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ABSTRACT

Although poor Rapid Automatized Naming (RAN) is a risk factor for reading and/or spelling difficulties (RSD) as well as for mathematical difficulties (MD), many questions surround this relationship. The main objective of the present study was to obtain insight in the relationship between alphanumeric vs. non-alphanumeric RAN and reading/spelling and mathematics in groups of 7-to-10-year-old children with RSD, MD, both RSD + MD, and in typically developing (TD) children. Analyses of variance between the groups showed that the RSD and comorbid (RSD + MD) groups were impaired on both alphanumeric and non-alphanumeric RAN, whereas the MD group was impaired only on non-alphanumeric RAN. Furthermore, non-alphanumeric RAN correlated with all measures except spelling, whereas alphanumeric RAN correlated with the reading and spelling measures only. These findings point towards different/additional cognitive processes needed in non-alphanumeric RAN compared to alphanumeric RAN, which affects the relationship with literacy and math.

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1. Introduction

The high comorbidity between reading and/or spelling difficulty (RSD) and mathematical learning difficulty (MD; e.g., Badian, 1999; Kovas et al., 2007; Landerl & Moll, 2010) makes research on the cognitive underpinnings of both an important subject of research. RSD (or dyslexia) is characterized by severe and persistent reading and/or spelling difficulties at word level (Snowling, 2000). MD (or dyscalculia) is defined as a severe and persistent problem in learning and quickly and/or accurately retrieving or applying mathematical knowledge (Ruijssenaars, Van Luit, & Van Lieshout, 2006). Studies describing the relationship between RSD and MD report two different conclusions regarding the shared underlying causes. One finding is that the cognitive profiles of children with RSD and children with MD seem to be largely different (e.g. Landerl, Fussenegger, Moll, & Willburger, 2009; Rubinsten & Henik, 2006; Tressoldi, Rosati, & Lucangeli, 2007; Willburger, Fussenegger, Moll, Wood, & Landerl, 2008). Another is that RSD and MD are linked and share some common underlying etiology (e.g. Simmons & Singleton, 2009; Vukovic, Lesaux, & Siegel, 2010; Willcutt et al., 2013). The present exploratory study contributes to this discussion by examining the role of one of the most promising candidates for explaining the overlap between RSD and MD: Rapid Automatized Naming (RAN). RAN is the ability to quickly retrieve and provide the names of highly familiar symbols (colors, pictures, digits, and letters; as designed by Denckla & Rudel, 1974).

Multiple issues surround the relationship between RSD, MD, and RAN. They are broadly divided into two clusters. The first issue pertains to the question which cognitive processes underlie RAN. In the field of literacy, some researchers have proposed that RAN is related to phonological processing. Within this view, one interpretation is that RAN mainly reflects the ability to access and rapidly retrieve phonological representations of orthographic codes from long-term memory (e.g. Bowey, McGuigan, & Ruschena, 2005; Lervåg & Hulme, 2009; Snowling, 2001; Torgesen, Wagner, Rashotte, Burgess, & Hecht, 1997). Others have purported that RAN predominantly taps skills related to rapid integration of phonological and visual processes (Manis, Seidenberg, & Doi, 1999; Wolf & Bowers, 1999; Wolf & Denckla, 2005), relevant for both orthographic and numeric representations (Georgiou, Tziraki, Manolitsis, & Fella, 2013). Related, RAN has been interpreted as measuring phonological processing speed combined with fast cross-modal matching of visual symbols and phonological codes (Vaessen, Gerretsen, & Blomert, 2009). In contrast to these phonology-related interpretations, it has also been proposed that poor RAN reflects a general access deficit in dyslexia (Jones, Branigan, Hatzidaki, & Obregón, 2010). This debate has not been settled yet, as research outcomes do not refute or fully endorse one single interpretation of RAN. Yet, it seems that many different cognitive skills are involved in

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RAN, including general processing speed (e.g. Georgiou et al., 2013; Kail & Hall, 1994; Van Daal, Van der Leij, & Adèr, 2013), attentional, visual, lexical, temporal, and recognition sub-processes (Wolf & Bowers, 1999; Wolf & Denckla, 2005).

In line with this ongoing discussion, the interpretation of the cognitive processes underlying RAN is also influenced by the design of the measure and therefore partly dependent on task format (e.g., De Jong, 2011). An important and influential task characteristic concerns the type of symbols that have to be named: naming of colors, pictures, digits, and letters. A distinction has been made between alphanumeric symbols (digits and letters) and non-alphanumeric symbols (colors and pictures; e.g., Närhi et al., 2005; Savage, Pillay, & Melidona, 2008; Van den Bos, Zijlstra, & Van den Broeck, 2003). The naming of digits and letters might require mainly phonological processing: the corresponding verbal codes of these stimuli are readily accessible at surface level. Naming of colors and pictures seems to demand additional steps. These stimuli might also require conceptual processing to establish *meaning* and subsequently the selection of the *appropriate* name code, before phonological processing results in articulating a response (Poulsen & Elbro, 2013; Theios & Amrhein, 1989).

