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Two sides of the same coin: ADHD affects reactive but not proactive inhibition in children

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ABSTRACT

Children with attention-deficit/hyperactivity disorder (ADHD) present a deficit in inhibitory control. Still, it remains unclear whether it comes from a deficit in reactive inhibition (ability to stop the action in progress), proactive inhibition (ability to exert preparatory control), or both.

We compared the performance of 39 children with ADHD and 42 typically developing children performing a Simon choice reaction time task. The Simon task is a conflict task that is well-adapted to dissociate proactive and reactive inhibition. Beyond classical global measures (mean reaction time, accuracy rate, and interference effect), we used more sophisticated dynamic analyses of the interference effect and accuracy rate to investigate reactive inhibition. We studied proactive inhibition through the congruency sequence effect (CSE).

Our results showed that children with ADHD had impaired reactive but not proactive inhibition. Moreover, the deficit found in reactive inhibition seems to be due to both a stronger impulse capture and more difficulties in inhibiting impulsive responses. These findings contribute to a better understanding of how ADHD affects inhibitory control in children.

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Attention-deficit/hyperactivity disorder (ADHD) is a common neurodevelopmental disorder, affecting more than 10% of the population worldwide, and its prevalence has significantly increased in children over the last decade (Polanczyk et al., 2015; Thapar & Cooper, 2016; Xu et al., 2018). Children diagnosed with ADHD often face difficulties completing tasks that require inhibitory control (Cubillo et al., 2011; Lipszyc & Schachtar, 2010; Mullane et al., 2009; Willcutt et al., 2005). However, inhibitory control is not a single function. Instead, it encompasses several different components, e.g., motor inhibition and interference (or cognitive) inhibition (Wöstmann et al., 2013). Motor inhibition refers to the ability to prevent or to suppress pre-planned movements (Mirabella, 2014; Mirabella & Lebedev, 2017). On the other side, interference inhibition is a more cognitive form of inhibition. It refers to the ability to resolve response conflict due to irrelevant and interfering stimulus features. In their turn, these components have two domains: proactive and reactive inhibition (Botvinick et al., 2001; Braver, 2012; Braver et al., 2007). Proactive inhibition is based on anticipating and preventing interference before it occurs, while reactive inhibition is based on detecting and resolving interference after it begins (Braver, 2012; Braver et al., 2007).

Several studies have already established that selective impairments of motor inhibition (mainly investigated with experimental paradigms including the stop-signal and the go/no-go tasks) characterize neurodevelopmental disorders. For instance, Mirabella et al. (2020) found that children affected by primary motor stereotypies have a deficit in reactive motor inhibition compared to typically developing (TD) children, but an intact proactive control. In contrast, Schmitt and colleagues (2018) found that patients with autism spectrum disorder without comorbidities showed a specific deficit in motor proactive control strategies, but an intact motor reactive inhibition. It has also been shown that while obsessive-compulsive patients have

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an impairment in both domains of motor inhibition, Tourette patients have a near-normal motor inhibition (Mancini et al., 2018). Finally, van Hulst and colleagues (2018) found that children with ADHD have a specific impairment in motor reactive but not proactive inhibition when performing a stop-signal task.

In the ADHD literature, studies investigating interference inhibition have primarily focused on reactive inhibition (for a review, see Mullane et al., 2009). In these studies, reactive inhibition has been assessed with conflict tasks, such as the Stroop task (Stroop, 1935), the flanker task (Eriksen & Eriksen, 1974), and the Simon task (Simon, 1969), which are specifically designed to induce a conflict between an automatic tendency to respond to an irrelevant but salient stimulus and a controlled goal-directed response to a relevant stimulus. In all these tasks, performance is poorer when the automatic response triggered by the salient but irrelevant dimension of the stimulus conflicts with the response required by the task instructions. Several studies (Homack & Riccio, 2004; King et al., 2007; Lundervold et al., 2011; Mullane et al., 2009; Ridderinkhof et al., 2005; Tsal et al., 2005) have reported that children with ADHD exhibit poor performance in conflict tasks (longer reaction times, more errors, and larger interference effects than their peers). But a few others have reported no deficit in participants with ADHD (Bluschke et al., 2020; Borella et al., 2013; Schwartz & Verhaeghen, 2008; Van Mourik et al., 2009). Therefore, there are inconsistencies in the pattern of findings that warrant further investigation of reactive control.

Although proactive inhibition mechanisms are also involved in inhibitory control, very few investigations have been conducted in individuals with ADHD. Preserved proactive inhibition has been found in children with ADHD performing a modified version of the flanker task (Bluschke et al., 2020) and adults with ADHD performing a Simon task (Suarez, Burle, et al., 2015). On the other hand, recent studies using electroencephalography (EEG) have suggested that proactive inhibition is impaired in adults and children performing a cued go-nogo task (Zamorano et al., 2020) or a switching task (Sidlauskaite et al., 2020). The diversity of populations, tasks, and indices used to explore proactive inhibition could explain mixed data. Therefore, as it has become increasingly clear that the phenotypes of neurodevelopmental disorders characterized by poor urge control are shaped by reactive and proactive inhibitory control impairments in both motor and cognitive domains (Mirabella, 2021), it is of great importance to study such features in ADHD with more comparable experimental conditions. In the present study, we investigated both proactive and reactive controls in the same sample of individuals and by using a single task, the Simon task. In contrast, most studies investigate only either reactive or proactive control.

