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How Distinctive are ADHD and RD? Results of a Double Dissociation Study

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Abstract The nature of the comorbidity between Attention-Deficit/Hyperactivity Disorder (ADHD) and Reading Disability (RD) was examined using a double dissociation design. Children were between 8 and 12 years of age and entered into four groups: ADHD only (n=24), ADHD +RD (n=29), RD only (n=41) and normal controls (n=26). In total, 120 children participated in the study; 38 girls and 82 boys. Both ADHD and RD were associated with impairments in inhibition and lexical decision, although inhibition and lexical decision were more severely impaired in RD than in ADHD. Visuospatial working memory deficits were specific to children with only ADHD. It is concluded that there was overlap on lexical decision and to a lesser extent on inhibition between ADHD and RD. In ADHD, impairments were dependent on IQ, which suggest that the overlap in lexical decision and inhibition is different in origin for ADHD and RD. The ADHD only group was specifically characterized by deficits in visuospatial working memory. Hence, no double dissociation between ADHD and RD was found on executive functioning and lexical decision.

Keywords ADHD · RD · Comorbidity · Executive functioning · Lexical decision

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Introduction

Attention Deficit Hyperactivity Disorder (ADHD) and Reading Disability (RD) are two common childhood disorders, which frequently co-occur. Research estimates the comorbidity of RD in children with ADHD between approximately 20–40% (Del'Homme et al. 2007; Semrud-Clikeman et al. 1992). The comorbidity of ADHD in the RD population is estimated between 26–50% (Holborow and Berry 1986; Lambert and Sandoval 1980).

The current study focuses on the nature of this comorbidity using neuropsychological measures. Neuropsychological functioning may be of particular importance in the context of the comorbidity of ADHD and RD, because it seems to be a translational domain between etiological factors and observable symptoms (Doyle et al. 2005). Overlapping neuropsychological deficits may provide insight into the factors contributing to the frequent co-occurrence of both disorders, whereas the non-overlapping deficits may indicate why some patients develop the one, but not the other disorder.

The current study addresses this overlap and the specificity of neuropsychological deficits in ADHD and RD by using a double dissociation design, which compares four groups: ADHD only, RD only, ADHD+RD and normally developing controls. In double dissociation studies, processes are selected that are presumed to be primarily impaired in one, but not in the other disorder. In previous double dissociation studies of ADHD and RD, research was directed towards executive functioning (EF), especially for ADHD. Processes studied previously in RD were precursors of reading, such as, phonological or rapid naming skills (Bental and Tirosh 2007; McGee et al. 1989; Pennington et al. 1993; Purvis and Tannock 1997, 2000; Willcutt et al. 2001). Deficits in EF have been suggested as the core deficits of ADHD (Barkley 1997; Nigg 1999; Quay 1997). In contrast, phonological and rapid naming deficits have been found primarily in RD (Snowling 2000; Stanovich 1988; Stanovich and Siegel 1994).

Earlier double dissociation studies in ADHD and RD have produced contradictory results, since EF deficits have been found in both ADHD and RD (Willcutt et al. 2005). Similarly, rapid naming deficits, thought specific for RD, have been found in ADHD (Pennington et al. 1993; Purvis and Tannock 2000; Willcutt et al. 2005). Three factors may have contributed to these contradictory findings.

The first factor is that different EF domains have been employed in double dissociation studies. The EF inhibition is believed to be primarily impaired in ADHD (Barkley 1997; Pennington et al. 1993; Robins 1992; Willcutt et al. 2001). However, inhibitory deficits have been found in RD, although to a lesser extent than in ADHD (Närhi and Ahonen 1995; Purvis and Tannock 2000; Van Der Schoot et al. 2000; Willcutt et al. 2005). Likewise, deficits in working memory (WM) have been reported in both ADHD and RD (Barkley 1997; Castellanos and Tannock 2002; De Jong 1998; Pennington and Ozonoff 1996; Willcutt et al. 2001). However, if WM is divided into verbal and visuospatial components, verbal WM deficits are more often associated with RD than with ADHD (Martinussen and Tannock 2006; Rucklidge and Tannock 2002; Swanson et al. 1999; Willcutt et al. 2001); whereas visuospatial WM deficits are more pronounced in ADHD than RD, although research concerning the specificity of visuospatial WM impairments in ADHD compared to RD is limited (Marzocchi et al. 2008).

A second factor that may have contributed to the contradictory results is a failure to take into account other co-occurring deficits in both ADHD and RD, which may be associated with EF, such as, pragmatic and arithmetic skills. Pragmatic deficits in both children with ADHD and RD may obscure the uniqueness of EF impairments in ADHD in double dissociation studies, since pragmatic deficits co-occur with EF impairments (Geurts et al. 2003; Griffiths 2007). Similarly, arithmetic deficits have been reported in both children with ADHD and RD and are associated with poor EF, such as, visuospatial WM (Van der Sluis et al. 2005).