This distinction relates to the second major issue, concerning the relations between RAN, RSD, and MD, specifically, whether the relationship with RAN is the same for both disorders. Studies show that children with either RSD or MD on average show lower scores on RAN outcomes than children without such difficulties (e.g. Cardoso-Martins & Pennington, 2004; Frijters et al., 2011; Mazzocco & Grimm, 2013; Van den Bos, Zijlstra, & Lutje Spelberg, 2002). Furthermore, research has compellingly shown that RAN is associated with and predictive of RSD (for a review of this research, see Kirby, Georgiou, Martinussen, & Parrila, 2010; Norton & Wolf, 2012). Although results regarding MD are more limited, several studies have found significant relations between RAN and MD (see Bull & Johnston, 1997; Chard et al., 2005; Landerl, Bevan, & Butterworth, 2004; Van der Sluis, De Jong, & Van der Leij, 2004). Further research is needed, as the relationship between RAN and mathematics might be partly different than between RAN and literacy, although this might be dependent on the type of RAN, which we turn to below.

With respect to reading, multiple studies have shown that alphanumeric RAN is a better predictor of reading outcomes than non-alphanumeric RAN, both in the general population and in differentiating between normal and poor readers (Bowey et al., 2005; Cardoso-Martins & Pennington, 2004; Heikkilä, Närhi, Aro, & Ahonen, 2009; Schatschneider, Carlson, Francis, Foorman, & Fletcher, 2002; Van den Bos et al., 2002, 2003; Wolf & Bowers, 1999). Non-alphanumeric RAN is an important predictor of (variation in) later reading in young children (prereaders), but at later ages this influence shifts to alphanumeric RAN (e.g. De Jong & Van der Leij, 1999; Kirby, Parrila, & Pfeiffer, 2003; Lervåg & Hulme, 2009). The increased automaticity of the print-to-sound translation typically targeted in alphanumeric RAN might relate to increased reading fluency. In other words, alphanumeric RAN becomes more strongly related to reading ability when children are increasingly exposed to digits and letters during formal instruction (Norton & Wolf, 2012). Because children are less intensively exposed to the non-alphanumeric stimuli, it is plausible that these do not become automatized in the same pace. The faster naming of stimuli that are more practiced than less-practiced stimuli is also shown by Pan, Yan, Laubrock, Shu, and Kliegl (2013), who studied digit naming versus dice pattern naming. On the basis of these findings, alphanumeric RAN has been proposed to serve as a 'microcosm' for reading (for an overview, see Norton & Wolf, 2012). In this view, the degree of automaticity is important; for typically developing readers it is easier to construct efficient pathways connecting more frequent visual symbols and their sounds, such as letters and digits, than those that are less frequent, such as colors and pictures. Children with RSD have more difficulties with this automaticity and therefore show slower performance on RAN digits and letters (Norton & Wolf, 2012).

The present study has assessed the relationship between spelling and RAN in addition to reading and RAN. In The Netherlands, the official guidelines prescribe that dyslexia must be diagnosed based on reading and/or spelling performance (see Blomert, 2013; Kleijnen et al., 2008; and Method). Although the literature has shown a relationship with reading difficulties, the relationship between spelling and RAN is not as clear-cut. Some studies have shown that alphanumeric RAN predicted later spelling skills after controlling for other relevant variables, such as initial reading skills, age, and IQ (e.g. Cardoso-Martins & Pennington, 2004; Furnes & Samuelsson, 2011; Savage et al., 2008). Other studies found that non-alphanumeric RAN predicted early spelling skills (e.g. Caravolas et al., 2012; Lervåg & Hulme, 2010). However, studies focusing on more consistent orthographies failed to find a longitudinal predictive relation between RAN and spelling acquisition (e.g., Landerl & Wimmer, 2008).

With respect to math, we are not aware of any studies specifically investigating the distinction between non-alphanumeric and alphanumeric RAN in relation to mathematical ability in general. Although some studies reported domain-specific deficits in alphanumeric RAN for children with MD, and in the rapid naming of digits in specific (Landerl et al., 2004; Van der Sluis et al., 2004), other studies did not find such a weakness (Landerl et al., 2009; Moll, Göbel, & Snowling, 2015). These differences may be explained by the types of mathematical difficulties exhibited by the MD groups, since the nature of mathematical difficulties might have an effect on how RAN is influenced. Moll et al. (2015) argued that mathematical problems can arise from either phonological weaknesses or number processing weaknesses. Children with phonological weaknesses especially show difficulties in mathematical tasks that involve reading, hence phonological processing, such as word problem solving. The performance of these children on RAN tasks might be more comparable to children with RSD. However, children with MD with a specific weakness in number processing seem to have difficulty with accessing quantities represented by digits, rather than quick access to digit words (Landerl et al., 2009). This relates to a domain-specific deficit in naming quantities, but not in the naming of digit words and pictures (Willburger et al., 2008).

