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ORIGINAL ARTICLE

Poor stimulus discriminability as a common neuropsychological deficit between ADHD and reading ability in young children: a moderated mediation model

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Background. Attention deficit hyperactivity disorder (ADHD) is frequently associated with poorer reading ability; however, the specific neuropsychological domains linking this co-occurrence remain unclear. This study evaluates information-processing characteristics as possible neuropsychological links between ADHD symptoms and RA in a community-based sample of children and early adolescents with normal IQ (⩾70).

Method. The participants ($n = 1857$, aged 6–15 years, 47% female) were evaluated for reading ability (reading single words aloud) and information processing [stimulus discriminability in the two-choice reaction-time task estimated using diffusion models]. ADHD symptoms were ascertained through informant (parent) report using the Development and Well-Being Assessment (DAWBA). Verbal working memory (VWM; digit span backwards), visuospatial working memory (VSWM, Corsi Blocks backwards), sex, socioeconomic status, and IQ were included as covariates.

Results. In a moderated mediation model, stimulus discriminability mediated the effect of ADHD on reading ability. This indirect effect was moderated by age such that a larger effect was seen among younger children.

Conclusion. The findings support the hypothesis that ADHD and reading ability are linked among young children via a neuropsychological deficit related to stimulus discriminability. Early interventions targeting stimulus discriminability might improve symptoms of inattention/hyperactivity and reading ability.

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Key words: ADHD, diffusion model, moderated-mediation, reading ability.

Introduction

Attention deficit hyperactivity disorder (ADHD) is characterized by a persistent pattern of inattention, hyperactivity, and/or impulsivity symptoms (APA, 2013). Most patients with ADHD present with co-morbid psychiatric disorders in youth, including oppositional defiant, conduct, anxiety, and/or learning disorders (Biederman *et al.* 1991; Murphy & Barkley, 1996; Pliszka, 1998; Angold *et al.* 1999).

The impairments associated with ADHD are particularly relevant to school-aged children due the potential impact on future occupational and social achievements (Sciberras *et al.* 2009). In this context, a better comprehension of co-morbid learning disorders in ADHD patients is especially relevant to develop more appropriate interventions (Stanford & Tannock, 2012). Studies have presented co-morbidity rates between ADHD and learning disorders that range from 10% to 90%, depending on the methodology, which

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differ in sample selection procedures and diagnostic criteria for both disorders (Biederman *et al.* 1991; DuPaul *et al.* 2013; Fortes *et al.* 2015).

Some authors (e.g. Willcutt *et al.* 2005; McGrath *et al.* 2011) argue that the frequent co-morbidity reported between ADHD and reading disability may be attributed to shared cognitive deficits. Competing models have tried to explain such co-morbidity (e.g. Neale & Kendler, 1995) and, to this end, the present study takes a neuropsychological approach (e.g. Rucklidge & Tannock, 2002; Willcutt *et al.* 2005). Specifically, this study aims to investigate the relationship between ADHD symptoms and reading ability through a moderated mediation model, which considers stimulus discriminability as a link accounting for this relationship, which is conditional upon age. For this purpose, ADHD symptoms and reading ability were both measured as a continuous trait (raw scores in their respective scales) and stimulus discriminability was assessed through diffusion model parameters derived from a basic processing efficiency task. First, we briefly describe the parameters of the diffusion model (e.g. Ratcliff, 1978). Second, we synthesize the research findings about how diffusion model parameters (stimulus discriminability in particular) are related to ADHD and reading disability. Finally, we present the research problem of the study and our main hypothesis.

The diffusion model: overview

There is a wide range of competing models that describe the process of making simple, binary decisions (e.g. Usher & McClelland, 2001; Wagenmakers *et al.* 2007; Brown & Heathcote, 2008). We focus on the well-validated diffusion model of Ratcliff and colleagues (e.g. Ratcliff, 1978; Ratcliff & McKoon, 2008; White *et al.* 2010). Diffusion models have been used to interpret behavioral and neuropsychological data taking into account both accuracy and speed for correct and incorrect answers (Ratcliff & McKoon, 2008). For that reason, the models provide advantages over the classical cognitive analysis of reaction time (RT) by decomposing the stages of processing used by the subject to make simple choices. They are applicable broadly to tasks that illicit decisions of the binary type (White *et al.* 2010). The binary response involves three different processes, namely, encoding the stimulus, decision-making and execution of the response.

The diffusion model focuses on the decision process. The model supposes that the binary decision occurs after a certain accumulation of information that results from noisy evidence. It encompasses different cognitive parameters that represent the three stages of processing: first, the encoding/motor response parameter (T_{er}) that is not part of the decision process; second, the boundary separation parameter (a or 0) that represents one of the poles of decision (yes/no, go/no-go, etc.) starting from the origin z; and finally, the drift rate parameter (v) that represents the quality of evidence of the stimulus.

