studies of childhood ADHD predominantly investigated auditory and visual attention systems, and found alterations at various stages of information processing (for a review, see Barry, Johnstone, & Clarke, 2003). Recently, this line of ERP research has focused on inhibitory control, performance monitoring, and ERP/energetic interactions (for a review, see Johnstone, Barry, & Clarke, 2013). These studies showed that ADHD and TD groups markedly differed in the ERP correlates of early orienting, inhibitory control, and error processing (Johnstone et al., 2013).

The two stimulus-locked ERP indices of inhibitory control usually obtained in Stroop tasks are the N450 and the conflict sustained potential (SP) (Liu, Yao, Wang, & Zhou, 2014). These components are thought to reflect separate stages of conflict processing: the detection of conflict, and the recruitment of cognitive control resources for later strategic adjustments (i.e., conflict resolution) (Lansbergen, van Hell, & Kenemans, 2007). The N450 occurring at 300–500 msec after stimulus onset is more negative for incongruent than for congruent trials and related to the activity of the anterior cingulate cortex (Szűcs & Soltész, 2012). The later SP beginning at approximately 500 msec is more positive following incongruent than congruent trials over the parietal cortex (Liu et al., 2014).

ERPs in childhood ADHD during a Stroop-like task have been scarcely obtained. The study of Miller, Kavcic, and Leslie (1996) used a modified version of the Color-Word Stroop task, which resembled a visual oddball paradigm. Larger P3b amplitudes with shorter latencies for targets in children with ADHD suggested that the clinical group invested greater attentional resources in the later stages of information processing to maintain a similar behavioral performance to TD children. Between-groups difference was also found in the early processing stages involving selective attention. Later, the results of van Mourik, Sergeant, Heslenfeld, Konig, and Oosterlaan (2011) showed that the congruency effect in the 450–550 msec time window was absent in children with ADHD in an auditory Stroop task, implying a poorer evaluation of conflict and allocation of attentional resources. This study also showed that children with ADHD used different neural sources to achieve comparable behavioral performance to that of TD children as reflected by the different scalp distribution of conflict SP in the two groups. However, the early processing of conflict was not impaired in children with ADHD. In the present study, we aim to contribute to these findings using a modified (animal) Stroop task in the visual modality.

ADHD-related alterations in the neural activity involved in inhibitory control have also been found using other tasks and electroencephalogram. In a Stop-signal task measuring response inhibition, the control N2 for Stop stimuli was reduced in children with ADHD, reflecting impaired response conflict monitoring (Pliszka, Liotti, & Woldorff, 2000). Using an oddball task, later cognitive ERP responses (P3) to task-relevant versus task-irrelevant stimuli were reduced in children with ADHD in comparison to TD children (Holcomb, Ackerman, & Dykman, 1985). This result might indicate that attentional resources allocated to the processing of target stimuli were not sufficient in ADHD.

As it was suggested by Sergeant (2005) that more attention should be paid to the interplay of computational processing stages, state factors (e.g., arousal), and EFs to understand the root cause of a possible inhibitory deficit in ADHD, in the present study we consider ADHD-related alterations in encoding and response organization, as well as conflict processing. Experiments that examined ERPs in the visual modality during sustained/selective attention tasks or EF tasks

are therefore relevant for the present study. Such studies report that the amplitude of ERP components related to the early processing of visual stimuli (the occipital P1 and N1 or N2) is usually reduced in ADHD (see Barry et al., 2003; Satterfield, Schell, & Nicholas, 1994; Steger et al., 2000). Further, analysis of the occipital N2 component indicated that children with ADHD do not process task-relevant and task-irrelevant (attended vs. nonattended and target vs. non-target) stimuli differently in an oddball task, while TD children do (Satterfield et al., 1994). Similarly, the amplitude of P1 was unaffected by cue validity in children with ADHD during an attention-shifting paradigm, while it was in TD children (Perchet, Revol, Fournieret, Mauguière, & Garcia-Larrea, 2001). One exception to this apparent “insensitivity” of children with ADHD was reported by Robaey, Breton, Dugas, and Renault (1992), who found a larger parieto-occipital N250 during classification and seriation oddball tasks in the ADHD group than the TD group. However, when reading was involved in one of the classification tasks, the N250 amplitude was attenuated in the ADHD group as compared to the TD group, which, again, might suggest poorer adaptation to task requirements (Robaey et al., 1992).

Previous research has also suggested motor functions are impaired in ADHD (e.g., Sergeant, 2005). However, movement-related potentials and response preparation processes are less studied. Most studies in this area investigated the contingent negative variation (CNV) (e.g., Banaschewski et al., 2008), and usually demonstrated that this component was decreased in children with ADHD compared to control participants. However, contradictory results also emerged. Early CNV processes were larger in children with ADHD when contingent rewards were provided than when noncontingent rewards were provided, whereas the reward-related effect was not present in the TD group (Newton, Oglesby, Ackerman, & Dykman, 1994). Further, Pliszka et al. (2000) concluded that covert orienting processes are impaired in participants with ADHD, because their preparatory slow positive wave did not differ between failed and successful Stop trials. In order to specifically evaluate motor preparation and whether it is impaired in ADHD, we measured the lateralized readiness potential (LRP).