A different interpretation for the findings on RAN and mathematics has been made by Georgiou et al. (2013), who suggest that the quality of visual–verbal associations may not be as important for mathematics as for reading, and that it might mainly be the processing speed element that is defective, as children with MD are thought to suffer from a deficit in the speed of activating information from long-term memory (D'Amico & Passolunghi, 2009). Such an interpretation would relate to either general RAN difficulties, or to non-alphanumeric RAN difficulties because these stimuli seem to require conceptual processing to establish meaning and the appropriate name code in addition to phonological processing (Poulsen & Elbro, 2013; Theios & Amrhein, 1989). The relationship between mathematics and (non-)alphanumeric RAN might thus be dependent on the specific mathematical problems of the participants. Furthermore, RAN performance might reflect different underlying abilities in MD than in RSD.

On the basis of the literature on RSD and MD, RAN difficulties can be expected for both children with RSD and MD. Yet, for children with RSD alphanumeric difficulties might be more prominent, whereas for those with MD either general RAN difficulties or specific non-alphanumeric difficulties might be found. Several studies have shown that children with both RSD and MD have more severe and broader RAN deficits than those with only one disability (D'Amico & Passolunghi, 2009; Moll et al., 2014; Van der Sluis et al., 2004; Willburger et al., 2008). However, only a few studies have looked at the individual types of stimuli and assessed the type of RAN-deficits in RSD and MD as well as RSD + MD groups separately. Pauly et al. (2011) and Willburger et al. (2008) reported a domain-general naming deficit, including both alphanumeric (digits and letters) and non-alphanumeric RAN (pictures), in children with comorbid RSD and MD as well as in children with RSD.

In sum, results regarding the relationship between alphanumeric and non-alphanumeric RAN and RSD and MD are not unequivocal. There is some evidence for distinct RAN problems in children with RSD and children with MD (Cardoso-Martins & Pennington, 2004; Landerl et al., 2009), although other studies report general RAN difficulties for both RSD and MD groups (Mazzocco & Grimm, 2013; Pauly et al., 2011; Willburger et al., 2008). Hence, the possible role of alphanumeric and non-alphanumeric RAN in reading, spelling, and mathematics needs to be explored further, both in typically developing children and in children with RSD, MD, and RSD + MD. This question is relevant in terms of our theoretical understanding of RSD and MD, as well as their comorbidity, and could also indicate how RAN could be used as part of the diagnostic assessment for difficulties in literacy and mathematics.

In this study, four different aspects of rapid naming (colors, pictures, digits, and letters) were assessed in children with reading and/or spelling difficulties (RSD), mathematical difficulties (MD), both difficulties (RSD + MD), and typically developing children (TD), to investigate: 1) to what extent non-alphanumeric and alphanumeric RAN scores are related to measures of reading, spelling, and mathematics, and 2) how children with RSD, MD, and RSD + MD differ with respect to their non-alphanumeric and alphanumeric RAN scores. Based on the literature, it was hypothesized that children with RSD would show poor performance on measures of alphanumeric RAN, whereas expectations were mixed for children with MD. For children with RSD + MD, poorer performance on both alphanumeric and non-alphanumeric RAN was anticipated. In addition, it was expected that alphanumeric RAN would be related more strongly to literacy than to math, in line with the interpretation that alphanumeric RAN relies more on phonology and the automaticity of reading.

2. Method

2.1. Participants

Participants were recruited through diagnostic centers, calls in professional magazines, and via the network of the researchers. Informed consent was obtained from all participants and their parents. A total of 133 children (39.8% boys) with a mean age of 8; 11 years (*SD* = 11 months) participated in this study. All children attended primary schools in The Netherlands (Grade 1 through 5), with the majority of children (95.5%) in Grades 2, 3, and 4. The IQ scores of the children were all within boundaries of normal development, as is required when investigating RSD and MD groups. Scores ranged between 70 and 134 (*M* = 103.12, *SD* = 12.09).