1. The Simon task: A paradigm to study inhibitory control

The Simon reaction time task is particularly suitable for studying inhibitory control (Hommel, 2011). In the Simon task, the participants must respond as quickly and accurately as possible, with either the right or the left hand, to the colour of a stimulus presented either to the right or the left of a central fixation point (e.g., right hand: green; left hand: red). Although the stimulus location is irrelevant to the task, performance is better (shorter mean reaction times and fewer errors) when the required response spatially corresponds to the stimulus location (congruent trials) than when it does not correspond (incongruent trials). This effect is called the Simon effect (Hedge & Marsh, 1975; Hommel, 2011; Simon, 1990). A widely accepted interpretation of the Simon effect is that the stimulus location automatically triggers a response impulse in the ipsilateral hand via a fast information processing route, while the relevant stimulus colour must be translated into the required response according to task instructions via a slower controlled processing route (de De Jong et al., 1994; Kornblum, 1994; Kornblum et al., 1990; Proctor et al., 1995). In theincongruent trials, the impulse triggered by the irrelevant location activates the non-required response, which then competes with the required one. This competition is thought to be at the origin of the performance impairment.

1.1. Proactive inhibitory control in the Simon task

In conflict tasks, such as the Simon task, proactive inhibition is assessed by the congruency sequence effect (CSE; Gratton et al., 1992). The CSE refers to the observation that interference effects are modulated by the nature of the preceding trial. After a congruent trial, RTs decrease for congruent trials and increase for incongruent trials resulting in a larger interference effect. On the other hand, after an incongruent trial, RTs decrease for the incongruent trials and increase for the congruent trials resulting in a smaller interference effect.

According to the conflict monitoring model (Botvinick et al., 2001; Egner, 2007), the interpretation of CSE is that during the incongruent trials, conflicts are produced by the coactivation of mutually incompatible stimuli and response representations, while in the subsequent trial, subjects increase their attention on task-relevant features. In the Simon task, this corresponds to the enhancement of the focus of attention on the colour of the stimulus and the reduction of the influence of task-irrelevant features, such as the spatial location of the stimulus. Thus, one finds a reduction of the interference effect when the subsequent trial is incongruent. On the contrary, when the subsequent trial is a congruent one, poorer performance is observed due to the reduction of the facilitation of the spatial location (Mayr et al., 2003).

1.2. Reactive inhibitory control in the Simon task.

A majority of studies evaluate the efficiency of reactive inhibition through the magnitude of the interference effect; a large interference effect indicates less efficient reactive inhibitory control. The ADHD literature commonly interprets a larger interference effect as reflecting difficulties in inhibiting inappropriate automatic and prepotent responses (Barkley, 1997; Nigg, 2001). However, these difficulties could be due to at least two distinct and dynamic processes involved in interference control, which are confounded in most studies. According to the « activation-suppression model» (Ridderinkhof, 2002), the first process, called impulse capture, is assumed to reflect the degree to which the response system is susceptible to activate location-driven automatic responses. The second process is assumed to reflect inhibitory control, which suppresses the incorrect impulse response (Ridderinkhof, 2002). Therefore, impairments in children with ADHD could be due either to stronger impulse capture, less efficient inhibitory processes, or both. A finer understanding of mechanisms involved in interference control would help to understand reactive control in ADHD better.

The Simon task interpreted in the theoretical framework of the "activation-suppression model" (Ridderinkhof, 2002) provides a very powerful experimental and conceptual context for separately investigating the expression and suppression of impulse response. This model postulates that two temporally and functionally distinct processes underlie conflict and its resolution. The first is rapid, automatic activation of an incorrect action impulse triggered by stimulus location, which conflicts with the selection of the appropriate response (according to stimulus colour). The second is the subsequent inhibitory control required to selectively suppress this incorrect response activation, which reduces interference between automatic and voluntary response activations (Ridderinkhof, 2002). These dynamic processes (automatic activation of action impulses and reactive inhibition) can be dissociated by analyzing performance across the full range of the RT distribution. Higher rates of errors and increased interference effects should be observed for the fastest RTs. By contrast, this pattern should be completely reversed for the slowest RTs as inhibitory control increases and suppresses interfering automatic responses. Therefore, by plotting error rates against RT (known as conditional accuracy functions, CAF; Suarez, Burle, et al., 2015; Van den Wildenberg et al., 2010; van Van Wouve et al., 2016; Wylie et al., 2009,2010a, 2010b, 2012) in the incongruent trials, higher error rates for the faster portion of the RT distribution should be observed, reflecting the strength of impulse capture. On the other hand, by plotting interference effects against RT (known as a delta-plot), a reduction in the interference effect at the slower portion of the RT distribution should be observed, reflecting the efficiency of inhibitory control (Ridderinkhof, 2002; Ridderinkhof, 2002; Suarez, Vidal, et al., 2015; Van den Wildenberg et al., 2010; Van Wouve et al., 2016; Wylie et al., 2010, 2013). Several studies using both non-clinical and clinical populations provide empirical support for this assertion (Burle et al., 2002; Grandjean et al., 2021b; Ridderinkhof et al., 2005; Suarez, Burle, et al., 2015; Suarez, Vidal, et al., 2015; Van Wouve et al., 2016; Wijnen & Ridderinkhof, 2007; Wylie et al., 2007; Wylie et al., 2009, 2010a, 2010b, 2012, 2013; for review, see Ridderinkhof et al., 2011; Van den Wildenberg et al., 2010) and have revealed that different manipulations could differently affect these two components of interference control (Fluchère et al., 2015; 2018; Grandjean et al., 2021a, 2021b; Ramdani et al., 2015).