The parameter a indexes the response style (greater values indicate a cautious answer style and lower values, an impulsive pattern of response). As T_{er} encompasses two different processes (i.e. encoding and motor response) its interpretation is not straightforward. With respect to the drift rate parameter, v, larger drift rate values indicate an easier classification of the stimulus proposed by the specific test (because drift rate assess the quality of evidence from the stimulus, the higher its value, faster and more accurate are the responses). For a complete explanation of the model, see Ratcliff & McKoon (2008) and White *et al.* (2010).

ADHD and the diffusion model parameters

Children with ADHD and comparison subjects consistently differ in their capacity for basic processing, as measured for instance by simple two-choice reaction-time (2C-RT) tasks (Metin *et al.* 2013; Salum *et al.* 2013, 2014). However, results for the parameters a and T_{er}, have been less consistent. Metin *et al.* (2013) and Salum *et al.* (2013, 2014) found that children with ADHD have poorer drift rates and faster non-decision times in 2C-RT tasks compared with controls. In both studies, no differences were found in boundary separation. Similarly, Karalunas & Huang-Pollock (2013) found the same pattern of results using working memory and executive function tasks. In a meta-analysis, Huang-Pollock *et al.* (2012) estimated the EZ diffusion model parameters from 12 studies and showed that drift rate values are smaller for ADHD than controls in sustained attention on the Continuous Performance Task but the groups did not differ in boundary separation or non-decision time.

Reading disability and the diffusion model parameters

Although reported yet in a small number of studies, diffusion models have been used to compare cognitive results from normal and impaired readers with interesting results (Ratcliff *et al.* 2004; Zeguers *et al.* 2011). Those studies suggested that while encoding representations with a poor quality of evidence from stimuli is associated with problems in reading acquisition, more time spent in non-decision processes is linked with acquired dyslexia. In addition, a more cautious pattern of response (>a) may be a common deficit in both acquired and developmental dyslexia.

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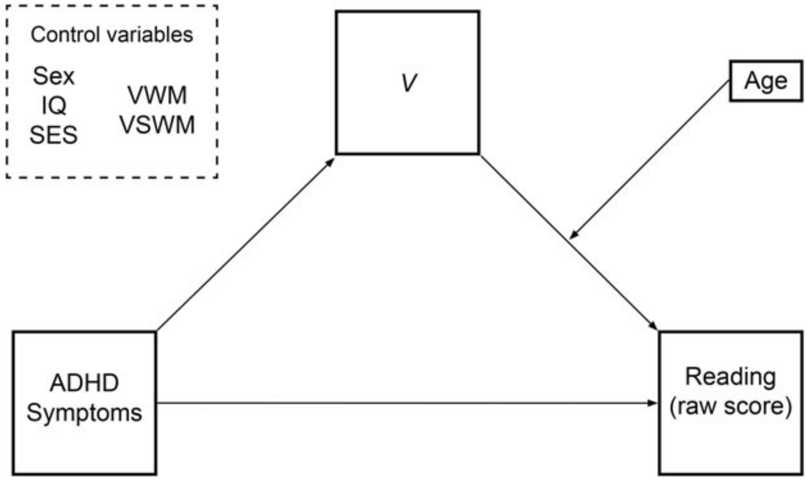

Fig. 1. Conceptual model of the moderated-mediation model. Control variables are depicted in the dashed square. ADHD, Attention deficit hyperactivity disorder; IQ, estimated intelligence quotient (WISC-IIII); SES, socioeconomic status; v, mean drift; VWM, verbal working memory (digit span backwards); VSWM, visuospatial working memory (Corsi Blocks backwards).

Another source of evidence about the developmental role of drift rates in normal development comes from studies of aging. Ratcliff *et al.* (2012) suggest that the U-shaped lifespan curve of RT development in which children and older adults present slower response times has a different explanation in the diffusion model. While slower RT in children is due to lower drift rates compared with young adults, in older adults it is due to cautious answers or greater values for the a parameter (Ratcliff *et al.* 2000; Thapar *et al.* 2003) and also slower encoding/motor responses (McKoon & Ratcliff, 2016). From the results of these studies, we may speculate that in normal development, the drift rate rises from childhood toward a plateau in adulthood, whereas slower ascent towards, or a lower maximal value of this plateau may be attained in abnormal development (e.g. dyslexia).

ADHD, reading disability, and diffusion model parameters: the research problem

As discussed in the previous sections, research findings from lexical decision tasks tend to suggest a lower drift rate in reading disability, and lower drift rates in basic information processing (BIP) tasks are seen in ADHD. Although lexical decision making and BIP tasks measure different cognitive processes, both rely on a common ability to encode visual information (either orthographic or perceptual). Therefore, it is reasonable to postulate that diffusion model parameters may provide interesting data on the reading skills of children with ADHD. Here, we hypothesize that low drift rate values may function as a shared deficit between ADHD symptoms and poorer reading performance.