Based on their test scores, dossier information about diagnoses, and received help, children were divided into four groups: a typically developing (TD), reading and/or spelling difficulty (RSD), mathematical difficulty (MD), and a comorbid (RSD + MD) group. It should be noted that not all children had received an official diagnosis, but were classified by clinical experts based on strict criteria for the present study, that were in line with the current diagnostic criteria in The Netherlands. The inclusion criteria for RSD were set at reading and/or spelling scores 1SD below the population mean (cf. Kleijnen et al., 2008; Kuijpers et al., 2003), combined with average scores on the mathematical tasks. For MD, the criteria were *both* math problem solving scores below the 25th percentile of the school curriculum tracking system (D/E scores; cf. Janssen, Verhelst, Engelen, & Scheltens, 2010) *and* basic arithmetic scores 1SD below the mean (of the control group), combined with average scores on reading and spelling measures. Children in the comorbid group had to fulfill the criteria of low performance for both RSD and MD. In the TD group, children had to show average scores on all measures of reading, spelling, and mathematics. Table 1 shows the participant characteristics of the four groups. The groups differed significantly on age, $F(3, 129) = 3.16$, $p = .03$, and IQ score, $F(3, 129) = 7.73$, $p < .01$.

Table 1
Participant characteristics per group.

Group	*n*	% boys	Age in years *M*	*SD*	Total IQ score *M*	*SD*
RSD	28	60.7	8.76[ab]	1.03	105.11[ab]	12.37
MD	31	22.6	8.95[ab]	1.02	101.74[bc]	11.80
RSD + MD	40	42.5	9.20[b]	0.86	97.20[c]	11.14
TD	34	35.3	8.57[a]	0.75	109.44[a]	9.78

Note. Means in the same column that do not share subscripts differ at *p* < .05.
RSD = reading and spelling difficulties, MD = mathematical difficulties, RSD + MD = comorbid, TD = typically developing.

2.2. Measures

2.2.1. Intelligence

Intelligence was measured using the *Wechsler Intelligence Scale for Children – 3rd edition – Dutch version* (WISC-III-NL; Kort et al., 2005). When the IQ score was already available from previous intelligence testing (in the past two years), this score was used for the analyses (27.8% of all cases). Otherwise, the IQ score was estimated based on a short version of the WISC-III-NL including the subtests Similarities, Block Design, Vocabulary, and Picture Completion. The reliability and validity quotients of this short version are all reported to be above .83 (Kaufman, Kaufman, Balgopal, & McLean, 1996).

2.2.2. Non-alphanumeric Rapid Automatized Naming

Non-alphanumeric RAN was measured by the colors and pictures task of the Dutch test *Continu Benoemen en Woorden Lezen* (CB&WL; Van den Bos & Lutje Spelberg, 2010). Each task contains 50 items ordered in five columns of 10 items, printed on a single page. The aim is to name these items column by column as fast and as accurately as possible. Rapid naming of colors consists of an A4 sheet with rectangular patches in the colors black, yellow, red, green, and blue. The picture task consists of line-drawn pictures of a tree, duck, chair, scissors, and a bike. Prior to testing, the child is asked to name the items of the last column to determine whether he or she is familiar with the presented stimuli. Naming time in seconds was converted into an age-equivalent standard score used for the analyses. The mean reliability of the non-alphanumeric tasks is good ($\alpha = .83$; Evers et al., 2009–2012).

2.2.3. Alphanumeric Rapid Automatized Naming

The alphanumeric RAN tasks (digits and letters) were also part of the CB&WL (Van den Bos & Lutje Spelberg, 2010) and had the same format as the non-alphanumeric tasks described above. In the digit task, the stimuli consist of five different digits (2, 4, 8, 5, 9) and in the letter task of five different letters (d, o, a, s, p). Prior to testing, the child was asked to name the items of the last column to determine whether he or she is already familiar with the presented items. Naming time in seconds was converted into an age-equivalent standard score used for the analyses. The mean reliability of the alphanumeric tasks is good ($\alpha = .84$; Evers et al., 2009–2012).

2.2.4. Word reading

Version B of the *Eén-Minuut-Test* (EMT; Brus & Voeten, 1979) was used to measure word reading fluency. The EMT is a list of 116 words of increasing difficulty. The child has to read the words aloud as quickly and accurately as possible. The number of correct words in one minute is converted into a grade-equivalent standard score. The mean reliability of the EMT is excellent ($\alpha = .90$; Evers et al., 2009–2012).

2.2.5. Pseudoword reading

Pseudoword reading was measured using *De Klepel*, version B (Van den Bos, Lutje Spelberg, Scheepstra, & De Vries, 1994), which has the same set up as the EMT. The task contains 116 pseudowords, with

word length increasing from one to four syllables. The child has two minutes to correctly read as many pseudowords as possible. The raw score was converted into a grade-equivalent standard score for the analyses. The mean reliability of the task is excellent ($\alpha = .92$; Evers et al., 2009–2012).