The LRP is an index of selective motor preparation; therefore it is useful for studying motor processes in real time. This component summarizes the electrical potential differences of electrodes placed over the motor cortex contra- and ipsilateral to the response hand in a single measure (Coles, 1989). By calculating the LRP, an incorrect response preparation (a positive-going deviation) followed by a correct response preparation (a negative-going deviation) can be detected in an incongruent (conflicting) experimental condition (Szűcs, Soltész, Bryce, & Whitebread, 2009). According to the arguments of Bryce et al. (2011, p. 682), the amplitude and latency of the initial incorrect response preparation can be considered to be indices of interference suppression, while the transition from incorrect to correct activation in the incongruent condition reflects the later response inhibition process. Such incorrect response preparation in an incongruent condition of an animal Stroop task has been found in TD children aged 5–8 years using the LRP (Bryce et al., 2011; Szűcs et al., 2009). Accordingly, the animal Stroop task is considered suitable to investigate impairments in both stages of inhibitory control in ADHD. The advantage of using a single task to measure each of these processes is that the extent of each impairment can be more reliably compared. Steger et al. (2000) concurrently investigated all the stages of information processing in one experimental paradigm, and a weaker response preparation was found in ADHD boys as indicated by the LRP. However, the study did not investigate latent incorrect response preparation, and a subsequent correct response preparation, which we aimed to analyze here.

To the best of our knowledge, no studies have tested motor preparation in a Stroop paradigm in children with ADHD to date, and following the whole perceptual-motor processing chain by means of ERPs is still infrequent in this field. Hence, the aim of the present study was to compare inhibitory control performance of children with ADHD and their matched TD peers in terms of behavioral measures and ERPs during a Stroop task. By tracking the LRP in an incongruent condition we intended to separately measure two processes that contribute to inhibitory control. In addition, we aimed to identify possible ERP deficits in ADHD at other stages of information processing such as perceptual encoding.

Although previous findings are inconclusive about the impairment of the two processes of inhibitory control, we hypothesized that children with ADHD have pronounced deficits in response inhibition, but not in interference suppression. Therefore, we expected enhanced and delayed secondary correct response preparation (negative-going LRP) for incongruent stimuli in ADHD. ERP components related to different stages of visual processing and attentional selection (the occipital P1 and N1) were investigated to check whether both groups could process the stimuli similarly. We predicted that the different processing of congruent and incongruent stimuli would be present only in the TD group. Also, these components were expected to be smaller in children with ADHD. According to previous Stroop findings, we expected more negative N450 and more positive conflict SP for incongruent than congruent stimuli in both groups, and we assumed that these amplitude enhancements would be reduced in ADHD children due to poorer conflict processing.

METHOD

Participants

Thirty-two children with ADHD (9–12.5 years) from the local child psychiatry hospital were invited to participate in the present study. Only those children who had been diagnosed with ADHD by a licensed clinical psychologist and a board-certified child psychiatrist according to the DSM-IV-TR (American Psychiatric Association, 2000) criteria were included in the sample (all ADHD-C subtype). The diagnosis of other co-morbid developmental psychiatric disorders (autism spectrum disorder, obsessive-compulsive disorder, specific language impairment, learning disorder, major depression) was denoted as an exclusion criterion in advance. However, two children in the final sample met the criteria for persistent depressive disorder, and one was also diagnosed with oppositional defiant disorder. Twenty-seven TD children from the same age range were recruited from nine primary schools.

Two children (one from each group) were excluded because of technical problems. After artifact rejection (see section EEG Recording and Pre-Processing), and following the selection of those from both samples who fulfilled the matching criteria (the groups were matched on gender and school grade), 14 children remained in each group (13 boys and 1 girl, see Table 1). Children with ADHD were in the age range (years:months) of 10:02 to 12:04 ($M = 11:02$), and children in the TD group were between 9:04 and 11:08 ($M = 10:08$). The two groups did not differ in age ($p = .122$, see also Table 1). All participants had normal or corrected-to-normal vision. None of them reported previous traumatic head injury, a sensory impairment or a history

TABLE 1
Descriptive Characteristics of Participants, and Basic Between-Group Differences in Rating Scale, Neuropsychological, and IQ Measures

	TD (<i>n</i> = 14)		ADHD (<i>n</i> = 14)		<i>t</i> / χ^2 / <i>Z</i>	<i>p</i>	<i>r</i>
	<i>M</i>	<i>SD</i>	<i>M</i>	<i>SD</i>			
Age [months]	128.8	8.3	133.9	8.8	-1.60	.122	.30
Left/Right/Mixed handed ^a	1/13/0		3/10/1		2.39	.326	-
Color-Word Stroop task: difference score for RT [msec] ^b	541	171	534	197	0.09	.928	.02
Phoneme Deletion accuracy [<i>T</i> -scores]	53.71	9.93	39.57	6.26	4.51	< .001	.66
Phoneme Deletion speed [<i>T</i> -scores]	52.29	6.83	41.14	8.56	3.81	.001	.60
Average RAN [<i>T</i> -scores] ^c	53.67	6.62	45.79	10.18	2.43	.022	.43
Corsi Blocks [<i>T</i> -scores]	53.07	9.75	45.21	7.52	2.39	.024	.42
WISC-IV Block Design [scaled score]	10.79	2.49	10.21	2.52	0.60	.551	.12
WISC-IV Similarities [scaled score]	12.71	2.13	10.50	3.41	2.06	.050	.37
WISC-IV Digit Span ^{d, e} [scaled score]	10.43	2.56	8.29	1.98	-2.27	.024	-.43
WISC-IV Vocabulary [scaled score]	13.50	1.61	11.93	2.53	1.97	.060	.36
SDQ Hyperactivity/Inattention [raw score] ^e	4.21	3.14	8.14	2.03	-3.14	.002	-.59
SDQ Total Difficulties Score [raw score]	10.07	6.44	22.64	7.08	-4.92	< .001	.69
CBCL Attention Problems [<i>T</i> -score] ^e	56.64	6.50	73.93	9.05	-3.76	< .001	-.71
CBCL Total Problems [<i>T</i> -scores]	56.92	8.56	79.85	10.76	-6.01	< .001	.76