The main goal of the present study is to test a mediation effect of drift rate in the relationship between ADHD symptoms and reading performance. It has been established that drift rate is influenced by age in lexical decision tasks (e.g. Ratcliff *et al.* 2012); therefore, age may function as a moderator of the relationship between drift rate on reading ability. Our hypothetical model therefore links ADHD symptoms to reading skills via an indirect path that includes drift rate (a mediator), which will differ as a function of age (moderator), resulting in a conditional indirect effect. Fig. 1 depicts the second stage moderated mediation model to be tested (Hayes, 2013). Traditional confounding variables of relevance, i.e. sex, IQ, and socioeconomic status (SES) will be considered as general covariates. Additionally, we considered verbal and visuospatial working memory as covariates because verbal working memory is a predictor of reading ability (Swanson *et al.* 2009) and recent studies have suggested that the role of visuospatial working memory in reading might be more important than previously thought (Pham & Hasson, 2014).

For testing the discriminant validity of the moderated mediation model, models for the a and T_{er} parameters were also assessed. The association between ADHD symptoms, reading ability, and the a and T_{er} parameters are less clear than the relationship with drift rate. A cautious pattern is associated with responses of people with dyslexia, aphasia, and children with normal development in reading tasks (Ratcliff *et al.* 2004, 2012; Zeguers *et al.* 2011), whereas no study has shown an association between a and ADHD symptoms

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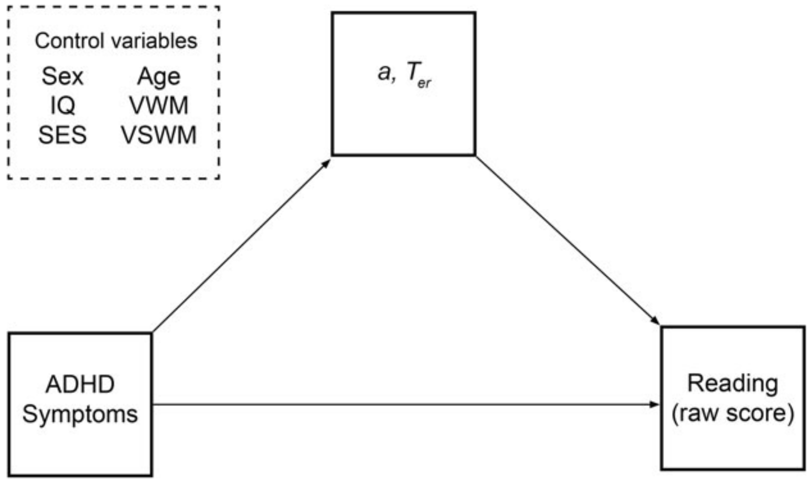

Fig. 2. Conceptual model of the mediation models. Control variables are depicted in the dashed square. ADHD, Attention deficit hyperactivity disorder; IQ, estimated intelligence quotient (WISC-IIII); SES, socioeconomic status; VWM, verbal working memory (digit span backwards); VSWM, visuospatial working memory (Corsi Blocks backwards); *a,* boundary separation; T_{er}, non-decision time.

(Huang-Pollock *et al.* 2012; Karalunas & Huang-Pollock, 2013; Metin *et al.* 2013; Salum *et al.* 2013, 2014). For this reason, caution may not function as a link between ADHD and reading ability. For the non-decision time parameter, contradictory results have been found both for ADHD and reading studies. Metin *et al.* (2013) and Salum *et al.* (2013, 2014) reported faster T_{er} values for ADHD samples, while Huang-Pollock *et al.* (2012) did not find any difference. On the other hand, lower non-decision times were found in childhood and aphasic samples compared to adults (Ratcliff *et al.* 2004, 2012), but dyslexic children and poor readers do not differ from controls (Zeguers *et al.* 2011). For this reason, the T_{er} parameter is less likely to explain the link between ADHD and reading ability.

As no *a priori* assumptions are made about the relationship between the *a* and T_{er} parameters and age (because results from the literature are less consistent for them), a simple mediation model will be tested (Fig. 2). In contrast to drift rate, we hypothesize that the parameters T_{er} and *a* will not mediate the relationship between ADHD and reading ability.

Method

Participants

The Ethical Committee of the Federal University of Sao Paulo approved the study (protocol no. 1.327.777/15). For this specific study, we used the baseline wave of a large longitudinal community school-based study from Brazil (Salum *et al.* 2015). Parents gave written consent for the children to participate, and children gave verbal assent.

Detailed information about the recruitment of the sample is available elsewhere (Salum *et al.* 2015). In summary, this sample of children attending second to ninth grades in 63 schools in the cities of São Paulo and Porto Alegre. From an original set of 8802 parents who answered the Family History Survey (FHS; Weissman *et al.* 2000), we recruited 1524 children with high-risk for mental disorders and 958 randomly selected children for evaluation ($N = 2482$). The final sample was composed of 1857 participants (61.20% from the high-risk group) after excluding children with low IQ (<70), those attending first grade, those who did not complete all tasks, and outliers at the diffusion model analysis. Therefore, 25.18% of the 2482 children were excluded.