2.2.6. Text reading

Text reading was measured with the B-version of the *AVI* (Visser, Van Laarhoven, & Ter Beek, 1996) consisting of 11 different texts of increasing difficulty. The level of the text corresponds to a didactic age, which reflects the number of months a child received formal education. For the analyses, the didactic age equivalent (i.e., educational age at which a corresponding score is generally achieved) for the text the child reads within the time and error range was used. The mean reliability of the test is sufficient (Evers et al., 2009–2012).

2.2.7. Spelling

The spelling level of the participants was measured with a shortened version of the *PI-dictee* (Geelhoed & Reitsma, 2000, see Van Viersen, Kroesbergen, Slot, & De Bree, 2014). Words were presented in a sentence. The child had to write down only the target word. The task was terminated when the child made six or more errors in one unit. For the analyses the total number of correct answers was used and converted into a total score (with the formula $+ 7 * {}^{15}/_7$). The mean reliability of the complete task is excellent ($\alpha = .92$; Evers et al., 2009–2012).

2.2.8. Basic arithmetic skills

The *Tempo Toets Rekenen* (TTR; De Vos, 1994) measures automation of basic arithmetic facts. The task consists of a sheet with five columns with 40 basic arithmetic operations each, including addition, subtraction, multiplication, division, and a mixed column. The child had one minute per column to make as many correct calculations as possible. The total number of correct answers was used for the analyses. Because there was no information available on the reliability of the TTR, Cronbach's α was calculated from the data in the present study and found to be excellent ($\alpha = .93$).

2.2.9. Math problem solving

In order to obtain a more general view of the mathematical performance of the children, data from the Dutch student tracking system (Janssen et al., 2010), obtained by the school of each child, were used for the analyses. Every six months, the children did an arithmetic–mathematics test in their classroom according to a standardized protocol, and the scores were recorded in the student tracking system. The tasks cover various subdomains of mathematics, such as digits and operations, fractions and percentages, and geometry, time and money. The test mainly consists of word problems. For the analyses, the most recent grade-equivalent standard scores were used. The mean reliability of this measure is excellent ($\alpha = .94$; Evers et al., 2009–2012).

2.3. Procedure

Children were tested individually by trained graduate students in one test session lasting for a maximum of three hours. During the session there was at least one break and, depending on the child, more breaks could be inserted. All children were given the same tasks in the same order. Tests were administered in a quiet room at the child's home, school, or at the university lab. The parents and/or teacher of the children received a report with the child's scores on the various tasks and a short conclusion.

2.4. Data analysis

Before data analysis, data were screened for missing values and outliers. Only 2.09% of the data points were missing, and therefore handled according to the default in SPSS version 22 (i.e., list wise deletion). There

were no univariate or multivariate outliers. Further data screening showed no violations of assumptions for (multivariate) analysis of variance.

Standard scores were computed based on the normative population average when available (i.e., for RAN non-alphanumeric, RAN alphanumeric, word reading, pseudoword reading). When standard scores were not available (i.e., for text reading, spelling, basic arithmetic skills, math problem solving), we controlled for possible linear and nonlinear effects of age by regressing the raw scores on age and age squared and saving the unstandardized residuals for further analysis (i.e., age-residual; see McGrath et al., 2011). Additionally, IQ score was entered as covariate in the analyses to eliminate the differences between the groups of children. All significance tests were interpreted with an alpha level of .05. Effect sizes (partial eta squared) were evaluated according to the guidelines of Cohen (1988), with .01 indicating a small effect, .09 a medium effect, and .25 a large effect.

Several analyses have been conducted. First, using Structural Equation Modeling (SEM) in Mplus version 7.3 (Muthén & Muthén, 1998–2012), a one-factor model and two-factor model of RAN were compared to each other. Second, Pearson correlational analyses were conducted between the various measures of RAN, reading, spelling, and mathematics to test whether non-alphanumeric RAN and alphanumeric RAN were differently related to these measures. Finally, a MANCOVA was used to test the differences between the four groups (TD, RSD, MD, RSD + MD) on the RAN measures and measures of reading, spelling, and mathematics.

3. Results

3.1. Factor analysis

As a preliminary step, it was investigated whether relations between the four subtests of RAN were best explained by one general RAN-factor or two separate RAN-factors. A two-factor solution was expected based on previous literature reporting the distinction between alphanumeric (digits, letters) and non-alphanumeric (colors, pictures) RAN. The two-factor model fitted the data significantly better than the one-factor model, $\Delta\chi^2(1) = 42.56$, $p < .001$ (see also Table 2). Accordingly, the two-factor solution was used in the analyses of the current study. The mean standard scores for the non-alphanumeric and the alphanumeric factor were used to detect a differential effect of RAN on reading, spelling, and mathematics.