To summarize, we investigated both reactive and proactive inhibitory control mechanisms in children diagnosed with ADHD by comparing their performance in the Simon task with that of TD children matched in age, gender, and education. We studied proactive inhibition through CSEs and investigated reactive inhibition by using dynamic analyses of performance with the aim of separately investigating the impact of ADHD on the expression and inhibition of impulse response.

2. Material and methods

2.1. Participants

The participants in the study were 39 children diagnosed with ADHD (aged 8–14 years; mean age = 10.49 years, SD = 2.2; male = 76.9%) and 42 TD children (aged 8–14 years; mean age = 10.5, SD = 2.0; male = 71.4%). All participants and their parents gave informed consent prior to the experiment. The ethical committee of Universidad del Norte approved this study (Number: 168 and date: 10.08.2017).

2.1.1. Selection procedure for the ADHD group

Children with ADHD were recruited from a sample of patients referred to the Instituto Colombiano de Neuropedadogia (Barranquilla, Colombia) by qualified neurologists. They all met DSM IV diagnostic criteria for ADHD (American Psychiatric Association, 2000). The assessment was conducted by trained neurologists specialized in ADHD separately with children and their parents and was based on a semi-structured clinical diagnostic interview (DSM IV checklist). In addition, to compare control and ADHD groups, the parents of each child filled out a behavioural rating scale, the EDAH scale (*Evaluacion Deficit de Atencion e Hiperactividad*, Farré & Narbona, 1998; Sánchez et al., 2010). All children were drug-naïve.

2.1.2. Criteria for the TD children group

Children from the TD group were recruited via local schools. They all attended age-appropriate classes. All children met the following inclusion criteria: absence of present or history diagnosis of ADHD, as determined by parent's completion of the EDAH, absence of any learning disability based on teachers' or neuropsychologists' reports, and no concurrent treatment with any psychotropic medication.

2.1.3. Exclusion criteria for both groups

Exclusion criteria included a diagnosis or indication of any additional psychiatric disorder (such as major depression, panic disorders, suicide risk, anxiety, substance abuse, psychoactive substance use, or psychotic disorder) using a Spanish version of the structured psychiatric interview (Children's Interview for Psychiatric Syndromes, CHIPS), absence of assent or parental consent, or intelligence quotient (IQ) < 70, as assessed by the vocabulary-block design short-form of the Wechsler Children Intelligence Scale (WISC III).

2.2. Complementary neuropsychological assessments

In addition to IQ measures, all participants were administered complementary neuropsychological tests to assess cognitive function. Working memory was assessed using the working memory index from the WISC IV, which includes arithmetic, digit span, and letter–number sequencing subtests. Attention was assessed using the d2 test (Brickenkamp & Zillmer, 1998), which evaluates attention and information processing speed. The test consists of 14 lines, each comprised of 47 characters, totalling 658 items. The characters are the letters *d* or *p,* which might appear with one or two little dashes above or below each letter. The participants must carefully scan each line and cross out every letter *d* with two little dashes (both above, below, or one above and one below). Participants were allowed 20 s per line. The resulting scores were: total number of characters processed, total correctly processed (total characters processed *minus* total errors made), omissions (sum of target symbols not cancelled), errors of commissions (sum of non-target symbols cancelled), concentration index (total number of correctly cancelled symbols *minus* incorrectly cancelled symbols), and fluctuation rate (maximum total items processed in a line *minus* minimum total items processed in a line).

2.3. Simon task

2.3.1. Stimuli and apparatus

Participants were comfortably seated facing a black screen computer (44 × 25 cm, 1600 × 900 pixels), located 80 cm away, upon which stimuli (circles) appeared. Participants gave the responses pressing one of two response keys either with the right or left thumb (one response key was located in each hand).[1] A computer running t-scope controlled all stimuli and responses (Stevens et al., 2006), and reaction times (RT) were recorded to the nearest millisecond (ms).

2.3.2. Task and procedure

The participant's task was to respond as quickly and as accurately as possible by pressing the appropriate response key depending on the colour of the circle (green or red). Each trial started with the appearance of a central fixation point. After a fixed delay of 400 ms, a red or a green circle appeared on either the right or the left of the fixation point. The distance between the fixation point and the centre of the coloured circle was 5 cm. Children had to briefly press the left or the right button according to the circle colour. The colour-response mapping was balanced across participants. The stimuli remained on the screen until children responded. The following trial began 1500 ms after the response or 2500 ms after the onset of the stimulus if the child had not yet given a response. No feedback was provided.

Two types of trials were possible: Congruent trials (CO), where the required response was ipsilateral to the stimulus location, and incongruent trials (INC), where the required response was contralateral to the stimulus location. Children first performed a training block to familiarize themselves with the task and stabilize their performance. The training block consisted of 32 trials, 16 CO trials (8 red stimuli and 8 green stimuli) and 16 INC trials (8 red stimuli and 8 green stimuli), pseudo-randomized to have equal frequencies of CO-INC, CO–CO, INC-CO and INC-INC transitions. The children performed two experimental blocks of 48 trials each, corresponding to 24 CO trials (12 red/12 green) and 24 INC trials (12 red/12 green), also pseudo-randomized to balance CO-INC, CO–CO, INC-CO and INC-INC transitions. A 5-minute break separated the blocks. The entire experiment lasted about 30 minutes.

