



## PAPER

# Eye–voice span during rapid automatized naming of digits and dice in Chinese normal and dyslexic children

Jinger Pan,<sup>1</sup> Ming Yan,<sup>2</sup> Jochen Laubrock,<sup>2</sup> Hua Shu<sup>1</sup> and Reinhold Kliegl<sup>2</sup>

1. State Key Laboratory of Cognitive Neuroscience and Learning, Beijing Normal University, China

2. Department of Psychology, University of Potsdam, Germany

## Abstract

*We measured Chinese dyslexic and control children's eye movements during rapid automatized naming (RAN) with alphanumeric (digits) and symbolic (dice surfaces) stimuli. Both types of stimuli required identical oral responses, controlling for effects associated with speech production. Results showed that naming dice was much slower than naming digits for both groups, but group differences in eye-movement measures and in the eye–voice span (i.e. the distance between the currently fixated item and the voiced item) were generally larger in digit-RAN than in dice-RAN. In addition, dyslexics were less efficient in parafoveal processing in these RAN tasks. Since the two RAN tasks required the same phonological output and on the assumption that naming dice is less practiced than naming digits in general, the results suggest that the translation of alphanumeric visual symbols into phonological codes is less efficient in dyslexic children. The dissociation of the print-to-sound conversion and phonological representation suggests that the degree of automaticity in translation from visual symbols to phonological codes in addition to phonological processing per se is also critical to understanding dyslexia.*

## Introduction

The simple task of rapidly naming digits (or letters, objects, colors, etc.) displayed in a matrix-like arrangement has served as a very reliable predictor of reading development and dyslexia for many years (Denckla & Rudel, 1974, 1976; for a recent comprehensive review see Norton & Wolf, 2012). The advantage afforded by rapid automatized naming (RAN) is a high degree of experimental control over stimulus material that promises to facilitate the isolation of components that may be the source of dyslexia. For example, Wolf and Bowers (1999) enumerated seven related component processes involved in rapid naming.

In general, RAN is faster for alphanumeric (letters and digits) than nonalphanumeric (colors and objects) material, and alphanumeric RAN has a stronger relationship with reading than non-alphanumeric RAN (Bowey, McGuigan & Ruschena, 2005; Cardoso-Martins & Pennington, 2004). This interaction is in good agreement with accounts of dyslexia in terms of a deficit

in mapping visual codes to phonological codes (e.g. Goswami & Bryant, 1990). In detail, however, exactly how this relation between RAN and reading skill comes about has not been resolved.

One problem with past contrasts of alphanumeric (digits, letters) and non-alphanumeric (objects, colors) RAN conditions is that items of different conditions differed not only in visual form, but also in pronunciation. In our experiment we used digits as alphanumeric and dice surfaces as nonalphanumeric, symbolic stimuli. That is, the five items in each condition mapped onto the same responses. As it was safe to assume that naming digits would be faster than naming dice because of a higher degree of automaticity in digit naming, we expected a larger dyslexia-related difference in the cognitively easier alphanumeric digit-RAN condition. This is an important contrast with the usual observation that differences between dyslexic and normal readers are larger in difficult task conditions (for a review, see Ramus & Szenkovits, 2008).

Address for correspondence: Reinhold Kliegl, Department of Psychology, University of Potsdam, Karl-Liebknecht-Str. 24/25, 14476 Potsdam, Germany; e-mail: kliegl@uni-potsdam.de; or Jinger Pan, State Key Laboratory of Cognitive Neuroscience and Learning, Beijing Normal University, 19th Xijiekouwai Street, 100875 Beijing, China; e-mail: jingerpan@gmail.com

### *Eye-voice span during digit-RAN and dice-RAN*

There is a second innovative design feature in this experiment. We set out to measure an important characteristic of fluent oral reading during RAN: the eye-voice span (EVS). The EVS is the distance between the currently fixated item and the currently pronounced item. The EVS is large during fluent and skilled oral reading (i.e. the eye is often ahead of the voice), but is also modulated by local processing difficulties due to, for example, the printed frequency of words (Buswell, 1920; Inhoff, Solomon, Radach & Seymour, 2011; Laubrock & Kliegl, in preparation). Applied to our RAN-condition by reader-group design, we expected a larger EVS for digit-RAN than dice-RAN, a larger EVS for normal than dyslexic children, and the group difference should be larger for alphanumeric than symbolic RAN.