^aIn case of cells with an expected count less than five, exact significance tests were selected for Pearson's chi-square; ^btwo children with attention deficit hyperactivity disorder (ADHD) had to be excluded due to problems in understanding the instructions and stammering, therefore *n* = 12 in both groups (their matched typically developing [TD] pairs were also excluded); the difference score of average reaction times measured in color-word and color conditions was used as an indicator of interference (Lansbergen et al., 2007); ^cthe mean performance of letter, number, and object conditions; ^dcollapsed measure across Forward and Backward subtests; ^ein case of violating the assumption of normality, Mann-Whitney *U* tests were performed, the *r* effect size indicator is calculated as Z/\sqrt{N} . *p*-values below .050 are **boldfaced**.

of any neurological condition (e.g., epileptic seizures, periods of unconsciousness). All analysis was performed after artifact rejection in both groups.

Our study was approved by the institutional review board of the local university and was conducted in accordance with the Declaration of Helsinki. Parents of children provided informed consent for the administration of neuropsychological tests (see section Neuropsychological Measures) and the EEG experiment (see section Stimuli and Procedure). Children gave an oral agreement before beginning each session.

Stimuli and Procedure

Participants performed the same animal Stroop task as in Bryce et al. (2011). Stimuli were colored pictures of two animals differing in real-life size simultaneously presented on a computer screen. One animal image was physically larger than the other, and the task was to select which animal was larger in real-life, regardless of the physical size on the screen. The image of the "physically smaller" animals had an average width of 3.53° and height of 2.88° in visual angle, while the "physically larger" animals had an average width of 8.22° and height of

6.71° (exact values varied according to the animal, e.g., the giraffe image was narrow but tall). If the animal displayed on the left side was larger in real-life, children had to press the left response key, if the animal displayed on the right side was larger in real-life, children had to press the right response key (“A” or “L” keys on a keyboard, respectively). Speed and accuracy were emphasized equally. In the congruent condition, the larger in real-life animal (e.g., giraffe) was displayed physically larger on the screen than the smaller in real-life animal (e.g., ladybird). In the incongruent condition, the larger in real-life animal was physically smaller on the screen than the smaller in real-life animal.

Each trial consisted of four events. The animal images were presented until the participant responded, or for a maximum of 4,000 msec. After that, there was a delay of 1,000 msec (a blank screen displayed), and then an image of an eye was presented for 500 msec to indicate that the participant should blink their eyes if necessary. After another delay of 1,000 msec (a blank screen), the next trial was presented. The experiment consisted of 6 blocks of 48 trials, and a practice block with 12 trials. Altogether 144 congruent, and 144 incongruent animal pairings were presented on a 17” LCD screen using Presentation software (v. 14.4 and 16.3; Neurobehavioral Systems) running on a personal computer with Windows XP.

In a first testing session, a battery of eight neuropsychological tests was administered (see section Neuropsychological Measures). Additionally, all children’s parents completed the Hungarian version of the Strengths and Difficulties Questionnaire (SDQ; Birkás, Lakatos, Tóth, & Gervai, 2008; Goodman, 1997), and the Hungarian version of the Child Behavior Checklist (CBCL; Achenbach, 1991; Vargha, 1998). EEG data were collected in a second testing session that lasted approximately 45 minutes. Children with ADHD taking methylphenidate discontinued their medication for at least 24 hours to allow a complete washout prior to test administration and visiting the EEG laboratory.

Neuropsychological Measures

Eight tasks were administered to investigate short-term memory, interference suppression, basic reading skills, and general IQ as all of these cognitive domains are compromised to some degree in ADHD (Willcutt et al., 2010). We used three subtests of the 3DM-H (Dyslexia Differential Diagnosis Maastricht; Blomert & Vaessen, 2009; Hungarian version; Tóth, Csépe, Vaessen, & Blomert, 2014): Phoneme Deletion, which measures phonological awareness, Rapid Automatized Naming (RAN), which examines the ability to rapidly name over-learned items (e.g., letters), and Corsi Blocks, which reflects the functions of visuospatial short-term memory. The Color-Word Stroop task (a computerized version of the Golden Stroop Test, see Golden, 1978) was also administered in order to investigate interference suppression. Children completed Block Design, Similarities, Digit Span (Forward and Backward), and Vocabulary subtests from the Hungarian version of the Wechsler Intelligence Scale for Children–Fourth Edition (WISC–IV)(Nagyné Réz, Lányiné Engelmayer, Kuncz, Mészáros, & Mlinkó, 2008; Wechsler, 2003).

Behavioral Data Analysis

In the animal Stroop task, fast impulsive responses with RTs shorter than 200 msec were eliminated, and we did not analyze omission errors (misses or responses longer than

4,000 msec). Accuracy was defined as the percentage of correct responses. Only correctly responded trials were included in RT analysis.