2.4. Analysis of data

We evaluated reactive inhibition using a dynamic analysis of INC accuracy rates and interference effects. We investigated proactive inhibition using a CSE analysis.

2.4.1. Reactive inhibition: A dynamic analysis of INC trials accuracy rate and interference effect

The dynamic analysis of accuracy in INC trials is based on conditional accuracy functions (CAF). A CAF was constructed for each participant: correct and incorrect responses in INC trials were considered together and their distribution was vincentized as a function of the RT speed (Ratcliff, 1979; Vincent, 1912). RTs were rank ordered and binned into five quintiles of equal frequencies (same number of trials). For each bin, the proportion of "correct" trials was computed. This showed accuracy as a function of increasing RTs (for more information, see Burle et al., 2002; Ridderinkhof, 2002; Suarez, Vidal, et al., 2015 among others). The first point of the distribution was used as an index of impulse capture strength: The lower the accuracy rate, the stronger the impulse capture.

For the dynamic analysis of the interference effect, a cumulative density function (CDF) of correct trials was estimated for each participant (Ratcliff, 1979; Vincent, 1912): RTs were rank ordered separately for each type of trial (CO and INC) and binned into five quintiles of equal frequencies (same number of trials). Then the mean of each bin was computed and these means were averaged across participants. Delta-plots were constructed by plotting the difference between corresponding INC and CO bin values (for more information, see Burle et al., 2002; Ridderinkhof, 2002; Suarez, Vidal, et al., 2015 among others). The slope of the last segment of the delta-plot (computed between the values of the fourth and the fifth quintiles) was used as an index of efficiency of inhibition of impulse response.

2.4.2. Proactive inhibition: Analysis of CSE

The Congruency Sequence Effect (CSE) refers to the evolution of the interference effect at the current trial (n) depending on the congruency at the previous trial (*n-1*). Therefore, we first categorized trials into 4 categories: CO trials preceded by an INC trial (INC-CO), CO trials preceded by a CO trial (CO–CO), INC trials preceded by an INC trial (INC-INC) and INC trials preceded by a CO trial (CO-INC). Then, we calculated interference effects for trials preceded by a CO trial (mean CO-INC RT *minus* mean CO–CO RT) and for trials preceded by an INC trial (mean INC-INC RT *minus* mean INC-CO RT). We expected the interference effect to be stronger in the first than in the second condition.

Table 1. Demographic and neuropsychological variables for both groups.

Variable	TD group (n = 42)	ADHD group (n = 39)	Statistic	*p*
Demographic variables	**Means (SD)**	**Means (SD)**		
Age	10.55 (1.990)	10.49 (2.151)	0,131	NS
School level	**Frequency (%)**	**Frequency (%)**		
Primary	19 (45.2)	26 (66.7)	0.052	NS
Secondary	23 (54.8)	13 (33.3)		
Gender				
Female	12 (28.6)	9 (23.1)	0.088	NS
Male	30 (71.4)	30 (76.9)		
Neuropsychological measures	**Means (SD)**	**Means (SD)**		
Estimated IQ index	113.6 (17.312)	94.69 (13.919)	5.39	<0.001
EDAH (centile)				
Hyperactivity (H)	28.18 (24.489)	80.74 (23.191)	9.021	<0.001
Attention (A)	24.88 (15.182)	82.18 (18.527)	13.823	<0.001
Conduct disorder	40.55 (24.561)	83.53 (23.778)	7.279	<0.001
Combined type (H + A)	20.91 (19.703)	86.24 (18.513)	13.99	<0.001
Working memory index	129.79 (16.708)	105.15 (14.188)	7.125	<0.001
D2 attention test (centiles)				
Total number of characters processed	37.86 (18.972)	28.33 (17.333)	2.353	<0.05
Total correctly processed	46.67 (18.564)	29.36 (19.506)	4.095	<0.001
Errors of omission	62.86 (8.635)	50.77 (20.696)	3.475	<0.01
Errors of commission	59.05 (14.281)	49.62 (19.848)	2.468	<0.05
Total performance	42.02 (20.514)	27.69 (19.896)	3.187	<0.01
Concentration index	52.38 (20.872)	31.54 (20.266)	4.554	<0.001
Fluctuation rate	33.69 (19.033)	53.33 (28.176)	3.649	<0.01

Note: TD = typically developing children; ADHD = Attention Deficit Hyperactivity Disorder; IQ = intellectual quotient (standard scores); WMI = working memory index; EDAH scale is a behavior rating scale filled by parents (centiles are presented).

3. Results

3.1. Demographic and neuropsychological variables

Demographic and neuropsychological variables are presented in Table 1. Children with ADHD had significantly larger EDAH score than TD children as well as lower IQ, working memory indexes and attentional scores.

3.2. Simon task performance

Extreme RT values, either excessively fast (< 150 ms, so-called anticipatory errors) or slow (> 3 standard deviations above the participant mean), were removed from the analysis. On average, this led to the exclusion of fewer than 1% of trials per participant.