3.2. Correlational analyses

To explore the associations among the tasks, Pearson correlational analyses were conducted for the total group (see Table 3). The literacy measures were all significantly related to each other and the same holds for the mathematical measures. Basic arithmetic skills and math problem solving were not significantly related to word reading and pseudoword reading, but only to text reading and spelling. The non-

Table 2
Fit statistics for the one- and two-factor model in the total group.

Model	χ^2	df	RMSEA	90% CI	CFI	SRMR
One-factor model	43.32	2	.39	[.29, .49]	0.77	.10
Two-factor model	0.76	1	.00	[.00, .21]	1.00	.01

Note. For both models, the 90% CI of the RMSEA exceeds the critical value of .10, not allowing us to reject the hypothesis of poor fit. However, since the other approximate fit measures indicate good fit and the CI of the RMSEA is influenced by sample size, with small sample sizes leading to broader intervals, this is not considered problematic (Kline, 2011). Sensitivity analyses found a better fit of the two-factor model than the one-factor model both in the total group and the separate subgroups.
df = degrees of freedom, RMSEA = root mean square error of approximation, CI = confidence interval, CFI = comparative fit index, SRMR = standardized root mean square residual.

Table 3

Pearson correlations between the RAN, literacy, and math measures for the total sample (N = 133).

	1.	2.	3.	4.	5.	6.	7.	8.
1. Non-alphanumeric RAN	–							
2. Alphanumeric RAN	.42**	–						
3. Word reading	.28**	.53**	–					
4. Pseudoword reading	.30**	.56**	.88**	–				
5. Text reading	.30**	.58**	.64**	.64**	–			
6. Spelling	.16	.34**	.30**	.40**	.57**	–		
7. Basic arithmetic skills	.43**	.16	.02	.01	.30**	.32**	–	
8. Math problem solving	.33**	.14	−.03	−.01	.21*	.29**	.59**	–

Note. RAN = Rapid Automatized Naming.

* $p < .05$.

** $p < .01$.

alphanumeric RAN-factor was significantly related to all measures, except for spelling. The correlations of the non-alphanumeric RAN-factor are highest with the mathematical measures, although the difference between mathematical problem solving and the reading measures is small. In contrast, the alphanumeric RAN-factor was significantly linked only to the reading and spelling measures, but not to the mathematical measures.

3.3. Multivariate and univariate analyses

The mean scores on the various tasks for each group are reported in Table 4. A MANCOVA with these measures as dependent variables, and IQ as covariate, revealed overall group differences, Wilk's $\Lambda = .22$, $F (24, 265) = 7.47$, $p < .01$, $_p\eta^2 = .39$. The univariate results are displayed in Table 4. All univariate tests resulted in significant group differences with a medium to large effect size.

As can be derived from the results in Table 4, the group differences on the tasks are in line with the expectations, in that 1) children with RSD scored lower than the TD group and the MD group on reading measures, 2) the children with MD scored below the TD and RSD group on the mathematical measures, and 3) the RSD + MD group differed from the MD group on the reading and spelling measures and did not differ from the MD group on the mathematical measures. There are two unexpected results: First, the RSD and MD groups did not differ statistically on spelling. Second, the RSD + MD group did not perform more poorly than the RSD group on math problem solving.

More pertinent to the relationship between RSD, MD, and RAN are the results of the univariate analyses (Table 4) on alphanumeric and non-alphanumeric RAN and group. The analyses showed that on non-alphanumeric RAN the RSD, MD, and RSD + MD groups scored approximately the same and significantly lower than the TD group. On alphanumeric RAN, however, the pattern mimics the reading outcomes,

with significantly lower scores for the RSD and RSD + MD groups compared to the TD and MD groups. The MD group did not show difficulties on alphanumeric RAN compared to the TD group.

4. Discussion

The aims of this study were to establish how non-alphanumeric and alphanumeric RAN scores are associated with measures of reading, spelling, and mathematics, and whether children with RSD, MD and RSD + MD differed with respect to their non-alphanumeric and alphanumeric RAN scores. The RAN tasks used were colors, pictures, digits, and letters. The RAN outcome measures were time taken to name aloud all items per task.

The results confirm a difference between alphanumeric and non-alphanumeric RAN, as the pattern of findings is different for both measures and different for all groups. Alphanumeric RAN performance correlated more strongly with literacy ability than non-alphanumeric RAN performance, in line with previous findings (e.g. Bowey et al., 2005; Heikkilä et al., 2009). Alphanumeric RAN did not correlate with mathematical outcomes. In contrast, non-alphanumeric RAN performance was associated with all reading and mathematical abilities, but not with spelling. The differential associations of reading and spelling with RAN indicate that the relation between spelling and RAN deserves more attention in studies on the role of RAN in literacy development.