A third complicating factor is the heterogeneity of the ADHD groups employed in some double dissociation studies, encompassing children either with the predominantly inattentive, predominantly hyperactive-impulsive, and combined ADHD subtypes (Klorman et al. 1999).

The current study sought to improve upon previous double dissociation studies in ADHD and RD by using both inhibition and visuospatial WM tasks. Additionally, a Lexical Decision task was used to measure reading skills. This task is more closely related to reading than the more frequently used measures of single phonological skills or rapid naming (Gijsel et al. 2004). Considerable effort was made to collect homogeneous groups. Children were carefully screened for pragmatic and arithmetic deficits and were excluded, when they had severe impairments in arithmetic and/or pragmatics. Only the combined subtype of ADHD entered into the study in order to provide more homogeneous ADHD groups.

Method

Participants

Children with ADHD and children with ADHD+RD were recruited in six pediatric outpatient clinics in The Netherlands and one outpatient clinic in Belgium. Children with RD were recruited by advertisements in Belgium, since they are not regularly seen by pediatricians. Normal controls were recruited in regular primary schools in the Netherlands. For the clinical groups, 155 children were screened out of which 60 children did not meet criteria for the study; 8 children did not meet the prescreening criteria, 3 children did not meet RD criteria, 34 children did not meet criteria for ADHD-Combined subtype (ADHD-C), 7 children had severely impaired pragmatic skills, 2 children showed arithmetic deficits, 2 children showed conduct disorder, 1 child had severe symptoms of depression and one child had a very low IQ and two children did not give consent to participate in the study. A total of 24 children with ADHD, 41 children with RD, and 29 children with ADHD+RD were enrolled in the study.

Thirty children were screened for the normal control group. Four children met criteria for ADHD, thus 26 children were enrolled in the normal control group. The final sample consisted of 120 children aged 8–12 years. In total, 38 girls and 82 boys participated in the study. All children were of Caucasian origin, except two children in the ADHD only group; one child was of Asian origin and the other child was half-African. Subject characteristics are presented in Table 1.

Measures to Obtain a Diagnosis of ADHD and RD

All participating children were screened for the presence of ADHD-C with the Disruptive Behavior Rating Scale (DBD; Pelham et al. 1992; Dutch translation: Oosterlaan et al. 2000). The DBD is a reliable and valid instrument to screen for ADHD, ODD and CD (Oosterlaan et al. 2000). To meet the criterion of pervasiveness of ADHD, the DBD was completed by both the parent and the teacher. The parent version of the Diagnostic Interview for Children (PDISC-IV-IV; National Institute of Mental Health

Table 1 Subject Characteristics

	ADHD n=24 (♀=4)		ADHD+RD n=29 (♀=6)		RD n=41 (♀=18)		NC n=26 (♀=10)		Pairwise Comparisons
Measure	*M*	*SD*	*M*	*SD*	*M*	*SD*	*M*	*SD*	p=0.05
Age in Years	9.00	(1.31)	9.83	(1.33)	10.10	(1.04)	9.31	(0.92)	NC,A<R
IQ	101.21	(15.02)	95.34	(8.64)	104.85	(9.18)	107.32	(9.40)	C<R,NC
Picture Arrangement	10.04	(3.30)	10.21	(1.95)	11.61	(2.51)	10.38	(1.96)	ns
Arithmetic	9.75	(3.62)	8.89	(2.58)	10.28	(2.99)	12.38	(2.81)	C,R,A<NC
Block Patterns	9.83	(2.76)	8.82	(2.73)	11.56	(2.46)	11.00	(2.46)	C<R,NC
Vocabulary	11.21	(2.87)	8.86	(2.62)	9.95	(2.65)	12.08	(2.22)	C,R<A,NC
DBD Parents									
Inattention	18.33	(4.50)	17.59	(3.63)	7.22	(4.60)	1.88	(2.12)	C,A>R>NC
H/I	17.92	(4.60)	18.31	(3.49)	4.22	(3.73)	2.58	(2.08)	C,A>R,NC
ODD	9.08	(4.67)	8.55	(4.05)	2.83	(2.55)	1.85	(2.24)	C,A>R,NC
CD	1.67	(2.68)	1.70	(1.79)	0.67	(0.06)	0.10	(0.30)	A>NC,C>R,NC
DBD Teacher									
Inattention	17.13	(4.91)	17.14	(3.68)	5.43	(4.67)	1.54	(1.90)	C,A>R>NC
H/I	16.50	(4.99)	17.17	(4.70)	2.80	(3.54)	1.31	(2.31)	C,A>R,NC
ODD	6.73	(5.11)	7.00	(4.56)	1.42	(2.43)	0.92	(1.69)	C,A>R,NC
CD	1.95	(2.69)	2.08	(1.88)	0.26	(0.59)	0.04	(0.20)	C,A>R,NC
CCC Pragmatic Score									
Parents	139.65	(10.40)	138.72	(10.03)	151.61	(7.35)	154.92	(6.20)	C,A<R,NC
Teacher	137.91	(10.22)	138.11	(12.20)	150.77	(7.04)	152.96	(8.45)	C,A<R,NC
PDISC-IV									
OCD	0.67	(2.01)	0.00	(0.00)	0.00	(0.00)	0.00	(0.00)	A>C,R,NC
Tic Disorder	1.25	(2.87)	0.00	(0.00)	0.00	(0.00)	0.00	(0.00)	A>C,R,NC
MD	1.58	(3.00)	0.14	(0.51)	0.00	(0.00)	0.00	(0.00)	A>C,R,NC
Inattention	15.92	(2.16)	16.00	(2.44)	5.02	(3.29)	1.00	(2.20)	A,C>R>NC
H/I	15.67	(1.92)	15.72	(2.25)	2.24	(2.93)	1.00	(1.98)	A,C>R,NC
ODD	6.92	(4.96)	4.83	(4.52)	0.49	(1.71)	0.38	(0.98)	A,C>R,NC
CDRS									
Raw Score	24.58	(4.28)	20.76	(2.29)	20.34	(5.14)	18.24	(1.71)	A>C,R,NC
Reading									
OMT[a]	−0.75	(10.36)	23.14	(8.95)	25.90	(9.09)	−8.12	(15.09)	R,C>A,NC
TRT[a]	3.08	(6.50)	22.97	(9.54)	25.51	(9.86)	−1.12	(5.92)	R,C>A,NC
PRT[a]	−3.67	(13.93)	23.97	(11.41)	26.54	(12.00)	−8.62	(18.33)	R,C>A,NC
Arithmetic									
SAT[a]	3.09	(14.13)	11.41	(13.62)	10.02	(8.34)	−4.92	(11.95)	C,R>NC
CSA	52.33	(32.22)	33.38	(20.46)	55.85	(31.56)	52.88	(23.54)	C<R