3.2.1. Overall Simon task performance

Two-way ANOVAs with group (ADHD *versus* TD) as a between subjects factor and Congruency (CO *versus* INC) as a within subjects factor, were performed using mean RT, error rate, and intra-subject variability as dependent measures.

Mean RTs. Figure 1A shows mean RTs for both ADHD (522 ms; SD = 86) and TD (507 ms; SD = 99) groups. Mean RTs were not different between groups ($F_{(1,79)}$ 0.54; $p = 0.46$; $\eta_p^2 = 0.006$), but they were significantly shorter in CO trials (495 ms; SD = 95) than in INC trials (533 ms; SD = 97; $F_{1,\ 79} = 57.64$; $p < 0.001$; $\eta_p^2 =$ 0.42). The interference effect (mean INC RT – mean CO RT) was larger in children with ADHD (58 ms) compared to TD children (20 ms) (Group × Congruency interaction) ($F_{1,\ 79} = 13.9$; $p = 0.0003$; $\eta_p^2 = 0.14$).[2]

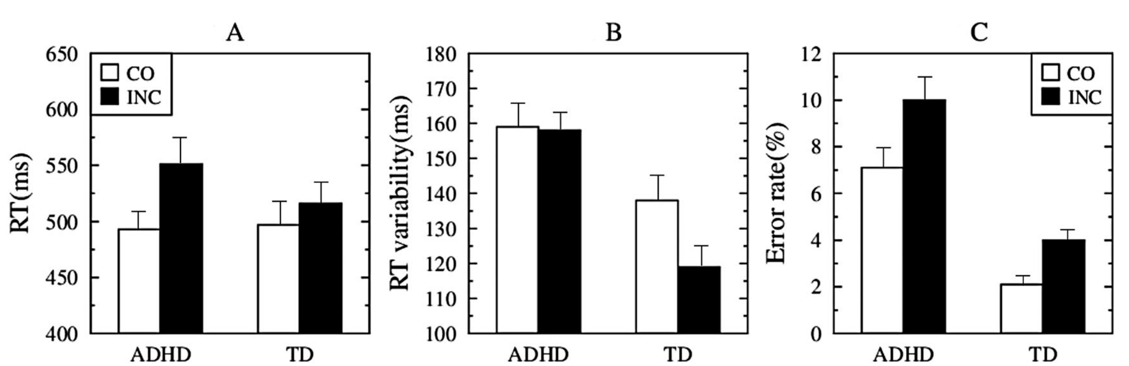

Figure 1. *Overall Simon task performance*. Mean reaction times (A), intra-individual variability (B) and error rates (C) for congruent (CO) and incongruent (INC) trials in typically developing children (TD) and children with ADHD (ADHD). Error bars are mean standard errors.

Intra-subject RT variability. Figure 1B shows intra-subject RT variability for both groups in both conditions. The intra-subject RT variability (corresponding to standard deviation, SD) was larger in children with ADHD (158 ms) compared to TD children (129 ms; $F_{1,\ 79} = 7.89$; $p = 0.06$; $\eta_p^2 = 0.09$) and larger in CO trials (148 ms) than in INC trials (139 ms; $F_{1,\ 79} = 5.85$; $p = 0.01$; $\eta_p^2 = 0.06$). There was a statistically significant Group x Congruency interaction ($F_{1,\ 79} = 4.76$; $p = 0.03$; $\eta_p^2 = 0.05$) with a larger congruency effect in the TD children.

Error rates. As shown in Figure 1C, children with ADHD committed more errors (8.6%) than TD children (3%; $F_{1,\ 79} = 53.98$, $p < 0.0001$; $\eta_p^2 = 0.40$). As usual, the error rate was higher in INC trials (7%) than in the CO trials (4%; $F_{1,\ 79} = 60.34$; $p = 0.39$; $\eta_p^2 = 0.43$). The interference effect was larger in children with ADHD (3%) compared with TD children (2%; $F_{1,\ 79} = 17.50$; $p < 0.001$; $\eta_p^2 = 0.18$).

3.2.2. Reactive inhibitory control

For the dynamic analysis of interference effect, as classically done, all values derived from the delta-plots were first submitted to separate repeated-measures ANOVAs to examine group differences on the entire functions and, more specifically, the second-order interaction Group x Congruency x Quintile. Then a pair-wise *t*-test was performed on the slope of the last segment of the delta-plot to evaluate the inhibition efficiency. For the dynamic analysis of accuracy rate, an ANOVA (Group x Quintile) was performed on the INC values, and a pair-wise *t*-test was carried out on the fastest RT bin of INC trials.

Dynamic analysis of the interference effect.[3] Figure 2A shows delta-plots representing the size of the interference effect as a function of quintiles for both ADHD and TD groups. There was a significant effect of the factor Quintile ($F_{4,\ 316} = 66$; $p < 0.0001$; $\eta_p^2 = 0.14$).

The evolution of the interference effect size with the quintiles was different between groups as confirmed by the second-order Group × Congruency× Quintile interaction ($F_{4,\ 316} = 4.06$; $p = 0.003$; $\eta_p^2 = 0.048$).[4] As classically observed, the interference effect decreased with the longest RTs for TD group. In contrast, it remained globally stable across quintiles for children with ADHD. The comparison of the slope values of the delta plot's last segments confirms that the interference effect decreased for the longest RTs in the control group (slope value = −12) but did not decrease for children with ADHD (slope value = 51; $t_{79} = 3.09$; $p < 0.002$).