The age range was between ages 6 and 15 years (mean = 9.81, S.D. = 1.86) and 47% of the children were female. SES was defined following the Associação Brasileira de Empresas de Pesquisas (ABEP, 2010). The ABEP system of socioeconomic classification is a scale ranging from 0 to 46 points, which corresponds to a categorization of eight classes ranging from A1 to E. In our sample, mean ABEP scores were 20.15 (S.D. = 4.73, minimum = 4, maximum = 40).

Measures

ADHD symptoms

ADHD symptoms were estimated from the 'Attention and activity' section of the Development and Well-Being Assessment (DAWBA; Goodman *et al.* 2000), with no skipping rules. DAWBA is a structured informant interview designed to generate ICD-10 and DSM-IV psychiatric diagnoses for children and

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adolescents. It is a valid and reliable tool for psychiatric diagnose (e.g. Goodman *et al.* 2011; Angold *et al.* 2012). For the present study, we used the validated Brazilian version of the instrument (Fleitlich-Bilyk & Goodman, 2004). Trained lay interviewers administered the instrument to biological parents (87.5% mothers). For the statistical analysis, dimensional inattention and hyperactivity-impulsivity scores (i.e. ADHD symptoms) were derived from DAWBA's 'Attention and activity' section (mean = 8.64, s.d. = 8.67, minimum = 0, maximum = 36). In our database, 201 students met criteria for a full ADHD DSM-IV diagnoses (35.82% predominantly inattentive; 13.43% predominantly hyperactive/impulsive; 36.82% combined subtype; and 13.93 other type).

Basic information processing task

BIP was evaluated in a 2C-RT task, which measures the ability to perform very basic perceptual decisions by pressing a button to indicate the direction of an arrow (right or left). There were 100 presentations of the arrow, half on the right and half on the left side of the computer screen. The stimulus duration was 100 ms and the inter-trial interval was 1500 ms. Task instructions emphasized both speed and accuracy. Participants received no rewards or feedback. Diffusion model parameters were estimated for stimulus discriminability (drift rate, v), cautious answering (boundary separation, a) and non-decision time (T_{er}). Correlations between the diffusion model parameters and mean RT and standard deviation RT are within expectations (v: mean = 0.31, s.d. = 0.16, minimum = −0.39, maximum = 0.68; a: mean = 0.12, s.d. = 0.03, minimum = 0.03, maximum = 0.23; T_{er}: mean = 0.25, s.d. = 0.12, minimum = −0.18, maximum = 0.78; data are available upon request).

Reading ability

Reading ability was assessed using the reading subtest of the School Performance Test (Stein, 1994), which contains one card presenting 70 isolated words. The validity and reliability of the subtest and its items have been previously established (e.g. Cogo-Moreira *et al.* 2013; Athayde *et al.* 2014; Lúcio & Pinheiro, 2014). Internal consistency (Cronbach's α coefficient) is fair (0.80). As with ADHD symptoms, we used the sum of the reading raw scores for data analysis (mean = 54.82, s.d. = 20.04, minimum = 0.0, maximum = 70).

Intelligence

Vocabulary and block design subtests of the Wechsler Intelligence Scale for Children (WISC-III) were used to estimate the Intelligence quotient (IQ), using the Tellegen & Briggs (1967) method. Residual associations with age were regressed out using Studentized residuals. The estimated mean IQ of the sample was 100.88 (s.d. = 15.34, minimum = 70.01, maximum = 154.95).

Verbal working memory (VWM)

As a measure of VWM, we used the raw score from the WISC-III digit span backward score (mean = 3.64, s.d. = 1.52, minimum = 0.0, maximum = 12).

Visuospatial working memory (VSWM)

To evaluate VSWM, we used the raw score of the backward Corsi Block-Tapping Test (mean = 4.89, s.d. = 2.05, minimum = 0.0, maximum = 14).

Statistical analysis

A conditional process analysis was used to evaluate the indirect effects of ADHD on reading scores. For the drift rate variable, the effect was tested in a second stage moderated mediation model and for the other two variables (i.e. a and T_{er}) by a mediation model. Bootstrapping bias corrected confidence intervals with 10 000 bootstrap samples were used to test the null hypothesis (i.e. the indirect effect of ADHD on reading ability is not significant). When confidence intervals contain zero, the null hypothesis is accepted. A macro implementation of PROCESS (version 2.16) for SPSS was used for data analysis (Hayes, 2016). The index of moderated mediation was used as a formal test for the mean drift model; its significance is evaluated via bootstrapping bias corrected intervals as well (Hayes, 2013).

