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Bexkens, A.; van den Wildenberg, W.P.M.; Tijms, J.

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Rapid Automatized Naming in Children with Dyslexia: Is Inhibitory Control Involved?

Anika Bexkens[1], Wery P. M. van den Wildenberg[1,2] and Jurgen Tijms[1,3,4]*

[1]*Department of Psychology, University of Amsterdam, Amsterdam, The Netherlands*
[2]*Cognitive Science Center Amsterdam (CSCA), University of Amsterdam, Amsterdam, The Netherlands*
[3]*Rudolf Berlin Center, University of Amsterdam, Amsterdam, The Netherlands*
[4]*IWAL Institute, Amsterdam, The Netherlands*

Rapid automatized naming (RAN) is widely seen as an important indicator of dyslexia. The nature of the cognitive processes involved in rapid naming is however still a topic of controversy. We hypothesized that in addition to the involvement of phonological processes and processing speed, RAN is a function of inhibition processes, in particular of interference control. A total 86 children with dyslexia and 31 normal readers were recruited. Our results revealed that in addition to phonological processing and processing speed, interference control predicts rapid naming in dyslexia, but in contrast to these other two cognitive processes, inhibition is not significantly associated with their reading and spelling skills. After variance in reading and spelling associated with processing speed, interference control and phonological processing was partialled out, naming speed was no longer consistently associated with the reading and spelling skills of children with dyslexia. Finally, dyslexic children differed from normal readers on naming speed, literacy skills, phonological processing and processing speed, but not on inhibition processes. Both theoretical and clinical interpretations of these results are discussed. Copyright © 2014 John Wiley & Sons, Ltd.

Keywords: rapid naming; inhibition; processing speed; phonological processing; dyslexia

Developmental dyslexia is characterized as a specific, severe and persistent deficit in the acquisition of reading and spelling skills that cannot be explained in terms of other cognitive abilities and educational circumstances (Galaburda, LoTurco, Ramus, Fitch, & Rosen, 2006; Grigorenko, 2001). It affects approximately 5–10% of the general population (Zeffiro & Eden, 2000). It is widely assumed that dyslexia is caused by a deficit in phonological processing, which consequently hinders the development of stable phoneme–grapheme associations (Ramus, 2003; Wallace, 2009).

One of the most widely used tests in clinical practice to diagnose children with dyslexia is the so-called rapid automatized naming (RAN) task that assesses the speed with which children name a continuously presented series of highly familiar visual stimuli as rapidly as possible. The stimuli to be named are typically letters,

*Correspondence to: Jurgen Tijms, Rudolf Berlin Center, University of Amsterdam, 1018XE Amsterdam, The Netherlands. E-mail: j.tijms@uva.nl

digits, colours or pictures of familiar objects, and it is assumed that the naming responses are themselves overlearned or automatized (Bowey, McGuigan, & Ruschena, 2005). Children diagnosed with dyslexia typically need more time to name the RAN items compared with age-matched controls (Bowers & Ishaik, 2003; Savage *et al*., 2005; Truman & Hennessey, 2006) irrespective of the orthographic complexity of one's language (Landerl *et al*., 2013; McBride-Chang, Liu, Wong, Wong, & Shu, 2012). Because of the multifaceted nature of the RAN task, we need to specify the cognitive abilities that drive RAN performance in order to understand why children with dyslexia fail on this task, and its association with reading disabilities (Jones, Obregón, Kelly, & Branigan, 2008; Kirby, Georgiou, Martinussen, & Parilla, 2010; Vukovic & Siegel, 2006).

According to the phonological deficit hypothesis of dyslexia, failure on RAN is a behavioural manifestation of a phonological processing deficit that is expressed by disturbances in the online process of activating phonological information during spoken-word production (Galaburda *et al*., 2006; Ramus, 2003; Truman & Hennessey, 2006). Wolf and Bowers (1999), however, demonstrated that phonological capacities alone cannot explain RAN performance. They postulated a double-deficit hypothesis of dyslexia, which assumes that either impairments in RAN or a phonological deficit can cause dyslexia. Individuals with a 'double deficit' are assumed to have more severe reading disabilities than those with a single deficit (Wolf & Bowers, 1999; Norton & Wolf, 2012). Findings supporting the independence of RAN and phonological processing include results revealing the following: (i) correlations between specific measures of phonological processing, such as phoneme awareness, and RAN are only modest (Swanson, Trainin, Necoechea, & Hammill, 2003); (ii) phonological processing and RAN contribute shared and independent variance to reading skills (Moll, Fussenegger, Willburger, & Landerl, 2009; Moll *et al*., 2014); and (c) children with both phonological processing and RAN deficits show the most severe reading deficits (Kirby, Parrila, & Pfeiffer, 2003; Powell, Stainthorp, Stuart, Garwood, & Quinlan, 2007), which is suggestive of a possible cumulative effect of multiple deficit sources.

In addition, it has been suggested that general information processing speed is involved in RAN. General processing speed imposes limits on the speed with which most cognitive processes are executed and is therefore assumed to limit both naming speed and reading speed (Kail & Hall, 1994). Indeed, several studies revealed that naming time was predicted by measures of general processing speed (Kail & Hall, 1994; Kail, Hall, & Casky, 1999; Narhi *et al*., 2005). Furthermore, the results of Kail *et al*. (1999) indicated that naming times and reading skills are associated because both are partly dependent on general speed of processing information (Kail *et al*., 1999). Powell *et al*. (2007) confirmed these findings but also demonstrated that RAN still made a unique contribution to reading after accounting for general processing speed as well as for phonological processing (see for an overview Kirby *et al*., 2010). These results suggest that cognitive mechanisms other than phonology and processing speed may drive RAN performance and its association with reading.

Another potential candidate function for involvement in RAN is inhibitory control. The RAN task usually involves the rapid naming of 50 items from a set of five different exemplars of a category of stimuli. This implies that several stimuli are maintained in working memory in a highly accessible state (cf. Baddeley, 1986) and that the activations of previously named stimuli compete with the current target stimulus for response selection. Inhibition of inappropriate response activation is necessary to select between competing response alternatives and appears to be important for an efficient rapid naming of target stimuli.