Dynamic analysis of the accuracy rate.[5] Figure 2B shows distributional analyses for accuracy rates in INC trials for the two groups of children. There was a significant effect of factor Quintile ($F_{4,316} = 88.89$ $p < 0.0001$; $\eta_p^2 = 0.52$). The Group X Quintile interaction was significant ($F_{4,\ 316} = 13.01$; $p < 0.0001$; $\eta_p^2 = 0.14$)[6] confirming that the difference between groups was different depending on the quintiles. When comparing the accuracy rate values for the first quintile in INCs, measuring

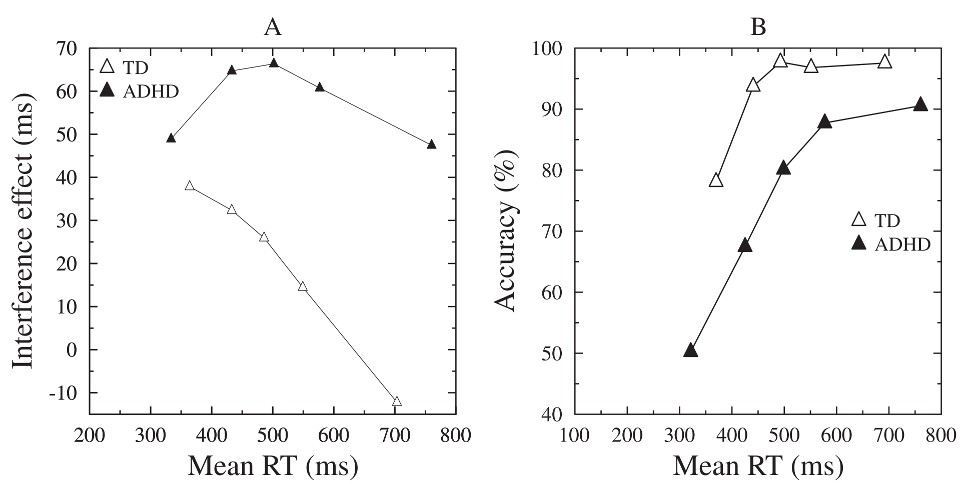

Figure 2. Reactive inhibition. (A) Delta plots showing interference effect size as a function of response speed, expressed in reaction time (RT) quintile scores for typically developing children (TD) and children with ADHD (ADHD). (B) Conditional accuracy function (CAF) for incongruent (INC) trials for typically developing children (TD) and children with ADHD (ADHD).

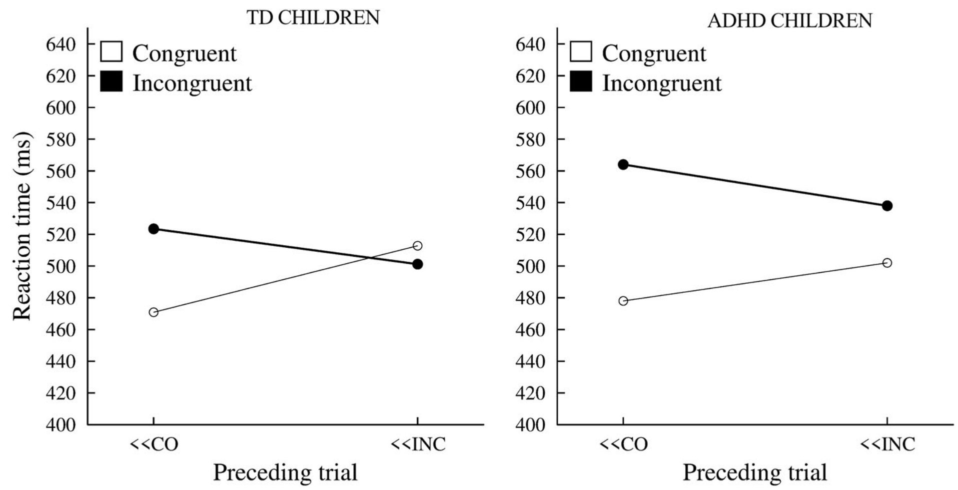

Figure 3. Proactive inhibition. Mean RTs for current congruent (CO) and incongruent (INC) trials depending on the congruency of preceding trials for typically developing (TD) children (left panel) and children with ADHD (ADHD) (right panel).

error rates for the fastest responses, we observed that children with ADHD committed more fast errors than TD children ($t_{79} = 6.46$; $p < 0.001$).

3.2.3. Proactive inhibitory control

A three-way ANOVA with Group (ADHD *versus* TD) as a between subjects factor and Current Congruency (*n* CO *versus* *n* INC) and Previous Congruency (*n*-1 CO *versus* *n*-1 INC) as within subjects factors, was performed using mean RTs as a dependent measure. The existence of a CSE means that the interference effect at the current trial is larger after CO trials than after INC trials. This would produce a significant Current Congruency x Previous Congruency interaction.

As observed in Figure 3, which illustrates CSE for both groups, the interference effect was larger after CO trials than after INC trials, as confirmed by the significant Current Congruency X Previous Congruency interaction ($F_{1,79} = 40.96$; $p < 0.001$, $\eta_p^2 = 0.34$).[7] But the second-order interaction (Group X Current Congruency X Previous Congruency) was not significant ($F_{1,79} = 0.47$; $p = 0.49$), suggesting that both groups did not differ with regards to the strength of the CSE. Bayesian analyses (Masson, 2011) confirmed that the probability of the null hypothesis being true was high (p(H0/D) 0.92).