Due to the multilevel structure of the data (i.e. children nested in schools), it was necessary to evaluate whether the observed variance within schools is less than the variance observed among schools. The extent of variance between v. within groups (also called homogeneity of variance) was described using an intraclass correlation coefficient (ICC). An ICC value less than 0.2–0.3, indicates that standard error estimates are unlikely to be biased (Stapleton & Thomas, 2008), i.e. there are similar variances within and between schools. The presence of one or more co-morbidity (e.g. depression, obsessive compulsive disorder, social phobia, etc.) was included as a covariate in *post-hoc* models.

Results

Model for mean drift

Inhomogeneity of variance was not detected (ICC = 0.045); therefore, ordinary least squares regressions were used. For the moderated mediation model, outcome variables were mean drift rate (v) and reading skills and age was the moderator (Fig. 1). Sex, IQ,

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Table 1. *Statistics of the moderated mediation model: results of the outcomes mean drift and reading score*

Variable	Outcome: mean drift			
	b	S.E.	*t*	*p* value
Constant	0.1466	0.0268	5.4700	<0.0001
ADHD symptoms (predictor)	−0.0017	0.0004	−4.1785	<0.0001
IQ (covariate)	0.0005	0.0002	1.9759	0.0483
Sex (covariate)	0.0288	0.0070	4.0909	<0.0001
SES (covariate)	0.0016	0.0008	2.0720	0.0384
Corsi Blocks Bkw (covariate)	0.0064	0.0020	3.2374	0.0012
Digit span Bkw (covariate)	0.0128	0.0026	4.8952	<0.0001
$F_{6,1850} = 23.1517$, $p < 0.0001$, $R^2 = 0.0690$				
	Outcome: reading score			
Constant	−39.5312	5.2683	−7.5035	<0.0001
ADHD symptoms (predictor)	−0.2151	0.0434	−4.9551	<0.0001
v (predictor)	95.8027	13.1163	7.3041	<0.0001
Age (moderator)	6.4116	0.4609	13.9108	<0.0001
$v \times$ age (interaction)	−8.5034	1.2937	−6.5728	<0.0001
IQ (covariate)	0.1288	0.0269	4.7817	<0.0001
Sex (covariate)	1.2177	0.7517	1.6198	0.1054
SES (covariate)	0.1853	0.0810	2.2875	0.0223
Corsi Blocks Bkw (covariate)	0.8425	0.2209	3.8136	0.0001
Digit span Bkw (covariate)	2.7431	0.2859	9.5948	<0.0001
$F_{9,1847} = 121.1430$, $p < 0.0001$, $R^2 = 0.3712$				

ADHD, Attention deficit hyperactivity disorder; IQ, estimated intelligence quotient (WISC-IIII); SES, socioeconomic status; v, mean drift; Bkw, backwards; b, unstandardized beta weight; S.E., standard error.

The first column presents the predictors, moderators, and covariates.

SES, and VWM and VSWM were control variables. Table 1 summarizes the overall model (regression coefficients, standard errors, *t*, and significance). Elevated ADHD symptoms (DAWBA raw scores) were associated with lower drift rate, independent of the covariates ($b = -0.0017$, $p < 0.0001$). Elevated ADHD symptoms were also associated with poorer reading ability (direct effect; $b = -0.2151$, $p < 0.0001$). The moderation component (age × v) was also significant ($b = -8.5034$, $p < 0.0001$). Nevertheless, such an interaction only estimates the effect of v on reading by age, and it does not quantify the relationship between the moderator and the indirect effect. Therefore, a formal test of the moderated mediation is required, which is given by the index of moderated mediation (Hayes, 2015).

The indirect effect proved significant, as the bootstrap confidence interval (CI) of the index of moderated mediation does not contain zero (effect = 0.0144, S.E. = 0.0044; 95% CI 0.0070–0.0246). Thus, the indirect effect of ADHD symptoms on reading ability through mean drift was dependent on age. The index of moderated mediation was positive, indicating that as age increases, the indirect effect becomes less negative. Table 2 presents the conditional indirect effect at three values of the moderator: the mean age (=9.82); the mean age, less 1 S.D. (=7.95); and the mean age plus 1 S.D. (=11.68). The findings indicate that ADHD symptoms led to poorer reading scores as a result of lower mean drift values, but the magnitude of this effect depended on age: at age 7.95, a child with one additional ADHD symptom was estimated to achieve 0.0478 fewer words correct; at age 9.82, a child with one additional ADHD symptom was estimated to achieve 0.0210 fewer words correct; and by the age of 11.68, the effect lost significance.