A Attention deficit hyperactivity disorder; *ADHD* Attention deficit hyperactivity disorder; *C* Attention deficit hyperactivity disorder+reading disorder; *CCC* Communication checklist for children; *CD* Conduct disorder; *CDRS* Children depression rating scale; *CSA* Cognitive subtests for arithmetic; *DBD* Disruptive behavior disorders rating scale; *H/I* Hyperactivity/impulsivity; *IQ* Intelligence quotient; *MD* Major depression; *NC* Normal controls; *OCD* Obsessive compulsive disorder; *ODD* Oppositional defiant disorder; *OMT* One minute test; *PDISC* Parent diagnostic interview scale for children; *PRT* Pseudoword reading test; *R* Reading disorder; *RD* Reading disorder; *SAT* Speeded arithmetic test; *TRT* Text reading test

[a]Mean Delay in Schoolmonths (a negative value indicates advance)

(NIMH), Shaffer et al. 2000; Dutch translation; Ferdinand et al. 1998 *Diagnostic Interview Schedule for Children, DISC-IV. Nederlandse Vertaling* [Dutch Translation]. Unpublished manuscript. Sophia Kinderziekenhuis, Rotterdam) was administered. Adequate reliability and validity have been reported for earlier versions of the PDISC-IV (Schwab-Stone et al. 1996). The diagnosis of ADHD as assessed by the PDISC-IV was based on the DSM-IV and the ICD -10. A diagnosis of ADHD-C was made if (a) scores on the DBD fell at least in the subclinical range (≥ 90th percentile) on both the Inattention and Hyperactivity/Impulsivity scales rated by both the parents and the teacher and (b) when the criteria for ADHD on the PDISC-IV were met.

All children were screened for RD using two Dutch technical word reading tests: the One Minute Test (OMT; Brus and Voeten 1973), the Pseudo-word Reading Test (PRT; Van den Bos et al. 1999) and a text reading test; the Text Reading Test (TRT; Visser et al. 1998). All have adequate validity (Van der Sluis et al. 2005). A diagnosis of RD was made, if children had at least 15 months delay on at least two of the three reading tasks, as indicated by DSM-IV criteria for RD.

Exclusion Criteria for All Groups

In order to study more homogeneous groups, children were excluded if they met the following diagnoses: former or current neurological disorders, such as, epilepsy diagnosed by a clinician. Likewise, patients were excluded with a former or current diagnosis by a clinician of depression, PDD, anxiety disorder, post-traumatic stress disorder, tic disorder (including Tourette syndrome), obsessive- compulsive disorder or conduct disorder. The PDISC-IV was included to assess current undiagnosed psychiatric comorbidities in the child. The PDISC screened for major depression disorder, obsessive- compulsive disorder, tic disorder, ADHD, oppositional defiant disorder and conduct disorder. Children were excluded, if they had a raw score of 40 or greater on the Children Depression Rating Scale (CDRS; Poznanski and Mokros 1996).

Severe pragmatic deficits were assessed by the Communication Checklist for Children (CCC; Bishop 1998; Dutch translation: Hartman et al. 1998, *De drie C's: Children's Communication Checklist* [The three C's: Children's Communication Checklist]. Unpublished manuscript. Vrije Universiteit, Amsterdam). If children obtained a pragmatic score of 132 points or lower on either the parent or the teacher version of the CCC, they were excluded (Geurts et al. 2004).