4. Discussion

The present study aimed to compare inhibitory control in children with ADHD and TD children when they were performing a Simon task. We evaluated both reactive and proactive inhibition.

The classical analysis of RTs and error rates revealed two main results. First, we observed a larger intra-individual RT variability in children with ADHD compared to TD children. This result is consistent with data found in prior studies, which report increased intra-individual RT variability in various RT tasks (Klein et al., 2006; Lipszyc & Schachtar, 2010; Tamm et al., 2012). This is also consistent with data obtained in the attentional D2 test, which revealed poorer performance in children with ADHD than in TD children. Previous work has proposed that the high intra-individual RT variability of participants with ADHD reflects attentional lapses, corresponding to fluctuations in sustained attention (Sonuga-Barke & Castellanos, 2007; Tamm et al., 2012). Processing of stimuli that arrive during attentional lapses could be impaired and/or delayed, thereby increasing the global variability of RTs in the Simon task, or indeed all other tasks requiring fast responses. But the exact nature of mechanisms and processes responsible for increased RT variability seems not yet clearly identified (for review, see Kofler et al., 2013; Kofler et al., 2014). Second, children with ADHD committed more errors without being faster than TD children, suggesting that they have difficulties with conflict monitoring. This was confirmed by the larger interference effect observed in children with ADHD relative to TD children. These results confirm data from previous studies (Lansbergen et al., 2007; Mullane et al., 2009) and support the idea of a deficit in conflict monitoring in children with ADHD. To further understand how ADHD affects conflict monitoring, we analyzed both reactive and proactive controls.

4.1. ADHD affects reactive inhibitory control

We investigated reactive inhibitory control by using dynamic analyses of accuracy rate in INC trials and of the interference effect in terms of RT. These analyses allow us to separately investigate the effects of ADHD on expression and impulse response inhibition. The dynamic analysis of accuracy rate showed that children with ADHD committed more fast errors in INC trials than TD children, suggesting that they were more vulnerable to impulse capture. In other words, they had more difficulties resisting the urge to press the response button ipsilateral to the stimulus location. The dynamic analysis of the interference effect revealed the usual decrease in interference effect at the longest RTs in TD children, but not in children with ADHD. This indicates that children with ADHD exhibited a deficit in suppressing inappropriate impulse responses as proposed by several authors (Barkley, 1997; Nigg, 2001). To summarize, the difficulties in conflict tasks observed in children with ADHD would come both from a stronger impulse capture and from more difficulties in stopping impulsive responses. Such deficits could explain why children with ADHD respond before the end of a question or cannot resist the urge to press an emergency button even if they know that it is absolutely forbidden.

Our findings confirm those of a recent study using dynamic analyses of performance to compare interference control between untreated children with ADHD, children with ADHD under methylphenidate (MPH), and TD children, when performing a Simon task (Grandjean et al., 2021b). Untreated children with ADHD were more vulnerable to impulse capture than treated children or TD children, and they were less efficient at suppressing impulsive responses than TD children. However, our results are only partially consistent with a study using a flanker task (Ridderinkhof et al., 2005) which showed that children with ADHD had difficulties with inhibiting automatic responses, but not with impulse capture. There are two possible explanations for this discrepancy. First, Ridderinkhof et al. based their conclusions on analyses of delta plots for accuracy (including all types of trials), while we directly compared the accuracy rates for the INC trials at the fastest responses, which is a better indicator of impulse response, as suggested by Ridderinkhof himself in more recent articles (Van den Wildenberg et al., 2010) and as used in several more recent studies (Grandjean et al., 2021a; Ridderinkhof et al., 2011; Van Wouve et al., 2016; Wylie et al., 2012, 2013). Second, a flanker task involves perceptive interference, whereas the Simon task involves motor interference. Data from a recent study comparing the two tasks have suggested that the control of inappropriate automatic responses is more difficult to elicit and less stable in flanker tasks (Burle et al., 2014). Even though these results are relatively consistent with previous data obtained in children, they contrast with a study by Suarez, Burle, et al. (2015) that showed that adults with ADHD did not exhibit impaired reactive control. This difference could be explained by the fact that adults have developed adaptive control strategies, particularly because participants were all high-functioning university students. Another possibility could be that structures involved in reactive control could mature more slowly in children with ADHD than in TD children (Cortese et al., 2012; Jiang et al., 2021), and maturation would be reached only in adulthood.

In conclusion, our results support the claim that ADHD affects reactive inhibitory control. This is consistent with data coming from neuroimaging studies which show that children with ADHD have abnormal activation in pre-supplementary motor areas (pre-SMA), the right inferior frontal gyrus (rIFG), the subthalamic nucleus, and the globus pallidus (Booth et al., 2005; Dickstein et al., 2006; Rubia et al., 2010) which are areas known to be involved in reactive inhibitory control (Aron, 2007; Forstmann et al., 2008).