As visual inspection indicated that the raw RT distributions within each congruency condition and group were not Gaussian in shape, we additionally fitted exponential-Gaussian (ex-Gaussian) distributions to the RT data. Previous studies suggest that participants with ADHD have qualitatively different RT distribution than typical participants, which could be characterized by ex-Gaussian distribution parameter values (Leth-Steensen, Elbaz, & Douglas, 2000). Ex-Gaussian distribution provides three parameters: mu (μ) and sigma (σ), which correspond to the mean and standard deviation of the Gaussian component of the RT distribution, and tau (τ) which indicates the positive skew or the mean of the exponential component. These parameters were estimated in each condition and group separately using the *simple egfit* function in MATLAB provided by Lacouture and Cousineau (2008).

Accuracy, RT, and the three ex-Gaussian parameters were entered into two-way mixed ANOVAs with Congruency (congruent, incongruent) as a within-subjects factor and Group (TD, ADHD) as a between-subjects factor. In all ANOVAs performed on behavioral and physiological measures (see section Other ERP Waves) partial eta squared (η_p^2) or r are reported as a measure of effect size. To control for Type I error, we used Bonferroni tests for pairwise comparisons.

EEG Recording and Pre-Processing

EEG activity was recorded using the Electrical Geodesics system (GES 300; Electrical Geodesics, Inc.) and Net Station 4.5.1 software. We used a 128-channel HydroCel Geodesic Sensor Net with saline electrolyte solution. Electrode impedance levels were kept below 50 k Ω . A sampling rate of 1,000 Hz was applied and Cz was used as a reference. A personal computer running Mac OS X collected the continuous EEG data.

Before offline analysis, spline interpolation of bad electrodes was performed if necessary. Zero–4 (mean: 0.71) channels per participant were interpolated in the TD group, and 0–3 (mean: 0.79) in the ADHD group. During pre-processing, the data was first band-pass filtered offline between 0.03–30 Hz (12 dB/oct), notch filtered at 50 Hz to remove additional electrical noise, and re-referenced to the average activity of all electrodes. Only correctly responded trials were included in the EEG analysis. Epochs extended from –100 to 1,000 msec relative to the presentation of the animal pair stimuli, and were baseline corrected based on the average activity from –100 to 0 msec. We applied an automatic artifact rejection algorithm implemented in Brain Vision Analyzer software (Brain Products GmbH) which was based on four criteria: the maximum gradient allowed for an epoch was 50 μ V/msec, we rejected those segments where the activity exceeded ± 150 μ V, the lowest activity allowed was 0.5 μ V, and the maximum absolute difference between the minimum and maximum voltages in an epoch was 200 μ V. Epochs containing artifacts at any of the electrode sites were rejected. A minimum of 19 artifact-free epochs were required in each condition (split by congruency and response hand) in order for a participant's data to be included. Of those children whose data remained in the analysis, the average of retained segments in the TD group was 40.6 (range of 23–65.5) and 38.5 (range of 20–63) in the congruent and incongruent condition, respectively; in the ADHD group it was 40.1 (range of 21.5 to 62.5) and 39.1 (range of 23.5 to 61.5). The average of retained segments in either condition did not differ across the groups (congruent: $t(26) = 0.09$, $p = .928$; incongruent: $t(26) = -0.11$, $p = .910$).

ERP Analysis

ERP Waves

We calculated the average activity of electrodes 65, 66, 69, 70 (left occipital pool), 83, 84, 89, 90 (right occipital pool), and of electrodes 71, 72, 75, 76 (parieto-occipital pool). Grand average ERP waveforms were calculated separately for each group and condition to determine the latency range of P1, N1, N450, and SP components.

We measured P1 and N1 components related to perceptual processing. According to the grand average ERP waveforms, the peak of P1 was at 134 msec (averaged for both groups and conditions) and the peak of N1 was at 194 msec (averaged for both groups and conditions) at the left and right occipital pools where these ERP components showed maximum amplitude. Therefore, P1 and N1 were determined at left and right occipital pools as the mean amplitude within the time interval 100–200 msec and 150–250 msec, respectively. We labeled P1 and N1 on the basis of their topography and serial order. The N1 appearing here could have also been labeled as N2 according to the timing of the component (see Bryce et al., 2011; Robaey et al., 1992; Satterfield et al., 1994; Szűcs et al., 2009). However, this component was only preceded by a large P1; therefore, we labeled it as N1.

N450 and SP, the two components related to conflict processing, were quantified and labeled according to previous Stroop studies (Lansbergen et al., 2007; Liu et al., 2014) and the grand average ERP waveforms. Both components showed maximum amplitude at the parieto-occipital pool and the peak of N450 was at 403 msec (averaged for both groups and conditions). The N450 and SP were measured at the parieto-occipital pool as the mean amplitude within 350–450 msec and 450–700 msec, respectively. A similar time window was chosen for SP in the study of Liu et al. (2014).

The mean amplitude of P1 and N1 were then entered into three-way mixed ANOVAs with Congruency (congruent, incongruent) and Hemisphere (left, right) as within-subjects factors, and Group (TD, ADHD) as a between-subjects factor. The mean amplitude of N450 and SP were analyzed by performing a Congruency (2) * Group (2) mixed ANOVA.