To test the hypothesis that the loss of significance in older children was secondary to the fact that most subjects presented maximum scores (ceiling effect) we analyzed the frequency of observed scores for the ceiling and floor effects (scores 70.0 and 0.0, respectively). While most of the children with 0.0 points were aged ⩽8 years (88.30%), not only the oldest children achieved the maximum score (55.82% of the sample aged between 8 and 11 years reached the ceiling). Since the effect remained significant at the mean age (~9.82 years), a ceiling effect does not reasonably explain the results. Another possibility would be the reduced

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Table 2. *Conditional indirect effects of ADHD on reading scores at values of the moderator age*

Age (range)	Effect	Boot S.E.	95% CI	Result
7.9523	−0.0488	0.0145	−0.0803 to −0.0236	Significant
9.8148	−0.0210	0.0070	−0.0375 to −0.0097	Significant
11.6773	0.0059	0.0050	−0.024 to 0.0179	Non-significant

ADHD, Attention deficit hyperactivity disorder; Boot S.E., bootstrap estimates; CI, confidence interval.

sample size at this range of age. Nevertheless, 21.90% of the sample was aged >11 years, while 27.41% was aged ⩽8 years.

One or more co-morbidities were present in 26.4% of the sample. Including the presence of one or more co-morbidity as a covariate did not change the models, so the results are presented without this variable (data available upon request).

Models for boundary separation and non-decision time

For the mediation models including a and T_{er} as mediators, age was not included as a moderator, but as a covariate (Fig. 2). The control variables were sex, IQ, SES, VWM, VSWM, and age. The model statistics are presented in Tables 3 and 4.

The models present a lack of evidence for an indirect effect of ADHD symptoms on reading that is mediated through the boundary separation parameter because the confidence interval contains zero (effect = −0.0031, S.E. = 0.0042, 95% CI −0.0021 to 0.0043). Similarly, no support for an indirect effect of ADHD symptoms on reading that is mediated by the T_{er} parameter was found (effect: −0.0009, S.E. = 0.0029, 95% CI −0.0085 to 0.0036).

Discussion

The present study investigated the relationship between ADHD symptoms and the ability to read single words using a community based school-age sample. Specifically, we tested the hypothesis that the drift rate parameter in a stimulus discriminability task would link these two outcomes, based on previous investigations that showed reduced values of drift in both ADHD and in children with reading disabilities (e.g. Zeguers *et al.* 2011; Metin *et al.* 2013; Salum *et al.* 2013, 2014). The data provide support for poor stimulus discriminability on simple choice tasks as a common neuropsychological deficit that links symptoms of ADHD and reading ability among school-aged children.

The results indicated that the presence of ADHD symptoms was related to drift rate, which in turn influenced reading ability, and that this indirect effect was moderated by age. Specifically, the relationship between drift rate and reading ability was moderated by age, such that mean drift had less impact on reading scores at higher ages. The effect of age on the indirect effect lost significance around the age of 11, an effect unlikely to be due to ceiling effects or sample size. The results concur with a moderating effect of age on the relationship between ADHD and academic skills demonstrated in a meta-analysis by Frazier *et al.* (2007).

The idea of discriminability (or the quality of evidence from stimulus) as a link between ADHD and reading is in line with the hypothesis that the frequent associations between ADHD symptoms and reading disability do not occur by chance. Some authors have demonstrated that this co-occurrence is largely due to shared genetic influences (e.g. Cheung *et al.* 2012, 2014; Greven *et al.* 2012); although a role of environment has also been found (e.g. Zumberge *et al.* 2007; Hart *et al.* 2010). Willcutt *et al.* (2005) argue that a useful approach would be to discover a neuropsychological deficit common to both disorders that may act as a 'trait' to be investigated as a correlate of genetic variations. They found that a deficit in processing speed was a common feature, and they replicated this effect in a cross-validation sample (Willcutt *et al.* 2010). The results of the present study concur with those findings, as the diffusion model parameters derived from the 2C-RT task may also reflect processing speed indirectly. Processing speed tasks usually have a cognitive and a motor component. We speculate that our results concerning the drift rate parameter are related to the cognitive aspect of the task. The motor component of processing speed is represented by the non-decision time (T_{er}) parameter (which encompasses both encoding process and response output). In our sample, T_{er} parameter did not function as a mediator of ADHD symptoms and reading ability, confirming our hypothesis (Zeguers *et al.* 2011; Karalunas & Huang-Pollock, 2013; Metin *et al.* 2013). The role of encoding remains unclear because it is a cognitive process closely associated with the T_{er} parameter. Therefore, of the parameters derived from the 2C-RT task, the drift rate parameter specifically might offer a useful phenotype to determine genetic variants that increase susceptibility to both ADHD and reading disorders.