4.2. ADHD does not affect proactive inhibitory control

We investigated proactive cognitive control through conflict sequential effects (CSE). Our data showed similar CSE for both groups, children with ADHD were able to enhance the level of conflict monitoring after an incongruent trial suggesting normal proactive control. Our data is consistent with some recent findings. An intact CSE has been found in children with ADHD with a modified version of the sequence flanker task (Bluschke et al., 2020). In addition, proactive but not reactive inhibition has been found to be normal in ADHD children in a study which used a modified version of the stop signal task to dissociate the two (van Hulst et al., 2018).

Different models have been proposed to explain the CSE in conflict tasks (for a review, see Egner, 2007). The conflict-monitoring model proposes that conflict adjustments result from a stronger attentional focus on processing task-relevant information (the stimulus colour in our task). This would reduce the influence of the irrelevant information (Egner, 2007). On the other hand, the feature integration model (Hommel et al., 2004) does not involve cognitive control mechanisms. It proposes that stimulus and response features are integrated into a common memory representation when they co-occur in time. Consequently, subsequent activation of either a stimulus or a response feature automatically coactivates the other features (Hommel et al., 2004; Mayr et al., 2003). Complete repetition but also complete alternation (where no previous feature binding has to be overcome) of all stimulus and response features should be processed more quickly, whereas partial repetitions in which one feature changes and others remain identical should be processed more slowly. Importantly, these mechanisms could not be exclusive. Indeed, CSE could come from additive contributions of conflict adaptation and feature integration effects (for review, see Egner, 2007; Notebaert et al., 2006). Finally, adjustements of attentional focus could also be based on subjects' expectancies regarding the nature of an upcoming trial (Egner, 2007).

To conclude, our data show that proactive inhibition is preserved in children with ADHD whose conflict-monitoring improved after incongruent trials, similar to that observed in TD children. We propose that conflict monitoring results from attentional adjustments and, more specifically, from a refocusing of attention on a specific event or on task-relevant information (Egner, 2007). Therefore, preserved proactive inhibition in children with ADHD could indicate a preserved ability to efficiently select relevant information or, in other words, preserved selective attention. Some other studies using a variety of tasks, such as speed classification tasks (Hooks et al., 1994), visual cueing tasks (Aman et al., 1998; DeShazo Barry et al., 2001), visual search tasks (Mason et al., 2003), and visual attention paradigms (McAvinue et al., 2015) have already concluded that selective attention seems preserved in children with ADHD.

5. General conclusion and limitations of the study

In conclusion, the present study's findings contribute to a better understanding of conflict monitoring deficits in children with ADHD. They suggest that reactive inhibition is affected, more specifically, children with ADHD are more prone to activating automatic responses and less efficient in inhibiting them. On the other hand, we found no evidence for a deficit in proactive inhibition, confirmed by Bayesian analyses.

From a clinical perspective, our results suggest that it is important to find treatments to strengthen inhibitory control processes in ADHD. The symptoms of ADHD are usually improved under Methylphenidate (MPH) (for review, see Wilens, 2003), which is one of the most frequently prescribed treatments for ADHD. It has been proposed that MPH reduces ADHD symptoms (Cantwell, 1996; Volkow, 2002a) by increasing the level of extracellular dopamine (DA) in the basal ganglia and frontal cortex (Madras et al., 2005; Rubia et al., 2011; Volkow, 1995; 2001). Interestingly, inhibitory processes are supported by striato-frontal dopaminergic projections (Aron, 2007; Ridderinkhof et al., 2004) and could then be enhanced by MPH. Treatment approaches like neurofeedback have also been shown to improve inhibitory control and decrease impulsivity in participants with ADHD (Enriquez-Geppert et al., 2019).

This study, however, contains at least one limitation. We reported a difference between groups concerning IQ. Even if this is not unique to the current sample, this difference could raise the question of whether our results would persist after controlling for IQ, particularly concerning reactive control. In this regard, it is interesting to notice that deficits in reactive control have already been found in children with ADHD when IQ was controlled in a study using the Simon task (Grandjean et al., 2021b). Previous research has shown no link between IQ and inhibitory processes (Bitsakou et al., 2008). Moreover, we carried out ANCOVAs adding IQ as a covariate and the results of analyses remained the same (see footnotes 2, 4, and 6 in Results section). Therefore, it seems reasonable to conclude that the effects of ADHD on reactive control cannot be explained with a difference of IQ.

Notes

1. A recent study has shown that RTs are not affected by the use of the right or the left hand in tasks assessing inhibitory control (Mancini & Mirabella, 2021).
2. An ANCOVA adding IQ score as a covariate confirmed the significant Group x Congruency interaction ($F_{1,78} = 5.64$; $p = 0.019$; $\eta_p^2 = 0.067$)
3. Section 2.2.1 *Mean RTs* reports the effect of factors Group and Congruency.
4. An ANCOVA adding IQ score as a covariate confirmed the significant Group x Congruency X Quintile interaction ($F_{4,\ 312} = 3.4$; $p = 0.009$; $\eta_p^2 = 0.041$)
5. Section 2.2.1 *Accuracy rate* reports the effect of factor Group.
6. An ANCOVA adding IQ score as a covariate confirmed the significant Group x Quintile interaction ($F_{4,\ 312} = 7.52$; $p < 0.001$; $\eta_p^2 = 0.087$)
7. The effect of factors Group and Current Congruency are already reported in section 2.2.1. *Mean RTs*. The factor Previous Congruency was significant ($F_{1,79} = 3.58$ $p = 0.06$; $\eta_p^2 = 0.043$).

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No potential conflict of interest was reported by the author(s).

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