LRP Measures

The LRP was calculated according to the equation of Coles (1989):

$$\left[(ER - EL)_{\text{left hand response}} + (EL - ER)_{\text{right hand response}} \right] / 2$$

where EL is the brain potential recorded from an electrode over the left motor cortex, and ER is the brain potential recorded over the right motor cortex. In our study, a cluster of electrodes surrounding C3 and C4 positions were selected to improve the signal-to-noise ratio. EL was calculated as an average of five electrodes close to the C3 position (electrodes 36, 29, 42, 35, 41), and ER was calculated as an average of five electrodes close to the C4 position (electrodes 104, 111, 93, 110, 103). In order to further enhance the signal-to-noise ratio, each participant's raw LRP in each condition was smoothed by a 150 msec moving average window (Bryce et al., 2011, p. 675). Point-by-point one-sample *t*-tests against zero were run on these congruent and incongruent LRP waveforms in each group separately to confirm whether they showed any

significant deviation from zero. This was done to confirm whether any correct or incorrect response activations were reflected in the LRP (see next paragraph). A deviation from zero was regarded as significant if the p -value was less than .050 for more than 20 msec.

According to the traditional computation above, a negative deviation in the LRP waveform reflects preferential activation of the correct response, whereas a positive deviation reflects preferential activation of the incorrect response (Coles, 1989). Consequently, in the congruent condition we expected only a negative LRP deviation reflecting correct response preparation, and in the incongruent condition we expected an initial positive LRP deviation reflecting incorrect response preparation, followed by a correct response preparation as in Bryce et al. (2011). Because of the absence of any significant negative deviation in the congruent condition, and the absence of an initial positive deviation in the incongruent condition (see section LRPs in the Results), we considered only the secondary deviation of the LRP in the incongruent condition (i.e., correct response preparation). Before obtaining peak measures, the smoothed incongruent LRP was jack-knifed (Ulrich & Miller, 2001). The peak was identified as the most negative point between 300 and 900 msec in each participant's smoothed and jack-knifed LRP waveform. One-way between-subjects ANOVAs were run on the peak amplitude and latency of the jack-knifed negative-going LRP in the incongruent condition with Group (TD, ADHD) as the only factor. In these ANOVAs, the computed F -values were corrected (referred as F_c) according to the formula established by Ulrich and Miller (2001).

EEG and behavioral data was analyzed with Brain Vision Analyzer software, MATLAB 7.11.0 (R2010b), STATISTICA 12, and IBM SPSS Statistics 19.

RESULTS

A summary of results obtained from statistical analyses of RT and ERP data is presented in Table 2. We report these results in detail below.

Neuropsychological and IQ Data: Sample Characteristics

Basic between-group differences in the main neuropsychological and IQ measures can be found in Table 1. Children with ADHD showed higher scores on the SDQ Hyperactivity/Inattention scale and the CBCL Attention Problems scale as compared to the TD group. Moreover, the ADHD group had higher ratings on the SDQ Total Difficulties Score and the CBCL Total Problems.

Children with ADHD showed marked impairments in phonological awareness (Phoneme Deletion) and rapid naming skills (average RAN) compared to TDs. Additional between-group differences emerged in short-term memory (WISC-IV Digit Span, Corsi Blocks) and in abstract reasoning (WISC-IV Similarities), indicating poorer performance in the ADHD group. The Color-Word Stroop task could not reliably differentiate the two groups.

Behavioral Results

The analysis of accuracy in the animal Stroop task yielded only one significant result—incongruent trials were responded to less accurately than congruent trials (correct %: 92.7% vs. 97.8%), $F(1, 26) = 32.38, p < .001, \eta_p^2 = .55$. Children with ADHD and TD children did not differ in accuracy.

TABLE 2
Summary of Results From ANOVAs Performed on Relevant RT and ERP Measures

	Group		Congruency		Congruency * Group		Hemisphere * Group		Hemisphere * Congruency		Hemisphere * Congruency * Group	
	F	p	F	p	F	p	F	p	F	p	F	p
RT	7.14	.013	82.70	< .001	0.02	.901	—	—	—	—	—	—
Accuracy	0.01	.941	32.38	< .001	0.05	.828	—	—	—	—	—	—
μ	3.16	.087	44.18	< .001	0.04	.852	—	—	—	—	—	—
σ	3.52	.072	4.25	.049	0.03	.875	—	—	—	—	—	—
τ	6.84	.015	0.83	.371	0.01	.913	—	—	—	—	—	—
P1	0.05	.827	3.36	.078	6.13	.020	0.39	.539	0.30	.591	3.58	.070
N1	0.43	.516	5.96	.022	7.23	.012	0.07	.794	0.72	.403	1.69	.206
N450	0.02	.901	0.19	.669	6.21	.019	—	—	—	—	—	—
SP	0.00	.976	17.27	< .001	5.58	.026	—	—	—	—	—	—
LRP (lat)	5.84	.023	—	—	—	—	—	—	—	—	—	—
LRP (A)	2.58	.121	—	—	—	—	—	—	—	—	—	—

Note. μ and σ correspond to the mean and standard deviation of the Gaussian component of the RT distribution, and τ indicates the mean of the exponential component. For P1, N1, N450, and SP mean amplitudes were calculated. For P1 and N1 measures the main effects of Hemisphere are not included, only the interaction effects involving Hemisphere as a factor. *F*-values that correspond to lateralized readiness potential (LRP) latency and amplitude measures were corrected because of jack-knifing. A = amplitude; lat = latency; — = the effect is not applicable in the given analysis. *p*-values below .050 are **boldfaced**.

Mean RTs showed that children with ADHD responded 196 msec slower than TD children (1,221 msec vs. 1,025 msec), $F(1, 26) = 7.14, p = .013, \eta_p^2 = .22$. Incongruent trials were responded to 126 msec slower than congruent trials (1,186 msec vs. 1,060 msec), $F(1, 26) = 82.70, p < .001, \eta_p^2 = .76$. We did not observe a significant Congruency * Group interaction effect.