A second argument for our hypothesis that RAN performance involves response inhibition is derived from repeated reports that not only children with dyslexia but also children with ADHD attain lower scores on RAN than controls (Tannock, Martinussen, & Frijters, 2000; Waber, Wolf, Forbes, & Weiler, 2000). Both Tannock *et al*. (2000) and Banaschewski, Hasselhorn, Tiffin-Richards, and Rothenberger (2005) revealed that children with ADHD both with and without co-morbid dyslexia were impaired on RAN tasks. This finding suggests that the poor RAN performance of children with ADHD cannot be attributed to the presence of phonological deficits but that another factor impedes their performance. A deficit in inhibitory processing makes a good candidate, as this is generally assumed to be the dominant cognitive deficit in ADHD. Children with ADHD are less able to inhibit irrelevant information (Ridderinkhof, Scheres, Oosterlaan, & Sergeant, 2005) and need more time to interrupt ongoing behaviour when signalled to do so (Barkley, 1999; Dimoska, Johnstone, Barry, & Clarke, 2003; Willcutt, Doyle, Nigg, Faraone, & Pennington, 2005).

Research on involvement of cognitive control mechanisms in general, and inhibitory processes in particular, in RAN is limited. Concerning inhibition, studies have shown a relation between RAN and the Stroop interference task, both in typical readers (Stringer, Toplak, & Stanovich, 2004) and in atypical readers (Amtmann, Abbott, & Berninger, 2007). In this task, the time required to rapidly name the ink colour of colour words written in a different colour of ink is measured (Amtmann *et al*., 2007). As rapid verbal processing of letter strings (although its naming is the to-be-suppressed response) and naming of colours are an integral part of Stroop performance, it is well possible that this naming and letter processing similarities between RAN and Stroop exceed the strength of their association. Indeed, in the study of Stringer *et al*. (2004), the two noninterference conditions of the Stroop task (rapid naming of colours and rapid naming of colour words), the Stroop interference condition and RAN were all significantly intercorrelated.

Savage, Pillay, and Melidona (2007) used the Same World–Opposite World subtest of the Test of Everyday Attention for Children battery to measure inhibition. This task consists of four trials, alternately presenting Same World and Opposite World. In the Same World section, children are required to read the digits 1 and 2 on a visual display. In the Opposite World section, the child has to say 'one' when they see a '2', and vice versa. The Opposite World score was used as a measure of inhibition. It was shown that after controlling for Same World score, the Opposite World score did not explain differences in RAN performance within a sample of typical readers. It should be noted however that the Opposite World appears to load stronger on set switching than on response inhibition, as children are required to shift from giving well-learned responses to novel responses in this test (Wu *et al*., 2011). The role of inhibitory processes in RAN remains thus an open question.

Notably, cognitive control over actions, including inhibitory control, has also been related to the development of reading skills (Gombert, 2003; Klimesh *et al*., 2001; Shaywitz & Shaywitz, 2008). On a cognitive level, the studies of both Savage, Cornish, Manly, and Hollis (2006) and Altemeier, Abbott, and Berninger (2008) suggested involvement of response inhibition in reading processes.

Unfortunately, as verbal measures of response inhibition were used in both studies, it remains unclear whether the verbal character of the task or the inhibitory processes were responsible for the association between task performance and reading skill (cf. Marzocchi, Ornaghi, & Barboglio, 2009). Nonetheless, the aforementioned findings suggest that inhibition might not only be a factor in naming performance itself but might possibly be involved in the association between RAN and reading proficiency as well.

The Current Study

The goal of the present study is to examine the following: (i) whether inhibitory processes explain RAN performance of children with dyslexia and (ii) whether inhibitory processes contribute to the association between RAN performance and reading skills in dyslexia. If inhibitory control is indeed involved in RAN performance, an important question concerns the specification of the underlying inhibition mechanism. Inhibition generally refers to two distinct cognitive control processes: motor control and interference control (Barkley, 1999). If the relation between inhibitory control and RAN performance is caused by the inability to suppress the impact of interfering information, as we have argued earlier, then interference control will be involved. However, the relation can also be caused by an inability to stop a prepotent response (e.g. to stop a behaviour that is already set in motion). To examine the underlying relation between inhibitory control and RAN performance, it is, therefore, important to test both manifestations of inhibitory control. A typical and popular motor control task is the Stop Task (Logan & Cowan, 1984; Van den Wildenberg *et al*., 2006; Verbruggen & Logan, 2008). In this task, participants react to a stimulus by pressing a button (go-response). This prepotent go-response has to be stopped upon the occasional presentation of a stop signal. From the reaction time (RT) distribution in this task, individual stop-signal latencies (stop-signal RT (SSRT)) can be estimated, which quantify the proficiency of stopping control over overt actions (Band, van der Molen, & Logan, 2003).

A typical interference control task is the Simon task (Craft & Simon, 1970). This conflict task is popular in experimental research (Peterson *et al*., 2002; Proctor, 2011; Ridderinkhof, 2002; Van den Wildenberg *et al*., 2011), and other than the commonly used Stroop task, the Simon task does not rely on reading proficiency. In the Simon task, subjects might be instructed to make a speeded left-hand or right-hand response on the basis of the colour of a stimulus that is presented to either the left or right of visual fixation. Although the spatial location of the coloured circle is irrelevant to successful performance on the task, faster RTs and higher accuracy rates occur when the position of the circle spatially corresponds to the response side signalled by the colour of the circle (e.g. a coloured circle that should be responded to by the left hand is presented to the left of fixation). Conversely, RT slows and accuracy rates decrease when the response signalled by the colour of the circle does not correspond (i.e. is noncorresponding) to the spatial location of the circle (e.g. a coloured circle calling for a left-hand response is presented to the right of fixation). The detrimental influence on performance of noncorresponding trials relative to the facilitative influence on corresponding trials is called the *Simon effect* and reflects the proficiency of interference control.