Children with severe arithmetic deficits were excluded. Severe arithmetic deficits were defined when a child had a delay greater than 20 school months on the Speeded Arithmetic Test (SAT; De Vos 1992) and a score below the 3rd percentile on the Cognitive Subscales for Arithmetic (CSA; De Clerq et al. 2002, *Cognitieve Deelhandelingen van het Rekenen* [Cognitive Subskills of Arithmetic]. Unpublished document. Universiteit Gent).

Children with an estimated IQ below 80 were excluded, as assessed by four subtests of the Wechsler Intelligence Scale for Children, Third edition (WISC-III): Picture Arrangement, Arithmetic, Block Design and Vocabulary (Wechsler 1992; Dutch translation: Kort et al. 2002). These four subtests correlate between r=0.93 to r=0.95 with Full Scale IQ (Groth-Marnat 1997).

Medication

Children were off stimulant medication at least 48 h before testing. In the ADHD only group, 13 children and 9 children in the ADHD+RD group were on stimulant medication. Children were not on other types of medication.

Neuropsychological Measures

Inhibition The Stop Signal Paradigm was administered to measure response inhibition (Lijffijt et al. 2005; Oosterlaan et al. 1998). The task consisted of two types of trials: go trials and stop trials. At the start of both trials, a fixation point was shown for 500 ms. Subsequently, the go stimulus (a cartoon plane) was presented for 1,000 ms at the centre of a computer screen. Subjects were required to indicate the position of the plane by pressing one of two response buttons that corresponded to the direction in which the plane pointed (right or left). Maximum reaction time was 1,500 ms. Stop trials were identical to go trials, but in addition a cross was superimposed on the plane, which remained on the screen for a maximum time of 1,000 ms minus delay time. Children were instructed not to press either button, when they saw the cross. Inter-trial interval was 1,000 ms. The delay between the onset of the go signal and stop signal was varied using a tracking algorithm. The initial delay between the go- and stop-signal was 175 ms (Osman et al. 1990). If the child succeeded in inhibiting the response, the delay between the onset of a go trial and the next stop signal was increased by 50 ms. If the child failed to inhibit his response, the delay between the onset of a go trial and stop signal was decreased by 50 ms. Six blocks, each of 64 trials were administered. In the first block, only go-trials were presented to practice fast and accurate responding to go-stimuli. In the following five blocks, both go- and stop-trials (16 per block = 25% of the trials) were presented in pseudo-randomized order. The first block was used for practice only.

Using a tracking mechanism, it was established that there was a 50% chance of response inhibition on stop trials. At this point, the go- and the stop-process were of equal duration (Logan and Cowan 1984). In this way, the finishing time of the go-process becomes an estimate of the finishing time of the stop-process: the stop signal reaction time (SSRT) can be determined by subtracting the mean delay time from the mean go-signal reaction time (MRT). Three additional variables reflecting the response execution process were obtained: MRT measured the speed of response execution; number of Omission Errors (indicated lapses of attention during response execution) and the number of Commission Errors (reflected potential impulsivity in response execution) (Halperin et al. 1992).

Visuospatial Working Memory The Corsi Block Tapping test was administered to examine visuospatial WM (Corsi 1972; Schellig 1997). Nine blocks were displayed on a computer touch screen. A small cursor on the screen tapped a span of blocks, starting with a two block span. After a tone, the child had to re-tap the demonstrated span by touching the screen. Depending on performance of the child, the span could be increased to nine blocks. For each span, two trials were presented, except if one of the trials was incorrectly tapped, then a third trial for that span followed. The task was discontinued, when two trials of a span were incorrectly tapped. The dependent variable was the maximum span number that the child was able to re-tap: WM Maximum Span.

Lexical Decision A Lexical Decision task was used to measure lexical access skills, which has been shown to be a reliable and valid measure of lexical decision (e.g. Meyer and Schvaneveldt 1971; Milne et al. 2003). The dual route model of reading aloud is used to explain the theoretical underpinnings of the lexical decision task (Coltheart et al. 2001). Briefly, this model contains two routes: the lexical and the sublexical route. The sublexical route uses rules of grapheme-to-phoneme conversion, thus words will be read letter by letter. The other, parallel route, the lexical route uses matching to whole word representations in the mental orthographical lexicon, the assumed mental dictionary. Since both the sublexical and the lexical routes are needed for reading, the lexical decision task is a potentially more ecologically valid measure of reading disorder than only phonological measures which tap only the sublexical procedure.

In the Lexical Decision task, participants had to decide if words, presented one by one on a computer screen, were Valid Words or Pseudowords. The words were preceded by a warning cross (1,200 ms) that appeared at the centre of the computer screen. The child was prevented from impulsive responding, since responding could only commence 300 ms after onset of presentation of the word. The word stayed on the screen until the response was given within 2,000 ms. The inter-trial interval was 3,500 ms. Pseudowords were derived from Valid Words by changing some of the letters with the restriction that the Pseudowords were still pronounceable and were consistent with Dutch orthography. All words were monosyllabic.