Furthermore, an important finding is that children with RSD, MD, and RSD + MD were equally impaired in their non-alphanumeric RAN as opposed to the TD group. A different pattern was found with regard to their alphanumeric RAN scores; only the RSD and RSD + MD group scored more poorly compared to the TD group, whereas performance of the MD group on alphanumeric RAN was equal to that of the TD group. The non-alphanumeric deficit in all three clinical groups compared to the alphanumeric deficit in only the RSD groups indicates that, although deficits in rapidly retrieving information from long-term memory is a common underlying factor in both RSD and MD, making a distinction between alphanumeric and non-alphanumeric RAN is meaningful.

Even though the present study was not set up to provide insight in the underlying causes for these differences, we took the liberty of speculating about possible explanations for our findings that could form the basis for future research on this topic. We discuss two different plausible interpretations. A first possible interpretation relates to the interaction between general cognitive processes and additional processes involved in the performance on either alphanumeric or non-alphanumeric RAN tasks. It can be argued that a general underlying cognitive process such as processing speed is impaired at a young age in children later diagnosed with either MD or RSD, which also explains the high comorbidity between both disorders (Van Daal et al., 2013). This is in line with findings that non-alphanumeric RAN predicts reading scores in young

Table 4

Means, standard deviations, and univariate test results of all measures per group.

Measure	RSD (n = 23) M	RSD (n = 23) SD	MD (n = 24) M	MD (n = 24) SD	RSD + MD (n = 30) M	RSD + MD (n = 30) SD	TD (n = 26) M	TD (n = 26) SD	F(3)	p	$_p\eta^2$
Non-alphanumeric RAN[1]	7.16[b]	2.91	7.27[b]	3.16	6.29[b]	2.66	9.56[a]	2.40	5.41	.002	.14
Alphanumeric RAN[1]	8.00[b]	2.65	10.02[a]	2.73	7.50[b]	2.53	10.04[a]	2.28	10.23	<.001	.24
Word reading[1]	6.04[b]	2.06	11.26[a]	2.70	5.65[b]	3.09	11.15[a]	2.38	31.98	<.001	.50
Pseudoword reading[1]	6.00[b]	2.48	11.32[a]	2.56	6.70[b]	2.76	11.38[a]	2.56	32.58	<.001	.50
Text reading[2]	8.58[b]	2.70	11.79[a]	3.21	8.93[b]	2.49	11.12[a]	2.57	13.42	<.001	.29
Spelling[2]	9.48[bc]	2.88	10.42[ab]	3.47	8.96[c]	2.47	11.28[a]	2.76	11.39	<.001	.26
Basic arithmetic skills[2]	11.29[a]	3.50	8.68[b]	2.44	8.77[b]	2.14	11.66[a]	2.76	12.87	<.001	.28
Math problem solving[2]	11.12[ac]	3.16	8.62[b]	3.16	9.31[bc]	2.61	11.06[a]	2.46	9.46	<.001	.23

Note. Group means in the same row that do not share subscripts differ at $p < .05$. For the RSD group, sensitivity analyses showed comparable results including and excluding children with spelling difficulties; results in the table are including children with spelling difficulties.

RSD = reading and spelling difficulties, MD = mathematical difficulties, RSD + MD = comorbid, TD = typically developing, RAN = Rapid Automatized Naming.

[1] Standard score based on general population average with $M = 10$ and $SD = 3$.

[2] Standardized score based on current sample average with $M = 10$ and $SD = 3$.

children (De Jong & Van der Leij, 1999; Kirby et al., 2003; Lervåg & Hulme, 2009). However, as children grow older, they presumably learn to compensate the shared impaired process with additional processes required for the separate naming tasks. For the MD group, formal reading instruction might positively affect performance on alphanumeric RAN. The strong focus on rote learning and the automatization of digits and letters in The Netherlands might have served as a compensation for their initial weakness in processing speed at a young age (cf. Pan et al., 2013). On the basis of this line of reasoning, it could be explained why the MD group did not show deficits in alphanumeric RAN. It may also explain why no differences were found between the RSD and the RSD + MD group: the phonological weakness underlying the reading or spelling problems in these groups restrained them from compensating for their impaired general processing speed. Hence, alphanumeric RAN seems to lose its predictive value in children without reading and spelling difficulties (cf. Frijters et al., 2011). In order to evaluate this interpretation more in depth, longitudinal studies are necessary to provide insight in the developmental patterns of RAN in relation to other cognitive skills. Further research is also needed into different paths of compensation (e.g., Van Viersen, De Bree, Kroesbergen, Slot, & De Jong, 2015).