The goal of the present study is to elucidate the role of inhibitory processes in RAN and the RAN–reading relationship. To do so, we tested inhibitory control, phonological processing, general processing speed, RAN and literacy skills in children with dyslexia. As phonological processing is typically measured by phonological awareness and phonological memory, we included both variables in our analyses. Notably, because alphanumeric (letters and digits) RAN tends to correlate higher with reading than nonalphanumeric (colours and objects) RAN (Jones, Branigan, & Kelly, 2009; Kirby *et al*., 2010), we conducted our analyses not only on the total RAN performance but also separately on alphanumeric and nonalphanumeric RAN. We hypothesize that response inhibition predicts RAN, even when phonological skills and general processing speed are accounted for. In addition, test performance of children with dyslexia was compared with that of control participants to quantify the specific contribution of the aforementioned domains to dyslexia.

METHOD

Participants

Children with dyslexia were recruited from the IWAL Institute. IWAL is a nationwide specialized centre for dyslexia in the Netherlands, and the children were referred to IWAL by a variety of sources, including schoolteachers, parents and psychological and educational services. These children were referred because of persistent and specific reading problems. All children were native Dutch speakers and diagnosed as dyslexic after an extensive cognitive diagnostic assessment by IWAL. Participants were selected in the age range of 9–12 years. To be included in the study, participants had to have below-average reading skills (a score of at least one standard deviation (SD) below average on a standardized reading test). Children with below-average IQ ($IQ \leq 85$) and those diagnosed with ADHD or using medication for ADHD symptoms were excluded from the study. Following these selection steps, a total of 86 children with reading disabilities was selected from two consecutive cohorts of referrals ($n_{cohort\,1} = 30$; $n_{cohort\,2} = 56$).

In addition, a group of 31 nondyslexic controls was selected. The control group was matched to cohort 1 on age and sex and was recruited from the same population of schools as those of the dyslexic samples to control for socio-economic status, demography and education. Parental informed consent was obtained for all participants.

Measures

Reading and spelling

Word reading fluency

Word reading skills were assessed by the One-minute Test (Brus & Voeten, 1973). It is a time-limited test consisting of a list of 116 unrelated words of increasing difficulty. The number of correctly read words within 1 min determined the score ($r = 0.89$–0.93, test–retest).

Spelling

Spelling skills were assessed using the Standard Dictation (Tijms & Gerretsen, 2008). The words making up the sentences are familiar to all elementary-school children. Moreover, the collection of words is a representative sample of the various spelling problems in Dutch. Scoring is based upon the number of spelling errors ($r = 0.90$, test–retest).

Text reading accuracy and text reading rate

These measures were assessed by the 'Livingstone' text (Schaap, 1986). This text reading test requires the oral reading of a story consisting of 64 lines of coherent text. Subjects are instructed to read the text as quickly and accurately as possible. The words in the text represent the various problems in the Dutch written language. The total number of reading errors provides the outcome measure for text reading accuracy, and the total time (in seconds) taken for reading the text provides the outcome measure for text reading rate (accuracy: $r = 0.93$–0.94; rate: $r = 0.97$–0.99, test–retest).

Cognitive measures

Phoneme awareness

This was measured by the following: (1) the Phoneme Analysis subtest of the Language Test for Children (TvK; Van Bon, 1984), which requires a child to say the word that results when a sequence of orally presented phonemes are blended ($r = 0.89$, internal consistency) and (2) a Dutch version of the Illinois Test of Psycholinguistic Abilities subtest Auditory Closure (TvK, Word Recognition; Van Bon, 1984), where the child listens to a word in which one or more phonemes are replaced by a short silence and is to say the correct word ($r = 0.74$, internal consistency).

Phonological memory

This was measured by the subtest Digit Span of the Dutch version of the Wechsler Intelligence Scale for Children (WISC-III; Kort *et al*., 2005). The number of digits that a child is able to repeat in correct or reversed serial order immediately after hearing them represents the score in this test ($r = 0.78$–0.85, internal consistency).

Rapid automatized naming

The RAN task consisted of four stimulus cards, respectively containing colours (red, yellow, black, blue and green), numbers (2, 4, 8, 5 and 9), objects (tree, duck, chair, scissors and bike) and letters (a, d, p, s and o). Each stimulus card consisted of five different items, each replicated 10 times. The items were arranged in a pseudo-random order, so that no individual item was repeated successively. The children were instructed to name the stimuli as quickly as possible, and the time taken to name all items of a card was used as the score (Van den Bos, Zijlstra, & Van den Broek, 2003; $r = 0.69$–0.87, test–retest). We used three RAN scores in our analyses: (i) RAN total as the sum of the RT for all four subtests;

(b) RAN numbers and letters as the sum of the RT for the number and letter cards; (iii) RAN colours and objects as the sum of the RT for the colour and object cards.

Vocabulary This was assessed by the subtest Vocabulary of the WISC-III (Kort *et al*., 2005; $r = 0.90$, test–retest) on which children are required to define a set of words that gradually increase in complexity.

General processing speed

A *choice RT task* was administered, which is a widely used measure to assess general processing speed (cf. Fry & Hale, 2000; Tuch *et al*., 2005). Participants were instructed to react as fast as possible to central screen arrows without making too many errors, by pressing the right button with their right hand when the arrow pointed right and the left button with their left hand when the arrow pointed left. The stimuli were response terminated. When no button was pressed, the arrow disappeared after 1500 ms. Between-trial intervals ranged from 1750 to 2250 ms. The task consisted of one practice block and two experimental blocks of 56 trials each.

Response inhibition: motor control

Motor control was measured by the *Stop-signal Task*. On this task, participants performed the choice task as described previously, but on 25% of the trials, the arrow changed colour (from green to red) at different intervals, upon which the choice response had to be stopped (stop trials). The initial duration of this interval was 200 ms. Depending on the performance of the participant, the intervals increased or decreased by 50 ms. When the subject succeeded in withholding the response, the interval was increased with 50 ms (making it more difficult to inhibit on the next stop trial). If the participant failed to withhold the response, the interval was shortened by 50 ms. The timing of the colour change, thus, was dynamically adjusted and targeted at 50% correct inhibits (Logan, Schachar & Tannock, 1997). The task consisted of one practice block and four experimental blocks of 56 trials each.