Since the Valid Words and Pseudowords were not very different, children had to read the words letter by letter (since the words did not obviously differ in orthography) thus they had to use knowledge of letter-sound (grapheme-phoneme relations), the sublexical route of reading. In addition, lexical decision is aided by matching the presented word with the stored word in the orthographical lexicon. Efficient access to the orthographical lexicon is facilitated by the word superiority effect, which refers to the notion that known words are read as “higher” cognitive units than individual letters or strings (Healy 1976). Thus, the use of the orthographical lexicon refers to the lexical route.

There was one practice block of 25 words, which could be extended once by 25 words, if 40% or less were correct. If the child failed the next practice block, the test was started, since we assumed that the task procedure was clear. The practice block was followed by five blocks each of 25 Valid Words and 25 Pseudowords presented pseudo-randomly.

The dependent variable was d′, measuring the accuracy of lexical decision by which subjects correctly identified Valid Words and Pseudowords, independent of response bias. The d′ was computed as: probit (hit rate correct Valid Words)—probit (false positive rate incorrect Pseudowords) (MacMillan and Creelman 1991). In this formula, hit rate refers to the number of correctly identified Valid Words divided by the total Valid Words; false positive rate refers to the number of incorrectly identified Pseudowords divided by the total number of Pseudowords. The hit rate and the false positive rate for each child were normalized by a probit function because responses were binomial. Mean reaction time (MRT) of the responses of the correctly identified Valid Words was recorded which indicated the speed of lexical decision making. Since Pseudowords are not stored in the orthographical lexicon, pseudowords have to be decoded. Processing speed of decoding was assessed by MRT on Pseudowords.

Procedure

Data was obtained during three visits. During visit 1, informed consent was obtained and potential eligibility determined, following this visit the DBD and CCC were completed by parents and teachers. On visit 2, all other

Table 2 Neuropsychological Performance Adjusted for Age for the Four Groups

Measure	ADHD *n*=24 *M*	ADHD *n*=24 *SD*	ADHD+RD *n*=29 *M*	ADHD+RD *n*=29 *SD*	RD *n*=41 *M*	RD *n*=41 *SD*	NC *n*=26 *M*	NC *n*=26 *SD*
Stop Signal Paradigm								
SSRT	268.57	13.74	297.61	12.15	275.05	10.46	238.38	12.91
MRT	520.04	17.32	558.64	15.32	590.64	13.19	490.90	16.28
Omission Errors	2.22	0.91	5.01	0.81	3.23	0.69	0.31	0.86
Commission Errors	6.74	1.20	6.98	1.06	4.14	0.91	3.33	1.13
Corsi Block Tapping test								
WM Maximum Span	4.46	0.18	5.06	0.16	5.00	0.14	5.41	0.17
Lexical Decision[a]								
d′	2.68	0.17	1.99	0.15	2.38	0.13	3.16	0.16
MRT Valid Words	1092.25	70.70	1333.65	61.36	1304.02	51.67	868.78	64.19
MRT Pseudowords	1249.25	84.25	1575.60	73.12	1572.39	61.58	951.62	76.50

ADHD Attention deficit hyperactivity disorder; *MRT* Mean reaction time; *NC* Normal controls; *RD* Reading disorder; *SSRT* Stop signal reaction time; *WM* Working memory

[a]Two children in the ADHD only and one in the ADHD +RD group were missing because they had just started reading instruction and therefore the Lexical Decision task was too difficult.

diagnostic and screening measures were obtained. During visit 3, the Stop Signal Paradigm, Lexical Decision task and Corsi Block Tapping test were administered using standardized instructions. The study was approved by a medical ethical committee.

Data Analysis

For the visuospatial WM task (Corsi Block Tapping test), 2.5% of the data were missing. These missing data were replaced by regression analysis following Tabachnick and Fidell (2007). Data were missing for three children, who had just started reading, on the Lexical Decision task. All variables were normalized using a Van der Waerden transformation based on rankings (Lehmann 1975).

In order to investigate the effects of ADHD, RD and the interactions between both, the dependent variables in the study were analyzed and covaried for age using a between group factorial ANCOVA. The study had a 2×2 design with ADHD as one factor with two levels (present or absent) and a second factor RD with two levels (present or absent). An alpha level of 0.05 was employed. Post-hoc testing was performed with Bonferroni t-tests which were corrected for multiple comparisons.

Results

Inhibition

The age adjusted means are displayed in Table 2 for each of the four groups. The results of the ANCOVA with age as covariate are presented in Table 3.