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Table 3. *Statistics of the mediation model: results of the outcomes boundary separation and reading score*

Variable	Outcome: boundary separation			
	b	S.E.	*t*	*p* value
Constant	0.1645	0.0067	24.4876	<0.0001
ADHD symptoms (predictor)	0.0001	0.0001	0.7638	0.4451
Age (covariate)	−0.0030	0.0004	−7.2137	<0.0001
IQ (covariate)	−0.0001	0.0001	−1.6179	0.1058
Sex (covariate)	−0.0027	0.0014	−1.8938	0.0584
SES (covariate)	−0.0002	0.0002	−1.4437	0.1490
Corsi Blocks Bkw (covariate)	0.0001	0.0004	0.3173	0.7510
Digit span Bkw (covariate)	−0.0009	0.0005	−1.6261	0.1041
$F_{7,1849} = 13.0597$, $p < 0.0001$, $R^2 = 0.0471$				
	Outcome: reading score			
Constant	−6.2794	4.1246	−1.5224	0.1281
ADHD symptoms (predictor)	−0.2274	0.0437	5.1983	<0.0001
a (predictor)	−49.4332	12.4180	−3.9831	0.0001
Age (covariate)	3.8531	0.2272	16.9564	<0.0001
IQ (covariate)	0.1325	0.0272	4.8729	<0.0001
Sex (covariate)	1.2853	0.7589	1.6937	0.0905
SES (covariate)	0.1302	0.0809	1.6104	0.1075
Corsi Blocks Bkw (covariate)	0.8944	0.2235	4.0012	0.0001
Digit span Bkw (covariate)	2.7823	0.2890	9.6268	<0.0001
$F_{8,1848} = 127.3385$, $p < 0.0001$, $R^2 = 0.3554$				

ADHD, Attention deficit hyperactivity disorder; IQ, estimated intelligence quotient (WISC-IIII); SES, socioeconomic status; *a*, boundary separation; Bkw (backwards); *b*, unstandardized beta weight; S.E., standard error.

The first column presents the predictors, moderators, and covariates.

Future research should include a direct measure of processing speed to test the stability of the model. At a first look, the results of McGrath *et al.* (2011) might suggest that the relationships observed between variables in the present study might change. Using regression analysis in structural equation modeling, the authors showed that only processing speed contributed independently to both ADHD symptoms and reading ability, whereas verbal working memory and naming speed were not significant. Nevertheless, in McGrath *et al.*'s model, reading and ADHD symptoms were correlated, i.e. there are no regression model linking these latent traits. Furthermore, in their model, both VWM and processing speed were direct predictors of the outcomes reading and ADHD symptoms. In the present work, two measures of working memory (i.e. verbal and visuospatial) and we assumed that both measures are predictors of mean drift and reading ability. While the model may change with inclusion of a processing speed measure, the results of McGrath *et al.* do not provide evidence regarding the effects of working memory (verbal and visuospatial) as covariates.

The present study also confirmed the hypothesized lack of significance for the boundary separation parameter as a mediator of the relationship between ADHD and reading ability. Although a more cautious pattern was present in reading performance studies (Ratcliff *et al.* 2004; 2012; Zeguers *et al.* 2011), no studies found a relationship between this deficit (i.e. the *a* parameter of the diffusion model) and ADHD symptoms (Huang-Pollock *et al.* 2012; Metin *et al.* 2013; Salum *et al.* 2013, 2014). Our data confirmed those findings, showing no influence of ADHD symptoms on boundary separation in the simple mediation model ($b = 0.001$, $p = 0.4451$; Table 3) although an effect of boundary separation (i.e. cautious answering) was demonstrated on reading scores regardless of ADHD symptoms ($b = -49.4332$, $p = 0.0001$; Table 3).

The demonstrated indirect relationship between ADHD and reading ability that was mediated by drift rate highlights the promise of using diffusion model parameters as continuous neuropsychological measures to improve our understanding of the complex co-occurrence of ADHD symptoms and reading ability. For this study, ADHD symptoms were derived from DAWBA item scores to test relationships between ADHD symptoms as a continuous measure and reading skills. Our results extend the findings of previous

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Table 4. *Statistics of the mediation model: results of the outcomes non-decision time and reading score*

Variable	Outcome: non-decision time			
	b	S.E.	*T*	*p* value
Constant	0.2890	0.0254	11.3685	<0.0001
ADHD symptoms (predictor)	−0.0007	0.0003	−2.2803	0.0227
Age (covariate)	−0.0073	0.0016	−4.6244	<0.0001
IQ (covariate)	0.0002	0.0002	1.1542	0.2486
Sex (covariate)	0.0531	0.0054	9.0675	<0.0001
SES (covariate)	0.0004	0.0006	0.7144	0.4751
Corsi Blocks Bkw (covariate)	−0.0028	0.0016	−1.7626	0.0781
Digit span Bkw (covariate)	−0.0023	0.0020	−1.1030	0.2702
$F_{7,1849} = 20.8292$, $p < 0.0001$, $R^2 = 0.0731$				
	Outcome: reading score			
Constant	−14.7961	3.7231	−3.9742	<0.0001
ADHD symptoms (predictor)	−0.2295	0.0440	−5.2187	<0.001
T_{er} (predictor)	1.3384	3.2930	0.4064	0.6845
Age (covariate)	4.0126	0.2263	17.7276	<0.0001
IQ (covariate)	0.1363	0.0273	4.9923	<0.0001
Sex (covariate)	1.3473	0.7812	1.7248	0.0847
SES (covariate)	0.1405	0.0812	1.7307	0.0837
Corsi Blocks Bkw (covariate)	0.8916	0.2247	3.9684	0.0001
Digit span Bkw (covariate)	2.8289	0.2901	9.7502	<0.0001
$F_{8,1848} = 124.3202$, $p < 0.0001$, $R^2 = 0.3499$				