Calculation of the stop-signal RT

From the RT distribution on this task, an SSRT can be calculated for each participant. The SSRT was estimated using the horse-race model, which assumes that the stopping and reaction processes compete for reaching a finishing time (Logan & Cowan, 1984). The RT distribution of the go process is independent of the presentation of the stop signal. The left side of the RT distribution (fast go RT) of nonsignal trials thus matches the RT distribution of stop trials that escape inhibition. The latency of the stop process can be estimated from the start and finish of the stop process. The start of the process is manipulated through the stop-signal delay. The finish time had to be inferred from the observed go-signal RT distribution. If responses are not inhibited on n% of the stop trials, the finish of the stop process should be equal to the nth percentile of the go RT distribution. The SSRT was calculated by subtracting mean stop-signal delay from the nth go RT

(Logan, 1994). A more detailed description can be found in the work of Colzato, Jongkees, Sellaro, van den Wildenberg, and Hommel (2014). The version of the Stop-signal Task used in the present study has been shown to have a good internal reliability (intraclass correlation coefficient = 0.72 for the SSRT; Soreni, Crosbie, Ickowicz, & Schachar, 2009).

Response inhibition: interference control

Interference control was measured by the *Simon task* (Craft & Simon, 1970). On this task, participants were instructed to press a left button (labelled with a green sticker) when the circle that appeared on screen was green and press the right button (labelled with a blue sticker) when the circle was blue. Participants only had to respond to the colour of the circle. The circles could, however, appear left or right of a central screen fixation point. Performance on this task is optimal when participants are able to take into account the relevant task aspect of the signal (colour) and ignore the irrelevant aspect of the signal (location). The task consisted of congruent and incongruent trials. In the congruent condition, the response hand signalled by the colour of the circle corresponded with the location of the circle (a green circle coupled with a left button press was presented to the left of fixation). In the incongruent condition, the location of the circle and the correct response hand do not correspond (a green circle coupled with a left button press that is presented to the right of fixation). The task consisted of one practice block and four experimental blocks of 56 trials each. Colour–hand instructions were counterbalanced between participants. The Simon effect was calculated by subtracting mean RT on the congruent trials from the mean RT on the incongruent trials.

In addition to the mean Simon effect, which is an RT measure of interference control, we computed delta plots that capture the dynamics of the Simon effect as a function of response speed. For a proper understanding of delta plots, it is important to look into the temporal dynamics of interference control. Ridderinkhof (2002) proposed a dual-process model of response inhibition: the activation–suppression hypothesis. A schematic representation of this hypothesis is depicted in Figure 1. The activation–suppression hypothesis proposes that activation related to the irrelevant stimulus features is selectively inhibited. This selective inhibition,

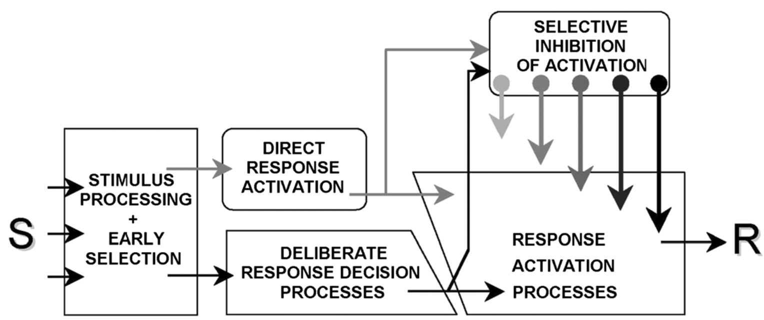

Figure 1. Elementary architecture of the dual-process model. The inhibition mechanism acts selectively upon response activation processes that are associated with the direct response activation route. The increasing size of the arrows from the suppression module schematically represents the operating dynamics of this module (i.e. suppression is not operational immediately and takes some time to build up; adopted from Ridderinkhof *et al*., 2005).

however, needs time to build up. Response inhibition thus gradually builds up as time progresses across a trial. Slower responses benefit more by selective response inhibition than faster responses. Faster responses will be less affected by selective response inhibition and will follow a direct route to response execution. This automatic route will facilitate correct responses on congruent trials but will interfere with the correct response on incongruent trials. With slower responses, the selective response inhibition has had time to build up, and this causes the activation of the incorrect response along the direct route to decrease. See Ridderinkhof, Van den Wildenberg, Wijnen, and Burle (2004) for a more comprehensive account of delta plots to quantify interference control.

Following Wylie *et al*. (2010), we used the first slope of the delta plot as a specific interference measure. An initial positive-going slope is associated with increasing interference between the incorrect response impulse and the correct goal-directed response (Wylie *et al*., 2010).

Thus, delta plot analyses empirically show an early automatic response impulse that is distinct from a later controlled top-down response suppression mechanism, whereas the mean RT of the Simon effect blends these two temporally separated processes. The version of the Simon task used in the present study has been shown to have a good reliability ($r = 0.87$–0.89; Wöstmann *et al*., 2013).

Procedure

Phonological and rapid naming tasks were administered during the diagnostic assessment of dyslexia. After the assessment, participants were asked to take a place at a computer station where two external buttons were installed at the table. After instructions, either the choice RT task or the Simon task started. Task order was counterbalanced. Each task started with a practice block. After each block, the experimenter repeated the instructions and continued the task. If accuracy was below 95% on an experimental block, one extra block was added after the last block.

RESULTS

In the first part of the study, 30 participants performed the stop task as well as the Simon task, choice RT task and the phonological tasks. Two of these participants were excluded from analysis because of missing data. In the second part of the study, 56 additional participants were tested. Three of these participants were excluded because of missing data. Summary statistics for all experimental tasks for the total sample of 81 children with dyslexia are presented in Table 1. As can be seen from Table 1, word reading fluency, text reading rate and spelling skills of the dyslexic groups were all substantially below the average level of the age-referenced normative sample, whereas their text reading accuracy was only slightly lower than average. Notably, this latter finding is typical for dyslexic readers in more transparent languages, such as Dutch (e.g. Landerl & Thaler, 2005).