No speed accuracy trade-off was present in any of the four groups, as indicated by the absence of a negative correlation between MRT and number of commission

Table 3 Effects of ADHD and RD on Neuropsychological Performance Covaried for Age

Measure	ADHD $F(1, 115)$	ADHD η_p^2	RD $F(1, 115)$	RD η_p^2	Interaction $F(1, 115)$	Interaction η_p^2
Stop signal paradigm						
SSRT	3.87[a]	0.03	6.44**	0.05	0.18	0.002
MRT	0.06	0.001	17.52**	0.13	3.20	0.02
Omission Errors	9.54**	0.07	16.71**	0.12	0.81	0.007
Commission Errors	8.62**	0.07	0.86	0.007	0.24	0.002
Corsi block tapping test						
WM Maximum Span	7.07**	0.05	0.23	0.002	8.99**	0.07
Lexical decision[b]						
d′	8.74**	0.07	19.85**	0.15	0.12	0.001
MRT Valid Words	4.68*	0.04	29.70**	0.21	2.37	0.02
MRT Pseudowords	4.07*	0.03	44.19**	0.28	4.35*	0.03

ADHD Attention deficit hyperactivity disorder; *MRT* Mean reaction time; *SSRT* Stop signal reaction time; *RD* Reading disorder; *WM* Working memory

[a]$p=0.052$

[b] Three children were missing

*significant at $p<0.05$, **significant at $p<0.01$

errors in the Stop Signal Paradigm. As expected, children with ADHD (ADHD present) had slower SSRTs compared to children without ADHD (ADHD absent), but this was not significant at the 0.05 level, $F(1, 115)=3.87$, $p=0.052$. This suggests that inhibition deficits were marginally present in children with ADHD. Inhibition deficits were clearly found in RD, see Table 3. Slower primary task processing as measured by MRT was observed in RD but not in ADHD. Both ADHD and RD were associated with lapses of attention during response execution as indicated by more omission errors. Children with ADHD were more impulsive in response execution than children without ADHD, since they committed more commission errors. No significant interaction occurred between ADHD and RD for any of the dependent measures of the Stop Signal Paradigm.

This analysis indicates a clear inhibition deficit in RD with slower processing and impulsivity (commission errors) and marginal inhibition deficits in ADHD. Both ADHD and RD were associated with lapses of attention (omission errors).

Visuospatial WM

Working memory demands had no effect on RD (see Fig. 1 and Table 3). Children with ADHD, as hypothesized, exhibited poorer visuospatial WM than children without ADHD as assessed by WM Maximum Span. A significant ADHD by RD interaction indicated that children with ADHD without RD had significantly poorer visuospatial WM compared to children with both ADHD and RD. The interaction was confirmed by post-hoc tests, ADHD only group versus ADHD+RD group, $t(51)=2.36$, $p<0.05$ and RD only versus normal controls, $t(65)=1.85$, ns.

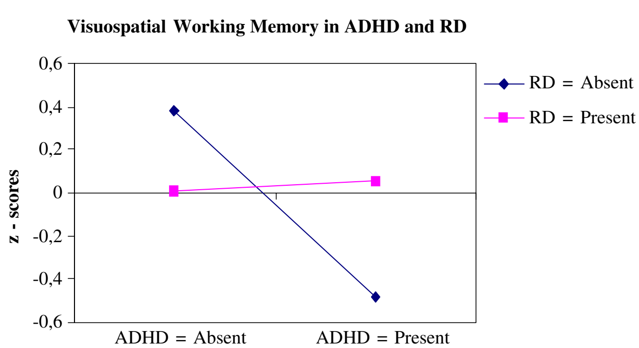

Fig. 1 Visuospatial WM as assessed with Block Sequence in the ADHD, ADHD+RD, RD and normal control groups as indicated by the presence or absence of ADHD and RD. Means were adjusted for age and expressed in z-scores (higher scores indicating better performance). Note: post-hoc testing indicated that the ADHD only group (ADHD present, RD absent) had a significant poorer performance on visuospatial WM than the ADHD+RD group (both ADHD and RD present)

These results demonstrated that children with ADHD had a clear deficit in visuospatial WM in contrast to children without ADHD. Adding ADHD to RD did not lead to a greater deficit in visuospatial WM than in only RD. Therefore, the ADHD main effect was carried by the ADHD only group which had the most pronounced deficits in visuospatial WM.

Lexical Decision

As expected, RD was associated in the lexical decision task with lower d′ and slower MRTs for Valid Words, indicating respectively poorer accuracy in lexical decision and slower decision speed, see Table 3. Children with ADHD were less accurate and slower in lexical decision than children without ADHD. There was no significant ADHD by RD interaction for d′ or MRT Valid Words. ADHD and RD were both associated with slower MRT to Pseudowords, indicating a slower decoding process in both RD and ADHD. A significant ADHD by RD interaction indicated that the ADHD main effect was carried by the ADHD only group, since the ADHD only group was slower on MRT Pseudowords than normal controls but faster than the two RD groups, see Fig. 2. The interaction was confirmed by post-hoc tests. Children with ADHD only were slower than normal controls, $t(46)=2.69$, $p<0.05$ but faster than children with ADHD+RD, $t(48)=3.28$, $p<0.05$ and children with RD, $t(65)=3.58$, $p<0.05$. Children with RD only were slower on Pseudowords than normal controls, $t(65)=6.89$, $p<0.05$. All effects of the lexical decision task were stronger in RD than in ADHD since the RD effect sizes fell in the large range whereas the ADHD effect size fell in the small or medium effect size range.