### *Eye movements during RAN and visual search*

To date there are three studies that have measured adult normal and dyslexic readers' eye movements during RAN tasks (Jones, Ashby & Branigan, 2013; Jones, Branigan, Hatzidaki & Obregón, 2010; Jones, Obregón, Kelly & Branigan, 2008). They also computed a time-based EVS as the time that elapsed between first fixating an item and pronouncing it, along with other first-pass and total fixation times per item.

Jones *et al.* (2008) focused on a contrast between two letter conditions. They showed that both high phonological similarity and high visual similarity in letter-RAN tasks slows naming speed for dyslexic and non-dyslexic groups, but more so in dyslexic readers. Group differences in time-based EVSs suggested that dyslexic readers have difficulties in inhibiting previously activated information and in processing upcoming information in the standard multiple-item RAN display. Moreover, dyslexic readers' difficulties in these domains primarily emerged in a measure that explicitly included the production phase of naming. Using a boundary paradigm, Jones *et al.* (2013) found similar results. Note that in these experiments subjects always named letters; different conditions required the pronunciation of different letters.

Jones *et al.* (2010) used object drawings as stimuli and manipulated the response format by requiring subjects to simply name or to semantically categorize the visual stimuli. They found similar differences between adult dyslexic and normal readers for the two response formats, which they interpreted as suggesting that the naming-speed deficit in dyslexic readers originates primarily in a general difficulty with retrieving information related to the visual stimulus (which can be either

phonological or semantic). They concluded that though achieving lexical phonological codes might be crucial to the RAN performance, it does not fully characterize the naming speed deficits among dyslexic readers. We suspect, however, that the deficit did not show up in their measure because they used an object task, for which naming might not be highly automatized.

Besides the three studies comparing normal and dyslexic adult readers, there is one RAN study (two experiments) measuring eye movements in first-grade children (Logan, 2009). The goal of this research was to examine the role of parafoveal information, information outside the direct visual focal point, in RAN. Logan manipulated the amount and type of information available to the right of the focal point. There was evidence for initial visual processing of the fixated and the next letter. Children with better RAN scores suffered more when parafoveal preview was denied than children with poor RAN scores. These results suggest that our measure of EVS should be sensitive to dyslexia at least in the digit-RAN condition.

There is an abundance of eye-movement studies documenting dyslexia-specific dissociations (e.g. Hawelka, Gagl & Wimmer, 2010; Prado, Dubois & Valdois, 2007). There are a few studies that have measured dyslexic and normal readers' eye movements in regular reading and in visual search. Hutzler, Kronbichler, Jacobs and Wimmer (2006) had dyslexic and control subjects orally read a series of pseudo-words in one condition and search through a list of consonant strings for items with identical adjacent letters in another. The groups' eye movements differed for reading, but not for visual search. Similarly, Prado *et al.* (2007) had subjects read four lines of text or, with vowels replaced by consonants, count the number of 'R's in them. Again, the two groups did not differ for visual search, but normal subjects read much more efficiently in the reading condition. Moreover, there was a striking similarity between visual-search and reading eye-movement measures for the dyslexic group; their reading was effectively like visual search. Similarly, Hawelka and Wimmer (2008) reported equivalent visual-search behavior during a target detection task for adult control and dyslexic readers. The authors ensured that task demands were purely visual and did not trigger any verbal-response tendencies.

Neither of these studies used symbolic or non-alphanumeric material, but still established equivalence of eye-movement control for dyslexic and normal readers during visual search. Thus, our chances of observing such a clear dissociation should even be higher for the digit-RAN vs. dice-RAN comparison, unless it is the naming process *per se* (in contrast to pure visual identification) that generated the group difference in these experiments.

### RAN in Chinese reading

The predictive value of RAN for reading changes during reading development in English samples (e.g. Kirby, Parrila & Pfeiffer, 2003; Torgesen, Wagner, Rashotte, Burgess & Hecht, 1997). Therefore, it is important to study its role in a language in which its predictive value for reading is strong and long lasting. Chinese offers a good opportunity for such a study. Previous studies have demonstrated that RAN predicts Chinese reading development from kindergarten on (Chow, McBride-Chang & Burgess, 2005), and continuing to late childhood (Pan, McBride-Chang, Shu, Liu, Zhang & Li, 2011) and adolescence (Chung, Ho, Chan, Tsang & Lee, 2011). It also predicts Chinese dyslexia (Chung *et al.*, 2011; Shu, McBride-Chang, Wu & Liu, 2006).