Dyslexic Readers Compared with Nondisabled Readers

In order to examine on which of our measures of interest the dyslexic readers deviated from their typical reading peers, we compared the performances on

Table 1. Descriptive statistics of the dyslexic sample ($N = 81$)

Measure		*M*	*SD*
Control variables			
Age (years : months)		10:9	1:2
Gender (M : F)		56:28	
IQ		107.22	8.57
Cognitive variables			
Phoneme analysis (RS)		23.04	3.96
Auditory closure (RS)		24.02	2.52
Digit Span (RS)		11.51	2.03
RAN letters (s)		27.70	6.34
RAN numbers (s)		28.53	6.62
RAN objects (s)		47.88	9.59
RAN colours (s)		45.93	10.20
RAN total (s)		150.04	27.94
Choice task			
RT (ms)		545	111
Accuracy (%)		88.66	3.89
Stop-signal task			
Response execution			
Go RT (ms)		608	85
Accuracy (%)		94.17	17.52
Response inhibition			
SSRT (ms)		242	57
Accuracy (%)		50.22	3.94
Simon task			
Congruent trials			
RT (ms)		652	114
Accuracy (%)		95.59	3.59
Incongruent trials			
RT (ms)		694	111
Accuracy (%)		92.18	4.89
Effect index			
Simon effect (ms)		42	33
Reading and spelling variables			
Word reading fluency	RS	50.12	14.40
	SS	80.86	13.44
Text reading accuracy	RS	35.99	19.83
	SS	93.52	14.91
Text reading rate	RS	523.72	159.49
	SS	73.83	25.99
Spelling	RS	45.24	29.48
	SS	75.49	14.31

Note. Text reading accuracy: $n = 69$. Text reading rate: $n = 70$. Stop-signal Task: $n = 30$.
RS, raw score; SS, standard scores (100 ± 15); RAN, rapid automatized naming; RT, reaction time.

inhibition, processing speed, phonology, RAN and the literacy skills of the cohort 1 dyslexic sample with those of a nondyslexic sample that was matched on age and sex. Additionally, two subtests of the WISC-III, that is, Vocabulary and Block Design, that show a high correlation with respectively Verbal IQ ($r = 0.86$) and Performance IQ ($r = 0.77$; Kort *et al*., 2005) were administered to test for differences in general cognitive abilities. *t*-Tests (two-tailed) were used to investigate differences between the groups for continuous measures, and chi-square was used for the categorical variable.

The results of these analyses are presented in Table 2. As can be seen in Table 2, there was a clear difference in word reading fluency between dyslexic readers and controls, with the control group reading about 50% more words within a minute than the dyslexic group. In terms of age-referenced standardized scores (having a mean of 100 and an SD of 15), the control group had approximately an average level of word reading fluency ($M = 105.71$, $SD = 14.26$), whereas the word reading level of the dyslexic readers ($M = 79.46$, $SD = 14.49$) was substantially below the mean of the age-related normative sample. The results of the *t*-tests showed that dyslexics and nondyslexics did not differ on their general cognitive capacities, age and sex ratio. Significant differences were revealed between children with dyslexia and nondyslexic controls on general processing speed (choice RT), as well as on word reading fluency, phonological memory (Digit Span) and all RAN measures. Dyslexic readers did not differ significantly from nondyslexic readers on the two response inhibition measures (Stop Task SSRT and Simon effect). Notably, after correction for multiple comparisons (false discovery rate; Benjamini & Hochberg, 2001), one difference, that is, phoneme analysis, was no longer considered statistically significant.

Contribution of Inhibitory Control and Other Predictor Variables in Naming Speed

As stated in the introduction section, we expected motor control to be uncorrelated with RAN. Therefore, we first analysed the results for the stop task in a subsample of children (cohort 1, $n = 30$). Hierarchical regression analysis was used to test whether SSRT contributed to the model, after age and general speed were accounted for. The results revealed that SSRT did not explain RAN performance, $F = 0.38$, $p = 0.85$. Adding SSRT to the model caused only a 0.1% change in explained variance of RAN. This finding indicates that stop performance is not a meaningful predictor of RAN performance. As SSRT did not contribute to the

Table 2. Descriptive statistics and differences between the dyslexic and the nondyslexic children

	Dyslexic ($N = 28$)		Nondyslexic ($N = 31$)			
	M	(*SD*)	*M*	(*SD*)	*t*	Cohen's *d*
Age (years : months)	10:11	(1:1)	11:2	(1:0)	0.83	
WISC vocabulary	35.52	(7.29)	37.97	(5.51)	1.39	
WISC block design	46.82	(11.11)	49.39	(9.39)	0.91	
Word reading fluency (RS)	50.79	13.32	75.53	12.73	7.43***	1.89
PA phoneme analysis	22.63	(3.83)	24.53	(3.48)	2.04*	0.52
PA auditory closure	24.03	(2.39)	24.87	(2.09)	1.46	
PM Digit Span	10.96	(2.10)	13.97	(2.61)	4.87***	1.27
RAN letters and numbers (s)	54.86	(11.05)	44.97	(8.50)	−3.94***	1.00
RAN colours and objects (s)	89.66	(17.26)	76.59	(13.32)	−3.33**	0.85
RAN total (s)	144.52	(25.87)	121.56	(14.02)	−4.36***	1.10
Choice RT (ms)	545	(112)	471	(72)	−4.21***	0.79
Stop task SSRT (ms)	242	(57)	258	(43)	1.21	
Simon effect (ms)	41	(34)	36	(33)	−0.78	
Gender (M : F)	18:12		17:15		0.30[a]	

Note. PA, phoneme awareness; PM, phonological memory; WISC, Wechsler Intelligence Scale for Children; RS, raw score; RAN, rapid automatized naming; RT, reaction time; SSRT, stop-signal reaction time.
[a]χ^2 statistic.
***$p < 0.001$, **$p < 0.01$, *$p < 0.05$.

prediction of RAN performance, we decided to drop SSRT from further analyses (to preserve power of the regression analyses and to avoid exposing children to unnecessary testing).