These results indicate that both RD and ADHD are associated with less accuracy and slower processing in lexical decision making. Both RD and ADHD were associated with decoding processing deficits; RD was associated with slowest decoding processing regardless of

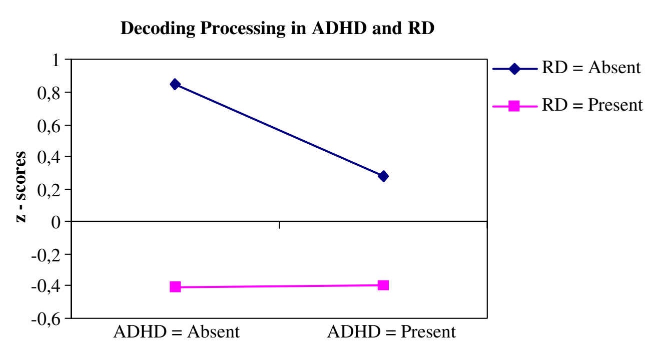

Fig. 2 Decoding processing as assessed by MRT on Pseudowords in the ADHD, ADHD+RD, RD and normal control groups. Means were adjusted for age and expressed in z-scores (higher scores indicate faster processing)

comorbid ADHD. However, the ADHD only group showed slower decoding but not to a level of impaired performance as in the RD groups.

Controlling for Age and IQ

We examined whether our findings for the EF tasks and the Lexical Decision task were independent of both age and IQ, see Table 4. Inspection of Table 4 indicates that all main effects for ADHD were lost after covarying for both age and IQ, with the exception of omission and commission errors. In contrast, the main effects for RD remained significant after covarying for both age and IQ. A significant ADHD by RD interaction emerged for MRT on the Stop Signal Paradigm, indicating that the RD group was slower than the normal control group. This finding was confirmed by post-hoc tests, RD-normal controls, $t(64)=4.36$, $p<0.05$. The other group comparisons were not significant, t-values between 1.02 and 1.91. The two previously observed interactions on visuospatial WM (Corsi Block Tapping test) and decoding processing (MRT on Pseudowords) remained significant, after covarying for both age and IQ.

Discussion

Results of this double dissociation study revealed that RD was associated with inhibitory deficits and slower processing. Impulsivity was associated with ADHD; inhibition deficits were marginally demonstrated in children with ADHD. Both ADHD and RD were associated with lapses of attention. Impairments in lexical decision were present in both ADHD and RD. RD, regardless of ADHD, was invariably associated with slower decoding processing. The ADHD only group had slower decoding processing speed compared to the normal control group but better than the RD groups. The ADHD only group was characterized by visuospatial working memory deficits. Findings for the ADHD factor were related to IQ; whereas findings for the RD factor were independent of IQ. These results indicate that there was no double dissociation observed in this study using a primary measure of inhibition, visuospatial WM and lexical decision making.

The first neuropsychological process in which we sought a double dissociation was inhibition. We observed here clear inhibition deficits in RD and modest inhibition difficulties in ADHD confirming previous reports (Närhi and Ahonen 1995; Purvis and Tannock 2000; Van Der Schoot et al. 2000; Willcutt et al. 2005). One possible explanation for the inhibitory deficits in RD may be that they are secondary to processing speed deficits in RD. Purvis and Tannock found that RD was not associated with inhibition deficits, when processing speed was marginally demanded, e.g. when a single response was required (as in the Conners Continuous Performance test). However, when two choice responses were required, children with RD exhibited inhibition deficits (as in the Stop task). The findings here indicate that inhibition deficits in children with RD are *not* due to processing speed deficits; no significant correlation was found between inhibition (SSRT) and latency of response execution (MRT) in the Stop Signal Paradigm. Thus, inhibition deficits in RD are, at least partly, genuine inhibition deficits.

The second primary EF task used for a possible double dissociation was visuospatial WM. Visuospatial WM impairments were most pronounced in children with ADHD only, and concurs with earlier findings (Martinussen et al. 2005; Marzocchi et al. 2008). Both the ADHD+RD and the RD groups did not differ from each other in visuospatial WM. The most impaired group on visuospatial WM was the ADHD only group. Visuospatial abilities have

Table 4 Effects of ADHD and RD on Neuropsychological Performance Covaried for IQ and Age

Measure	ADHD $F(1, 113)$	ADHD η_p^2	RD $F(1, 113)$	RD η_p^2	Interaction $F(1, 113)$	Interaction η_p^2
Stop signal paradigm						
SSRT	2.03	0.01	4.50*	0.03	0.30	0.003
MRT	0.21	0.002	12.42**	0.09	3.90*	0.03
Omission Errors	4.49*	0.03	11.22**	0.09	1.16	0.01
Commission Errors	7.55**	0.06	0.75	0.007	0.33	0.003
Corsi block tapping test						
WM Maximum Span	1.59	0.01	2.65	0.02	10.76**	0.08
Lexical decision[a]						
d′	2.88	0.02	11.57**	0.09	0.54	0.005
MRT Valid Words	1.50	0.01	20.72**	0.15	2.93	0.02
MRT Pseudowords	1.32	0.01	33.15**	0.23	5.05*	0.04