To summarize, we set out to compare digit-RAN with dice-RAN in Chinese dyslexic and control children. The two sets of stimuli have identical output demands, but differ in the degree of automaticity of mapping perceptual symbols onto phonological output. To the degree that dyslexic children have developed a less automatic mapping, we expect a larger group difference in the digit than in the dice task, for which naming cannot be assumed to be highly automatized in either group. Arguably, the EVS provides a fairly direct measure of working memory capacity during reading-related tasks. By using gaze duration and the EVS in different RAN conditions as predictors of psychometric RAN, we further evaluate whether automatic translation of visual symbols into sounds affects phonological working memory, and the relative contributions of visual processing and phonological working memory, respectively, to RAN performance.

## Method

### Participants

The sample consisted of 30 fifth graders (15 boys and 15 girls) with reading difficulties and a control group of 26 children (11 boys and 15 girls) from the same grade. Table 1 shows that the two groups were matched by age and nonverbal IQ, (based on Picture Completion in the Wechsler Intelligence Scale for Children Chinese revision, C-WISC; Gong & Cai, 1993). In addition, children in the dyslexic sample had a score of above 85 in C-WISC, with two exceptions (83 and 84), and the average score was 95 ( $SD = 8$ ). All were recruited from three primary schools in Beijing. All participants were native Mandarin speakers and had normal or corrected-to-normal visual acuity. Parents of children signed a form giving their consent to the testing.

The diagnosis of dyslexia was based on criteria previously established in studies in mainland China (e.g. Shu *et al.*, 2006; Zhang, Zhang, Shu, Xi, Wu, Zhang & Li, 2012). A character recognition test with 150 characters (Zhang *et al.*, 2012) was used in the present study. All characters were expected to be learned by grade 6 (Shu, Chen, Anderson, Wu & Xuan, 2003). They were ordered by difficulty. Children were asked to orally name the characters, and the test stopped when they failed 15 successive items. One point was awarded for each correctly named character. The dyslexic children scored at least 1.5  $SD$  below their respective age means in this test. In addition, as dyslexic children are often characterized by slow reading, we also tested reading fluency. This is a silent sentence reading test including 100 simple sentences (e.g. The sun rises in the west). Children were asked to read sentences as fast as possible

**Table 1** Means (standard deviations) and group comparisons (Control–Dyslexic) of reading and cognitive measures

Measures	Dyslexic ( $N = 30$ )	Control ( $N = 26$ )	$t$ -value
Age (year)	10.7 (.3)	10.6 (.4)	−1.08
Psychometric measures			
Character recognition	85 (10)	128 (10)	16.17***
Reading fluency ( $n$ of chars)	514 (165)	1091 (209)	11.54***
Picture completion (Performance scale in C-WISC)	9.8 (2.6)	10.4 (2.9)	.70
Digit-RAN (s)	20.8 (3.6)	14.7 (3.1)	−6.79***
Dice-RAN (s)	27.8 (4.2)	23.6 (3.6)	−3.90***
Eye-movement measures Digit-Gaze (ms)	386 (50)	317 (34)	−6.08***
Dice-Gaze (ms)	472 (44)	426 (42)	−3.97***
Digit-EVS (AOI)	.81 (.25)	1.10 (.27)	4.16***
Dice-EVS (AOI)	.73 (.18)	.88 (.21)	2.75**

Note: \*\*\* $p < .001$ ; \*\* $p < .01$ . RAN = rapid automatized naming, Gaze = gaze duration, EVS = eye-voice span, AOI = area of interest.

and judge whether the meaning of the sentence was correct within 3 minutes. This test has been used to measure reading fluency in mainland China in previous studies (Pan *et al.*, 2011; Zhang *et al.*, 2012).

#### *Design, apparatus, and procedure*

We used a 2 by 2 quasi-experimental design, with group as a between-subjects factor and stimulus type as a within-subject factor. In digit-RAN, five numbers, 1, 2, 3, 4, 5, were used, and in dice-RAN, we used dice with 1 to 5 dots. Eye movements were recorded with an EyeLink 1000 desktop system (1000 Hz). Stimuli were presented on a 19-inch View Sonic G90f Monitor (1280\*1024 resolution; refresh rate 85 Hz). Voice was recorded to hard disk using an Optimus Dynamic microphone connected to an ASIO compatible Sound Blaster Audigy sound card inside the PC, guaranteeing a fixed audio latency of 10 ms.