Subsequently, hierarchical regression analyses were performed for the full sample of children with dyslexia ($N = 81$). After controlling for age in step 1, processing speed was entered in step 2, phoneme awareness and phonological memory were entered in steps 3 and 4, respectively, and finally the two interference control measures, that is, Simon effect and activation slope, were entered in respectively steps 5 and 6 to test whether they explained additional variance in RAN performance.

It is repeatedly reported that alphanumeric RAN (letters and numbers) is more strongly related to reading than nonalphanumeric RAN (colours and objects; Jones *et al*., 2009; Kirby *et al*., 2010); we therefore decided to run three separate models with, respectively, RAN total, RAN numbers and letters and RAN colours and objects as the regressor variable. The results of these analyses are presented in Table 3. The results of the model with RAN total as regressor variable showed that, after controlling for age, both processing speed and phoneme awareness accounted for a significant amount of the variance in RAN performance. Phonological memory did not contribute to RAN. Additionally, it was revealed that the final two steps, entering the predictors Simon effect and activation slope, also led to significant changes in R^2. These two interference control measures together captured 15% of the variance in the total RAN performance. A comparison of the results for RAN numbers and letters and those for RAN colours and objects reveals some interesting findings. In contrast to processing speed that accounts for a constant amount of variance in RAN performance, phoneme awareness is only a

Table 3. Hierarchical regression analyses for variables predicting RAN performance ($N = 81$)

Regressor	Step	Predictors	ΔR^2	ΔF	*p*
RAN total	1	Age	0.17	16.43	<0.001
	2	Processing speed	0.20	24.67	<0.001
	3	Phoneme awareness	0.07	4.93	0.010
	4	Phonological memory	0.01	0.75	0.391
	5	Simon effect	0.06	8.19	0.004
	6	Activation slope	0.09	15.93	<0.001
		Total R^2	0.60		
Number and letter RAN	1	Age	0.15	13.51	<0.001
	2	Processing speed	0.17	19.48	<0.001
	3	Phoneme awareness	0.11	7.19	0.001
	4	Phonological memory	0.01	1.28	0.262
	5	Simon effect	0.03	3.67	0.059
	6	Activation slope	0.07	11.00	0.001
		Total R^2	0.54		
Colour and object RAN	1	Age	0.14	12.93	0.001
	2	Processing speed	0.16	18.01	<0.001
	3	Phoneme awareness	0.04	2.21	0.117
	4	Phonological memory	0.00	0.26	0.614
	5	Simon effect	0.06	7.49	0.008
	6	Activation slope	0.08	10.61	0.002
		Total R^2	0.48		

Note. Step 3 phoneme awareness: this factor consists of both phoneme analysis and auditory closure.
RAN, rapid automatized naming; RAN total, composite score of all four RAN subtests.

significant predictor of RAN numbers and letters, whereas the interference control measures, in particular the Simon effect, appear to be more strongly associated with RAN colours and objects than with RAN numbers and letters.

Predictors of Reading and Spelling Skills

In a second series of hierarchical regression analyses, the impact of processing speed, phoneme awareness, interference control and RAN on four reading and spelling measures was examined (Table 4). After controlling for age in step 1, processing speed was entered in step 2, phoneme awareness in step 3, phonological memory in step 4 and interference control (both Simon effect and activation slope) in step 5. RAN was entered in the final step to test its impact on reading when taking processing speed, phoneme awareness, phonological short-term memory and interference control into account. Separate models were run with respectively RAN total, RAN numbers and letters and RAN colours and objects as the predictor variable.

When entered as the first predictor after age, RAN total contributes variance to both word reading fluency and spelling (model 1, step 2a). However, after processing speed, phoneme awareness and interference control were accounted for, RAN was no longer predictive for the reading and spelling performances (model 2, step 6a).

In addition to RAN total, Table 4 also presents the results for RAN numbers and letters and those for RAN colours and objects separately. RAN numbers and letters is shown to be significantly associated with word reading fluency, text reading rate and spelling when entered as the first predictor after age (model 1, step 2b). In contrast to the results of RAN total, RAN numbers and letters still explains a significant proportion (9%) of the variance in word reading fluency (but not in text reading rate and spelling) after controlling for the effects of processing speed, phoneme awareness, phonological memory and interference control (model 2, step 6b). The only significant association of RAN colours and objects is with spelling when entered as the first predictor after age (model 1, step 2c).

Furthermore, processing speed is a significant predictor of word reading fluency and text reading accuracy and marginally significant ($\Delta F = 3.84$, $p = 0.053$) for text reading rate (model 2, step 2). In addition to the variance explained by processing speed, our phonological measures showed significant associations with reading and spelling, although phoneme awareness only so with the two reading rate measures, whereas phonological memory was most strongly associated with the two accuracy measures, that is, text reading accuracy and spelling (model 2, step 3/4). Interference control, when entered after processing speed and phonology, did not explain any variance in reading or spelling (model 2, step 5).

DISCUSSION

The present study was designed to examine the role of inhibitory processes, phonological abilities and processing speed as underlying cognitive mechanisms in RAN. In particular, our goal was to elucidate the role of inhibitory processes in naming speed.