Shapiro-Wilk tests showed that RTs deviated significantly from the normal distribution in both groups in both conditions (for all tests: $W \leq .875, p < .001$). When ANOVAs were performed on ex-Gaussian parameters, the mean RT (μ) in the incongruent condition was higher than in the congruent condition (783 msec vs. 681 msec), $F(1, 26) = 44.18, p < .001, \eta_p^2 = .63$, and the within-trial variability (σ) was greater (115 msec vs. 98 msec), $F(1, 26) = 4.25, p = .049, \eta_p^2 = .14$. Children with ADHD had a larger number of RTs in the exponential upper tail of the distribution (τ of 448 msec vs. 329 msec), $F(1, 26) = 6.84, p = .015, \eta_p^2 = .21$. The Congruency * Group interactions were not significant on any parameter.

ERPs

P1 and N1

Grand average ERP waveforms split by congruency for each group are presented in Figure 1. There was a significant Congruency * Group interaction on the mean amplitude of P1, $F(1, 26) = 6.13, p = .020, \eta_p^2 = .19$. Pairwise tests indicated that in the ADHD group, the P1 was larger in the incongruent than in the congruent condition (14.26 μ V vs. 12.76 μ V, $t(13) = -2.68$,

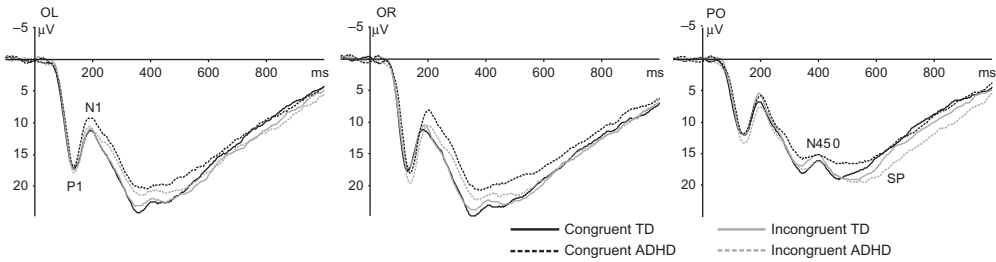


FIGURE 1 Grand average event-related potential (ERP) waveforms associated with perceptual processing (P1 and N1) and conflict processing (N450 and SP) split by congruency for each group at left and right occipital electrode pools (OL and OR) and at parieto-occipital electrode pool (PO), respectively. Please note, negativity is plotted upwards here.

$p = .032$, $r = .60$). This within-group difference was not present in the TD group, and the two groups did not differ from one another (for all other tests: $|t| \leq 0.70$, $p \geq .999$, $r \leq .15$).

The N1 was $0.85 \mu\text{V}$ smaller (more positive) in incongruent than congruent trials ($12.71 \mu\text{V}$ vs. $11.87 \mu\text{V}$), $F(1, 26) = 5.96$, $p = .022$, $\eta_p^2 = .19$, and there was a significant Congruency * Group interaction, $F(1, 26) = 7.23$, $p = .012$, $\eta_p^2 = .22$. Pairwise tests demonstrated that the N1 was attenuated (more positive) in the ADHD group in the incongruent condition as compared to the congruent condition ($12.54 \mu\text{V}$ vs. $10.76 \mu\text{V}$, $t(13) = -3.09$, $p = .007$, $r = .65$). A similar difference did not appear in the TD group, and the two groups did not differ from one another (for all other tests: $|t| \leq 1.11$, $p \geq .999$, $r \leq .21$).

N450

Only the Congruency * Group interaction was significant on the mean amplitude of N450, $F(1, 26) = 6.21$, $p = .019$, $\eta_p^2 = .19$, but none of the pairwise tests indicated further significant differences (for all tests: $|t| \leq 1.86$, $p \geq .293$, $r \leq .46$). In the TD group, the mean value was $17.09 \mu\text{V}$ in the congruent condition and $16.11 \mu\text{V}$ in the incongruent condition, while in the ADHD group the mean value was $15.55 \mu\text{V}$ in the congruent condition and $16.94 \mu\text{V}$ in the incongruent condition.

SP

The mean amplitude of the SP was $1.87 \mu\text{V}$ larger in the incongruent than in the congruent condition ($17.67 \mu\text{V}$ vs. $15.80 \mu\text{V}$), $F(1, 26) = 17.27$, $p < .001$, $\eta_p^2 = .40$. There was also a significant Congruency * Group interaction, $F(1, 26) = 5.58$, $p = .026$, $\eta_p^2 = .18$. Pairwise tests showed that the SP was larger in the incongruent condition than in the congruent condition *only* in children with ADHD ($18.24 \mu\text{V}$ vs. $15.31 \mu\text{V}$, $t(13) = -4.16$, $p = .001$, $r = .76$). All other pairwise tests were not significant ($|t| \leq 1.442$, $p \geq .999$, $r \leq .37$).

LRPs

We did not find a significant negative deviation from baseline (correct response preparation) in the congruent LRP in either group. Further, no significant positive deviation from baseline (incorrect response preparation) was found in the incongruent condition at the early phase. However, a robust correct response activation was present in the later phase in the incongruent condition in both groups. This negative deviation was between 464–762 msec in the TD group, and between 470–944 msec in the ADHD group (see Figure 2). One-way ANOVAs on the peak amplitude and latency of the smoothed and jack-knifed incongruent LRP revealed a between-group difference in the peak latency of this correct response activation, $F_c(1, 26) = 5.84$, $p = .023$, $r = .43$. This indicated that children with ADHD initiated a correct response in the incongruent condition 41 msec later than TDs (623 msec vs. 582 msec).