ADHD, attention-deficit/hyperactivity disorder; IQ, estimated intelligence quotient (WISC-IIII); SES, socioeconomic status; *a*, boundary separation; Bkw (backwards); *b*, unstandardized beta weight; S.E., standard error.

The first column presents the predictors, moderators, and covariates.

studies that linked ADHD, and particularly its inattentive subtype, to reading problems (e.g. Greven *et al.* 2012; Cain & Bignell, 2014; Pham, 2016). In other words, our data support an influence of ADHD symptoms independent of categorical classifications, consistent with a dimensional view of the ADHD phenotype (e.g. McGrath *et al.* 2011; Willcutt *et al.* 2012; Salum *et al*. 2014; Wagner *et al.* 2016).

It is necessary point out some limitations of this study. Some variables previously linked to reading ability or ADHD symptoms, such as rapid automatized naming tasks and measures of executive function were not assessed as potential confounders, although the observed effects were shown to be independent of sex, IQ, working memory (verbal and visuospatial) and SES. Although our results are highly significant, we did not assess their specificity. Executive tasks might also be included in a similar manner to determine the best mediators and to test the independence of the observed effect. In addition, ADHD symptoms were assessed only by a structured interview (i.e. DAWBA) administered to biological parents by trained interviewers as opposed to psychiatric assessments of the children directly or using data from teachers. In addition, data from this large community school-based sample may not generalize to predominantly clinical populations. Finally, the cross-sectional design does not permit conclusions about causality between the linked variables. As Winer *et al.* (2016) explain, despite the utility of mediational analysis to help establish causality, the 'statistical result is not evidence for a causal chain in which a predictor variable leads to a mediator variable, which leads to an outcome variable' (p. 2). This work took mediation models as atemporal associations, because no *a priori* assumptions were made about how the relationship between ADHD symptoms and reading abilities might unfold over time. For this aim, a longitudinal design would be required. Therefore, the results should be interpreted as relationships between predictors and outcomes rather than as relationships between causes and consequences.

Conclusion

The present study establishes a specific neuropsychological factor related to both ADHD and reading ability. The results demonstrate a role of stimulus

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discriminability in basic information processing as a mediator of the relationship between ADHD and poorer reading. Moreover, the relationship between ADHD and reading ability mediated by mean drift was dependent on age, disappearing in older children. As a particular measure of stimulus discriminability, mean drift obtained from diffusion modeling represents a potential common neurobiological mechanism between these ADHD symptoms and reading ability. The findings may have implications for improving diagnostic accuracy, and for the development of treatments (Kendler & Neale, 2010). Interventions might aim to improve stimulus discriminability in patients with ADHD or reading disabilities, particularly as early interventions for children at risk for both disorders.

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Declaration of Interest

Luis A. Rohde has received honoraria, has been on the speakers' bureau/advisory board and/or has acted as a consultant for Eli-Lilly, Janssen-Cilag, Novartis and Shire in the last 3 years. He receives authorship royalties from Oxford University Press and ArtMed. He also received travel awards for taking part in 2014 APA and 2015 WFADHD meetings from Shire. The ADHD and Juvenile Bipolar Disorder Outpatient Programs chaired by him received unrestricted educational and research support from the following pharmaceutical companies in the last 3 years: Eli-Lilly, Janssen-Cilag, Novartis, and Shire. Ary Gadelha and Pedro Mario Pan have received continuous medical education support from AstraZeneca, Eli-Lilly and Janssen-Cilag. G. V. Polanczyk has received grant or research support from the National Council for Scientific and Technological Development (CNPq), the São Paulo Research Foundation (FAPESP), Fundação Maria Cecilia Souto Vidigal, Grand Challenges Canada, and the Bill & Melinda Gates Foundation. He has served as a consultant to Shire and Johnson & Johnson. He has served on the speakers' bureau of Shire and has developed CME material for Shire and Janssen-Cilag. He has received royalties from Editora Manole. Maria Conceição do Rosário has received honoraria, has been on the speakers' bureau/advisory board and/or has acted as a consultant for Novartis and Shire in the last 3 years.

Patrícia Silva Lúcio, Giovanni Abrahão Salum, Walter Swardfager, Joachim Vandekerckhove, Andréa Parolin Jackowski, Jair de Jesus Mari, and Hugo Cogo-Moreira declare no potential conflicts of interest.

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