ADHD Attention deficit hyperactivity disorder; *MRT* Mean reaction time; *SSRT* Stop signal reaction time; *RD* Reading disorder; *WM* Working memory

[a]Three children were missing

*significant at $p<0.05$, **significant at $p<0.01$

been suggested as compensatory skills for the reading deficits in patients with RD (West 1997). The evidence here indicates that visuospatial WM deficits are specifically related to ADHD only and not to RD. This finding suggests that the differentiation of ADHD from RD should be further sought in the area of visuospatial WM.

A clear RD effect was shown on all dependent measures of the lexical decision task, the third measure of interest. Results support the validity of the lexical decision task in children with RD. However, children with ADHD were impaired in lexical decision but to a lesser degree than children with RD. The findings in ADHD may in accordance with findings of Willcutt et al. (2005) who demonstrated that children with ADHD were slightly impaired in orthographical processing compaired to normal controls. The orthographical processing deficits may have been caused by an impaired lexical route that taps orthographic codes.

RD was ubiquitously associated with slower processing in tasks used in the study. Our results contrast with those of Shanahan et al. (2006), who found that processing speed deficits were common to both ADHD and RD. However, our results are consistent with Wolf and Bowers (1999), who found that deficits in processing speed were related to reading difficulties.

A robust finding here was that children with ADHD, regardless of comorbid RD, had lower IQs compared to children with RD only and normal controls. After covarying for IQ, the majority of main effects for ADHD were lost, suggesting that IQ is essentially related in EF and lexical decision in children with ADHD. This finding is consistent with the meta-analysis of Frazier et al. (2004), who showed that IQ effect sizes were larger than for EF when comparing ADHD to controls. Interestingly, RD effects are not modified by IQ. This suggests that there is a functional communality in ADHD for both EF and IQ in contrast to RD. Further work is needed to determine how to use this functional communality to differentiate ADHD from RD.

The failure to find a double dissociation on inhibition, visuospatial WM and lexical decision making should be considered with some issues in mind. Firstly, the sample size was small. However, it should be noted that there were main effects reported here with large effect sizes even with small a sample size Secondly, it could be argued that the ADHD group was poorly diagnosed. This seems unlikely, since we applied a rigorous inclusion and exclusion procedure both in terms of associated psychiatric and neuropsychological disorders. Thirdly, the overlap in lexical decision and the inhibition deficits of RD may have been due to sub-threshold findings of ADHD in RD and vice versa. Children with RD only here had significant elevated ratings of inattention compared to normal controls. Hierarchical regression analyses (results may be obtained from the first author) revealed that following age and IQ, both inattention and technical reading contributed to inhibition deficits. This suggests that inattention and inhibition in the RD groups studied here may have a common functionality. Inattention and technical reading did not contribute to visuospatial WM, after IQ and age. Hence, results on visuospatial WM were independent of technical reading and inattention. Overlap in lexical decision was not due to ADHD symptoms but due to technical reading. Although technical reading abilities were poorer in children with ADHD only than in normal controls, this difference was not significant, which suggest that the overlap in lexical decision was not due to sub-threshold findings of RD in ADHD.

A fourth issue concerns the cognitive domains studied were only inhibition, visuospatial WM and lexical decision. The specificity of the visuospatial WM finding would have been enhanced, if a verbal WM task had been administered. Work by others suggest that verbal WM deficits are not specific to either ADHD or RD (Willcutt et al. 2001, 2005) but that visuospatial WM might be specific to ADHD (Martinussen et al. 2005). Results here suggest that visuospatial WM should be further explored for specific effects and that RD may be better differentiated from ADHD via early lexical decision encoding processes.

A fifth issue concerns the relationship between pragmatics and arithmetic performance. Both were related to the dependent variables (results may be obtained from the first author). Hence, could the overlap in lexical decision in ADHD and RD and less in inhibition deficits be due to confounding effects of arithmetic and pragmatics? Pragmatic deficits were only seen in children with ADHD regardless of comorbid RD, hence pragmatic effects could not account for the inhibition deficit in RD. Arithmetic deficits were seen only in children with RD which may have led to inhibition deficits in RD. In addition, the overlap in lexical decision can not be explained by overlap in arithmetic or pragmatic deficits in ADHD and RD. Notwithstanding, it would be useful in future work to select groups varying along the two processes of arithmetic and pragmatic skills to determine the their role in key EF measures (Jonsdottir et al. 2006).

In this study, we found no double dissociation on lexical decision and inhibition between ADHD and RD. Since the ADHD only group was characterized by visuospatial WM, and children with RD regardless ADHD were slowest on decoding processing compared to ADHD only and normal controls. Visuospatial WM and decoding processing seem more useful candidates to demonstrate a double dissociation.

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