A second, probably more plausible, interpretation could be that some common underlying processes are needed for performance on both alphanumeric and non-alphanumeric RAN, but an additional process is required for non-alphanumeric RAN. Following this interpretation, children with RSD might be impaired in the common underlying process, while children with MD are only impaired in the additional (unique) process. As such, the RSD group might have difficulties in timed phonological processing of visually presented stimuli. This deficit is especially apparent in alphanumeric RAN, as it involves automatized print-to-sound translation of orthography and phonology, which has been proposed to be often particularly deficient in children with dyslexia (e.g. Blomert & Willems, 2010; Pan et al., 2013; Wimmer & Schurz, 2010). This explains our findings that alphanumeric RAN and literacy abilities are closely related, as well as the poorer alphanumeric RAN performance of the RSD and RSD + MD groups, indicating a phonological weakness. However, phonological skills are not necessarily impaired in children with MD (Koponen, Salmi, Eklund, & Aro, 2013; Landerl et al., 2009), which tentatively accounts for the low association between mathematics and alphanumeric RAN.

Non-alphanumeric RAN, however, might mainly tap elements related to *conceptual* processing (i.e., recalling information from memory) and matching visual and verbal codes, which is important for both reading and mathematics (Georgiou et al., 2013; Manis et al., 1999; Wolf & Bowers, 1999). Non-alphanumeric RAN could thus be argued to require additional conceptual processing compared to only phonological processing in alphanumeric RAN, as meaning has to be established first, followed by selection of the appropriate name code prior to phonological processing (Poulsen & Elbro, 2013; Theios & Amrhein, 1989). Thus, children with MD might have difficulty with the conceptual processing of the quantities represented by the digits and not the access to digit words per se (cf. Landerl et al., 2009), although it should be noted that this might be different for participants with various mathematical problems (see Moll et al., 2015).

In conclusion, the findings show that RAN is associated with both RSD and MD, but at the same time alphanumeric and non-alphanumeric RAN require cognitive processing of stimuli at a different level, which affects the relationship with literacy and math. The interpretation we provide is that non-alphanumeric RAN might represent conceptual processing, next to general naming abilities and phonological access needed in alphanumeric RAN (in line with Poulsen & Elbro, 2013).

4.1. Limitations and future research

Although these findings shed more light on the relationship between RAN, RSD and MD, some limitations need to be noted. First, participant selection in this study was limited in terms of the percentage of clinical diagnoses. In order to validate the results of this study, a replication study with a larger sample of clinically diagnosed children needs to be performed. Secondly, a study relying on more in-depth looking data could shed light on similarities and differences between the groups and between the different types of RAN. The span of orthographic processing might be related to alphanumeric visual span for instance (cf. De Jong, 2011), but not to non-alphanumeric RAN. In order to assess this, different task formats need to be investigated. Also, using a fine-grained performance measure such as the eye-voice span (e.g. Jones et al., 2010; Pan et al., 2013) could show whether processing of the visual stimuli in both alphanumeric and non-alphanumeric tasks takes place in the same way for RSD and MD groups. Furthermore, a retrospective longitudinal study on RAN development as well as literacy and mathematical development is needed to ascertain whether the development of RAN abilities changes over time, that is, whether non-alphanumeric RAN is poor from the outset or becomes impaired during development. Van den Bos et al. (2002) have taken such an approach for literacy, although not in a population with learning disabilities. Mazzocco and Grimm (2013) have used such an approach for math, but did not include RAN of colors. Such a retrospective longitudinal study can also ascertain whether the children with MD indeed show poor alphanumeric RAN at the onset of literacy and mathematical instruction and whether they improve their alphanumeric RAN skills after starting formal education. Additionally, follow-up studies could take into account the output demands and include a dice naming task, as was done by Pan et al. (2013) for instance. In both digit and dice naming, the output needed is a number. This non-alphanumeric design does not demand semantic and conceptual processing. The expectation would then be that MD children would not perform poorly on digit and dice naming, but would on color and object naming. In contrast, the RSD groups would perform poorly on all four measures.

4.2. Practical implications

One practical implication of the findings is that both alphanumeric and non-alphanumeric RAN factors should be considered separately in future studies. Using one general RAN factor can misrepresent the precise problems of children with learning difficulties. Moreover, differentiating between alphanumeric and non-alphanumeric RAN could aid diagnosis of individual disabilities, as well as comorbid difficulties, and renders more detailed information on the locus of underlying cognitive impairments. Accordingly, the RAN profile of children may reflect the possible causes of their problems, with children with RSD possibly having both phonological and conceptual processing difficulties and children with MD having only conceptual processing difficulties.

Acknowledgments

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