Table 4. Hierarchical regression analyses for variables predicting reading and spelling skills ($N = 81$)

Step	Predictors	Word reading fluency ($N = 81$)			Text reading accuracy ($N = 69$)			Text reading rate ($N = 70$)			Spelling ($N = 81$)		
		R^2	ΔR^2	ΔF	R^2	ΔR^2	ΔF	R^2	ΔR^2	ΔF	R^2	ΔR^2	ΔF
Model 1: RAN entered directly after age													
1	Age	0.26	0.26	28.39***	0.22	0.22	18.81***	0.12	0.12	9.06**	0.12	0.12	9.72**
2a	RAN total	0.34	0.08	9.42**	0.24	0.02	1.23	0.16	0.04	2.96	0.20	0.08	7.47**
2b	RAN letters and numbers	0.45	0.18	25.77***	0.23	0.01	0.57	0.28	0.15	13.81***	0.20	0.08	7.33**
2c	RAN colours and objects	0.29	0.02	2.21	0.24	0.02	1.30	0.12	0.00	0.11	0.18	0.06	5.09*
Model 2: RAN entered as last predictor													
1	Age	0.26	0.26	28.39***	0.22	0.22	18.81***	0.12	0.12	9.06**	0.12	0.12	9.72**
2	Processing speed	0.31	0.04	4.65*	0.33	0.11	10.05**	0.17	0.05	3.84	0.16	0.04	3.40
3	Phoneme awareness	0.37	0.07	4.11*	0.38	0.05	2.62	0.26	0.09	3.69*	0.17	0.01	0.53
4	Phonological memory	0.40	0.03	3.55	0.43	0.06	6.04*	0.26	0.00	0.01	0.25	0.08	7.65**
5	Interference Control	0.41	0.00	0.23	0.45	0.01	0.70	0.27	0.01	0.50	0.26	0.01	0.45
6a	RAN total	0.42	0.01	1.67	0.45	0.00	0.00	0.27	0.00	0.08	0.29	0.02	2.18
6b	RAN letters and numbers	0.50	0.09	12.73**	0.45	0.00	0.21	0.31	0.05	3.89	0.29	0.03	2.29
6c	RAN colours and objects	0.41	0.00	0.07	0.45	0.00	0.04	0.30	0.03	2.35	0.28	0.01	1.14

Note. Models with different subscripts (a, b or c) are separate models.
RAN, rapid automatized naming.
$^*p < 0.05$. $^{**}p < 0.01$. $^{***}p < 0.001$.

Cognitive Mechanisms Involved in Rapid Automatized Naming

We examined the role of two distinct response inhibition processes, that is, motor control and interference control, whereby motor control refers to the ability to stop a prepotent response and interference control refers to the ability to suppress the impact of interfering information. In line with our expectations, the results revealed that interference control, but not motor control, was significantly related to RAN performance. Notably, this relation of interference control with RAN was significant after accounting for processing speed as well as phonological abilities. The interference control measures together captured 15% of the variance in the total RAN performance. It was thus shown that those dyslexic individuals with poorer interference control had poorer performances on the RAN tasks. Although significantly related to both types of RAN tasks, the results further revealed that interference control, in particular the magnitude of the Simon interference effect, appeared more strongly associated with RAN colours and objects than with RAN numbers and letters.

We can therefore conclude that interference control is one of the cognitive processes involved in RAN. The RAN tasks consisted of the rapid naming of 50 items from a set of five different exemplars of a category of stimuli. This implies that several stimuli are maintained in working memory in a highly accessible state (see results of Jones, Branigan, Hatzidaki, and Obregón, 2010, for support of this account of the naming process) and that the activations of previously named stimuli compete with the current target stimulus for response selection. Our results suggest that the inhibition of inappropriate response activation is necessary to select between competing response alternatives and is therefore important for an efficient rapid naming of target stimuli. It is interesting to take a closer look at the apparently stronger association of response inhibition with colour and object naming than with the naming of letters and numbers. Colours and object terms refer to categories with variable and overlapping boundaries, and often more than one plausible name for a given stimulus is present. In this sense, colours and objects are categories of stimuli with fuzzy semantic boundaries (Tannock *et al*., 2000). In contrast, letter and number terms have well-defined, nonoverlapping boundaries and belong to categories with a limited set of stimuli. This implies that, in contrast to letters and numbers, colours and objects give rise to response competition of alternative candidate names (Tannock *et al*., 2000), above that of the competing stimuli of the RAN task. The naming of colours and objects therefore appears to put greater demands on inhibition control mechanisms than that of letters and numbers.

Besides the role of interference control, our results further demonstrated that both processing speed and phoneme awareness contribute to RAN performance. Interestingly, when RAN was divided into alphanumeric and nonalphanumeric naming speed, it was shown that phoneme awareness was significantly related to letter and number naming (explaining 11% of the variance), but not so to the naming of objects and colours. This finding suggests that the component in dyslexic individuals' naming speed performances that is shared with phoneme awareness is unrelated to problems with accessing phonological representations or output phonology because in these cases nonalphanumeric RAN should also be related to phoneme awareness. Instead, findings point to the involvement of prelexical processes.

Processing speed was shown to be the strongest contributor to naming speed, explaining 20% of the variance in RAN performance of dyslexic readers. In contrast to the other two factors, processing speed accounted for a constant amount of variance in RAN performance over alphanumeric and nonalphanumeric tasks. This finding appears to be in accordance with the studies of Kail and colleagues (Kail & Hall, 1994; Kail *et al*., 1999) and seems confirmative of their assumptions that RAN taps the general speed at which cognitive processing occurs (Kail *et al*., 1999). It should however be noted that different measures are used in the pertinent literature for general processing speed. In the present study, a basic (visuospatial) choice RT task was used to measure processing speed, whereas Kail and colleagues used more complex measures such as matching of two identical digits in a row of digits (Kail & Hall, 1994; Kail *et al*., 1999). The results of multitask experiments suggest that different processing speed measures that span a wide range of complexity all index a general or task-independent construct of processing speed (Fry & Hale, 2000). Accordingly, Powell *et al*. (2007) showed substantial correlations within a dyslexic sample between scores on a choice RT task and on a matching task comparable with the ones used by Kail and colleagues (Kail & Hall, 1994; Kail *et al*., 1999). Nonetheless, as our task might tap a partly different construct than that indexed by Kail and colleagues, there needs to be some caution in the linking of these results.

In sum, the present study is compatible with previous studies by showing that both general processing speed and phonological abilities are involved in RAN. It extends the existing literature by demonstrating that response inhibition, more specifically cognitive interference control, is an additional cognitive mechanism involved in RAN performance. Our results, thus, emphasize the multifaceted nature of the RAN task.