DISCUSSION

We examined whether impairments in the two processes of inhibitory control are present in children with ADHD. We also investigated whether visual processing of stimuli and the separate stages of conflict processing are different in each group. Accordingly, we analyzed RT and accuracy data, the LRP and other ERPs time-locked to the presentation of the congruent/incongruent stimuli in the animal Stroop task.

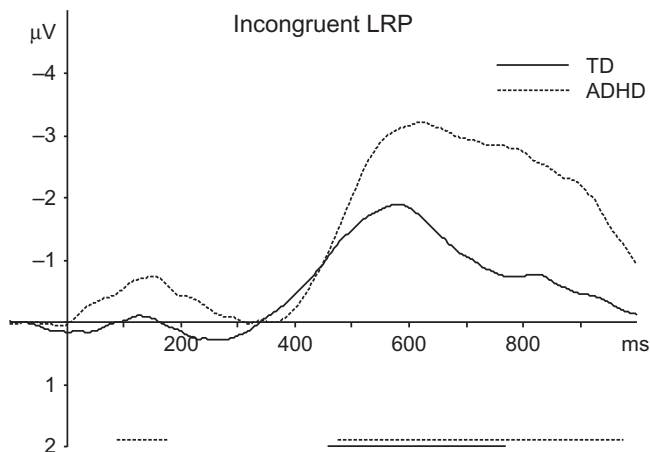


FIGURE 2 Grand average of the smoothed lateralized readiness potential (LRP) in the incongruent condition for typically developing (TD) and attention deficit hyperactivity disorder (ADHD) groups. Horizontal lines indicate time points in which the LRP deviated significantly from zero. Please note, negativity is plotted upwards here.

Behavioral Findings

The neuropsychological test results validated the clinical diagnoses of ADHD, and indicated that ADHD affects various aspects of information processing. The clearest between-group differences emerged in basic reading skills—phonological awareness and rapid naming—which might support the proposition that various language-related impairments are among the symptoms of ADHD (Willcutt et al., 2010).

Further, in the animal Stroop task, children with ADHD were slower to give correct responses irrespective of congruency, but there were no between-groups differences in accuracy. Slower responding is typical in children with ADHD, but the effect size of between-group differences in mean RTs varies greatly (Karalunas & Huang-Pollock, 2013). Our finding on accuracy contradicts some previous results (e.g., Karalunas & Huang-Pollock, 2013), but it is not without example (Banaschewski et al., 2008). The present results might suggest a speed–accuracy trade-off for children with ADHD, with slower responding allowing more accurate responses in all conditions. Children with ADHD also had more excessively long RTs shown by the higher τ values. Larger τ values are likely a consequence of attention lapses and greater trial-by-trial variability, which generally describes children with ADHD (e.g., Karalunas & Huang-Pollock, 2013; Leth-Steensen et al., 2000). Higher variability in performance may be due to a difficulty in allocating sufficient effort to maintain task performance (see also van Mourik et al., 2011), which is related to the suboptimal energetic regulation in ADHD (Sergeant, 2005).

The entire sample was slower and less accurate in the incongruent than in the congruent condition of the animal Stroop task, reflecting the standard Stroop effect. However, as in other studies (Miller et al., 1996; van Mourik et al., 2011), the Stroop effect was comparable across ADHD and TD groups (128 msec [ADHD] vs. 124 msec [TD]). Further, there were no group differences in performance on the Color-Word Stroop task. Therefore, our behavioral results do not entirely support the classical theory of Barkley (1997) about deficits in inhibitory subprocesses. Instead, we provide evidence for the notion that impaired inhibitory control is not obligatory in ADHD (Nigg et al., 2005).

LRP Findings

Unexpectedly, neither group showed correct response preparation in the congruent condition, nor an incorrect response preparation in the incongruent condition. These findings are in contrast to previous results obtained in the same task in younger TD children (Bryce et al., 2011; Szűcs et al., 2009). Movement artifacts in the whole sample might have obscured the assumed correct response preparation in the congruent LRP. In this study we used a keyboard as a response device, while in Bryce et al. (2011) participants gave their responses on specially designed response pads. However, even though the response pads used in the study of Szűcs et al. (2009) were different from those used in the study of Bryce et al. (2011), the LRPs were quite similar both in children and adult samples, suggesting the reliability of this component irrespective of response device.

Since we did not detect a positive deviation at all in the incongruent LRP, we are unable to comment on a possible impairment of interference suppression (the early stage of inhibitory control) in ADHD. The lack of this deviation could have originated from irrelevant noise. In accordance with the present findings, several previous studies of Szűcs and co-workers (e.g.,

Szűcs & Soltész, 2012) did not observe incorrect response preparation in the incongruent LRP in adults using a numerical Stroop task. It is also conceivable that the experienced conflict was lower or different in the animal Stroop task than in other Stroop tasks (see also Lansbergen et al., 2007; van Mourik et al., 2011). Further, poorer performance on incongruent trials (slower RT, lower accuracy) might reflect the contribution of cognitive processes other than inhibitory control (e.g., the activation of semantic memory, categorization or matching of physical and real-life sizes).