Why Naming Speed Is Related to the Reading and Spelling Skills of Children with Dyslexia

In a series of hierarchical regression analyses, we examined the impact of RAN, processing speed, phonological abilities and interference control on four reading and spelling measures. As expected, when entered first (after controlling for age), RAN was a clear predictor of reading and spelling skills. Differences in processing speed, phonology and interference control were considered as potential explaining factors of the RAN–reading relationship, and therefore in a subsequent series of analyses, these variables were entered into the regression equation before RAN. After variance in reading and spelling associated with processing speed, inhibitory control and phonology was partialled out, naming speed was no longer consistently associated with the reading and spelling skills of children with dyslexia. Naming speed, as reflected by the total RAN performance, was left explaining only 0–2% of the variance in literacy skills. Only one significant association remained present, that is, the association of alphanumeric RAN with word reading fluency. This is a notable result, as in the pertinent literature, naming speed is always reported to retain a significant relation with reading.

Although the association of alphanumeric RAN with word reading fluency was the only association that retained its significance, this appears to be an interesting one. Successful acquisition of letter–speech sound mappings appears to be crucial in learning to read. For the development towards a fluent reader, this letter–speech sound mapping must be both accurate and rapid (Wallace, 2009). Letter–sound pairs appear to develop into unique audiovisual objects that enable fluent or rapid word reading (Blau, van Atteveldt, Ekkebus, Goebel, & Blomert, 2009). Dyslexic readers however show a persistent failure to develop this automatic letter–speech sound integration (Blau *et al*., 2009; Blomert, 2011; Wallace, 2009), and dyslexic readers' poor letter–speech sound binding has been shown to correlate with their word reading fluency (Aravena, Snellings, Tijms, & van der Molen, 2013; Froyen, Willems, & Blomert, 2011). As orthographic–phonetic mapping appears to be a factor distinguishing alphanumeric from nonalphanumeric naming, it seems reasonable to assume that alphanumeric RAN has a specific sensitivity for the quality of these letter–speech sound mapping processes, thus associating RAN with the word reading fluency of dyslexic children (cf. Jones *et al*., 2010; Moll *et al*., 2009; Vaessen & Blomert, 2010). Interestingly, the acquisition of letter–speech sound associations has been shown to boost the development of phoneme awareness (Castles, Wilson, & Coltheart, 2011; Dehaene, 2009; Fletcher-Flinn, Thompson, Yamada, & Naka, 2011). This fits with our finding that phoneme awareness was associated with alphanumeric RAN, but not nonalphanumeric RAN.

Another notable result from our analyses was that interference control did not make a unique contribution to the reading and spelling skills of children with dyslexia. This finding suggests that although interference control is a cognitive mechanism involved in RAN and thus a potential cause of poor RAN performance, it appears not to be involved in the relation of RAN with reading and spelling skills.

Thus, our findings suggest that the relation between naming speed and reading skills can be largely explained by the shared variance with phonological abilities and processing speed, as well as arguably by letter–speech sound integration processes manifested by alphanumeric naming speed only.

The Performance of Dyslexic Readers Compared with that of Nondyslexic Readers

We contrasted the performance of the dyslexic readers on the experimental variables with that of a group of nondyslexic readers, which was comparable with respect to age, sex ratio, general cognitive abilities and schooling background. As expected, the dyslexic group deviated significantly from the nondyslexic controls on all reading and spelling skills, RAN and phonological abilities (in particular on phonological memory).

With regard to inhibitory control, our results showed that children with dyslexia do not differ from nondyslexic children on motor control, nor on interference control. This finding suggests that although interference control is a cognitive mechanism that is involved in RAN, it does not appear to be a factor contributing to the poor performance on RAN of children with dyslexia.

In contrast, the dyslexic readers were significantly impaired in general processing speed, as measured by a (visual) basic choice RT task. This speed impairment seems not to be due to IQ, as no significant differences were present between the dyslexic and nondyslexic readers on IQ measures. This finding is in agreement with several previous studies indicating slower or more variable processing speed in reading-disabled children (Catts, Gillispie, Leonard, Kail, & Miller, 2002; Shannahan *et al*., 2006). Notably, a deficit in processing speed appears not to be a dyslexia-specific deficit, as this is also reported in other developmental disorders, especially ADHD (Goth-Owens, Martinez-Torteya, Martel, & Nigg, 2010; Shannahan *et al*., 2006; see also Miller, Kail, Leonard, & Tomblin, 2001 for specific language impairment).

Although this study was not oriented towards children with ADHD, it seems to provide some insight into their RAN performance. Children with ADHD have repeatedly been shown to perform poorly on naming speed tasks, especially on the rapid naming of colour and objects. Poor inhibition is generally considered a typical characteristic of ADHD, and children with ADHD have also been shown to perform poorly on processing speed measures. As the present study revealed a relation of RAN with processing speed and inhibition, the latter especially on colours and object naming, it provides a reasonable explanation for the characteristics of the RAN performance of children with ADHD. Obviously, a replication of the study with ADHD children is needed to confirm this.

From a clinical point of view, our results support the sensitivity of rapid naming, in particular alphanumeric naming, as a cognitive indicator for dyslexia, as it appears to be tapping both poor phonological and letter–speech sound mapping processes that are characteristic for dyslexia and dyslexic children's poor processing speed. At the same time, our results raise some note of caution concerning the specificity of RAN, as the processing speed involved in RAN can also be associated with other developmental disorders and poor inhibitory processes that are atypical for dyslexia also impair rapid naming performance.

Limitations

It is good to note that our predictors explained between 48% and 60% of the variance in RAN performance. Although this seems to justify the conclusion that phoneme awareness, processing speed and response inhibition are important factors in RAN performance and in the RAN–reading relationship, it is clear that a substantial proportion of RAN variance remains unexplained. This unexplained variance can partly be attributed to test reliabilities. However, some factors were absent in the present study that have previously been suggested to be involved in RAN, for example, serial processing demands (De Jong, 2011), (para)foveal visual processing (Jones, Ashby, & Branigan, 2013) and articulation and pause times of naming (Georgiou, Papadopoulos, Fella, & Parrila, 2012). A future, more elaborated study including more variables would nonetheless be interesting as it might give a more complete view on the different factors involved in RAN, their intercorrelations and their relative weights in explaining RAN performance.

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