Correct response preparation was observed in both groups in the incongruent condition, and children with ADHD organized and initiated this correct response later than TD children. This is partly in line with previous findings about impaired preparatory processes in ADHD (Perchet et al., 2001; Pliszka et al., 2000); however, it is not possible to directly compare our results with these studies as the correct response preparation in the congruent condition was absent. Nevertheless, we hypothesized that inhibitory problems in ADHD occur at a later stage of information processing (i.e., response inhibition). It is possible that the delayed peak latency of the incongruent LRP originated from weaker response inhibition per se in the ADHD group, which was previously shown by ERPs (e.g., Pliszka et al., 2000). Alternatively, it might have resulted from more effortful information processing, which was apparent in ERPs related to perceptual processing and conflict processing. However, these two explanations are not necessarily mutually exclusive. This is further elaborated below.

ERPs Related to Perceptual Processing and Conflict Processing

In contrast to our expectation, we did not detect between-groups differences in ERPs related to visual processing (P1 and N1). However, the congruency effect was modulated by the clinical status of participants, as congruency affected the occipital P1 and N1 amplitudes *more* in the ADHD than the TD group. These unexpected within-groups differences in such early stages of processing deserve closer examination.

There was also evidence that congruency affected the N450 component, a measure of conflict detection, differently in each group. However, pairwise tests were inconclusive about differences between conditions and/or groups. In the animal Stroop task, congruency effects on the amplitude of ERPs between 280 and 420 msec have been previously shown in children aged 5–8 years as a negative deflection over the posterior electrodes sites (Szűcs et al., 2009). However, in the present study, this congruency effect more clearly appeared later in time, as the SP (considered to reflect conflict resolution). Interestingly, this congruency-related effect on SP amplitude appeared only in the ADHD group, which contradicts the findings of van Mourik et al. (2011) but corroborates the observed P1 and N1 findings. Therefore, children with ADHD might have used more resources to make the real-life size difference decisions and to resolve the conflict arising from the task-irrelevant stimulus dimension.

In our interpretation, the alteration of P1, N1, and SP amplitudes across conditions could be a consequence of larger effort investment by the ADHD group to resolve a conflict. This would be in line with the study of Miller et al. (1996), which suggested that children with ADHD invested more attentional resources in processing the task-relevant stimuli during the Stroop task. In support of this idea, van Mourik et al. (2011) emphasized that ADHD-related problems in conflict processing became evident at the stage of evaluating the conflict (P3) and at response selection (SP) without behavioral manifestations. Using tasks other than the

Stroop paradigm, less efficient processing of task relevance has also been observed at earlier (Perchet et al., 2001; Satterfield et al., 1994) and later processing stages (Holcomb et al., 1985) in children with ADHD. These findings corroborate the current evidence of weaker adaptation to task demands in this disorder. We also found support for previous ERP findings about the existence of impairments at multiple stages of information processing in ADHD during a Stroop task (cf. Miller et al., 1996). Further, the impaired early processing found in the current study and in the study of Miller et al. (1996) might be specific to Stroop tasks obtained in the visual modality as it was absent in an auditory Stroop task (van Mourik et al., 2011). Clearly, more studies are needed using the same Stroop paradigm in different modalities to support this hypothesis.

In sum, it is possible that the delayed peak latency of correct response preparation in the incongruent LRP in the ADHD group originated from the need to overcome a stronger distraction at an earlier phase of processing that started around 150 msec. The source of this distraction would have been the task-irrelevant conflicting dimension. By providing ERP evidence for altered visual processing in children with ADHD, we highlight an important aspect of behavior that has not been encompassed by the different models of heterogeneity related to the cognitive profile of ADHD (Nigg et al., 2005; Sjöwall et al., 2013). In addition, our ERP as well as behavioral findings support the regulatory models of ADHD, which suggest that impaired inhibitory control performance in ADHD could originate from the suboptimal regulation of state-related (e.g., the level of arousal, effort, and activation) and task-related factors (Johnstone & Galletta, 2013; Sergeant, 2005).

SUMMARY AND CONCLUSION

This study investigated the inhibitory control of children with ADHD and their TD peers, measured by an adapted Stroop task. We investigated all stages of information processing from encoding to motor preparation using various RT and ERP measures. At the behavioral level, both groups were equally successful at resolving response conflict, but children with ADHD were slower to give correct responses irrespective of congruency. The organization and initiation of this correct response tendency was delayed in children with ADHD. We propose that the delayed preparation of a correct response in the incongruent condition was the result of enhanced effort allocation at earlier phases of processing, such as perceptual processing and conflict resolution.

We suggest that impaired performance on various neuropsychological measures, higher overall RTs with more frequent attention lapses in the animal Stroop task, in conjunction with more effortful stimulus processing, conflict resolution, and response organization probably imply marked dysfunctions at multiple stages of information processing in children with ADHD. However, our results only partly support the hypothesis that children with ADHD have impaired response inhibition. Instead, we endorse the view that the cognitive profile of ADHD is highly heterogeneous and that multiple deficit models should be further pursued (Willcutt et al., 2010).

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Authors' contributions: A.K. and Á.T. performed EEG data acquisition, collected questionnaires, analyzed data, and wrote the article; D.B. and D.Sz. designed the experiment, assisted with data

analyses, and wrote the article; F.H. assisted with data analysis and wrote the article; P.N. provided clinical expertise in diagnosing and recruiting children with ADHD and wrote the article; V.Cs. wrote the article.

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