Participants were calibrated with a standard 9-point grid of the right eye. After validation of calibration accuracy, a fixation cross appeared at the upper left corner of the screen. When fixation was detected within an area of 1° centered on the fixation cross within 1 second, the cross disappeared and a matrix of 10 columns by 3 rows of items from the same stimulus type appeared on a screen with a grey background; otherwise a recalibration was automatically scheduled.

Each stimulus was printed in black centered on a white rectangle occupying a space of approximately 2° by 2° of visual angle. The space between each rectangle on the same row was about 1.5° of visual angle, and the space between rows was about 5.5° of visual angle. Each screen used six repetitions of each of the five different items per stimulus type. Items were randomly arranged but adjacent items were not the same. Participants were to name the 30 items as accurately and rapidly as possible. There were 10 screens for each stimulus type, and the presentation order of stimulus types was counterbalanced between subjects.

We also obtained RAN scores on a psychometric paper test with digits and dice. In both conditions, five items were each repeated 10 times in a random order, and children were asked to name the items as accurately and rapidly as possible. Each child named the lists twice and the average scores were calculated across the two trials for each condition.

#### *Data analysis*

For eye-movement data, analyses are based on first-pass fixations. Fixations were assigned to items, and spaces between items were evenly divided and assigned to

adjacent items. This way an area of interest (AOI) was defined for each item, occupying about 3.5° of visual angle. Standard eye-movement measures of reading were determined, such as first-fixation durations (FFDs, the first fixation on an item irrespective of number of fixations), single-fixation durations (SFDs, items that received exactly one first-pass fixation), gaze durations (GDs, sum of all first-pass fixations), saccade amplitude (SA, the amplitude of the outgoing saccade in first-pass fixations in terms of numbers of AOIs), landing positions (LPs, the landing position in terms of AOI of an incoming saccade in first-pass reading). As in normal eye-movement-based reading research, data from fixations at the first item and the last item in each row were not analyzed. Fixation durations and gaze durations with extreme values (FFD < 60 ms or > 800 ms and GD < 60 ms or > 1000 ms), and items with a blink and items following those with blinks were excluded from analyses (about 5%).

Eye-voice spans (EVSs) were calculated for the correctly pronounced items (about 99%). We calculated the spatial distance between the currently fixated item and named item relative to fixation onset. Only fixations in first pass reading without blinks were included in the analyses. We excluded first and last items in each line, items articulated during a fixation on the first and last item in each line, and items articulated during fixations with extreme values (< 60 ms or > 800 ms) from analyses. EVSs smaller than -5 and larger than 5 were excluded from analyses (about 0.3%). A Praat (Boersma & Weenink, 2012) script was used to preprocess the sound waves and locate the beginning and the end of the voiced parts by crossings of intensity threshold. We then manually dragged item boundaries to the subjective real boundaries by listening to stretches of speech signal repeatedly. We located the boundary in the middle of each ambiguous stretch when we encountered ambiguous boundaries due to co-articulation.

Statistical inferences are based on linear mixed models (LMMs) with crossed random effects for subjects ( $n = 56$ ) and items ( $n = 10$ ) using the lmer program of the lme4 package (Bates, Maechler & Dai, 2012) in the R environment for statistical computing and graphics (R Development Core Team, 2012).

LMMs are the multivariate statistics of choice for these data because they allow us to take into account between-subject and between-item variance within a single analysis (for a general discussion see, e.g. Baayen, Davidson & Bates, 2008; Kliegl, Wei, Dambacher, Yan & Zhou, 2011; Quené & van den Bergh, 2008). More importantly in the present context, they provide tests of (quasi-)experimental manipulations (reader group, psychometric RAN condition), within-subject covariates



(e.g. GDs and EVSs from eye-movement-based RAN conditions), and interactions between factors and covariates. Standard multiple-regression analysis (MRA) does not handle repeated measures, because it assumes independence of all observations; repeated measures MRA (Lorch & Myers, 1990) is susceptible to overfitting, as shown by simulations (Baayen, 2008).

Specifically in this experiment, the within-subject factor 'condition' tested the difference between psychometric RAN for digits and dice. Eye-movement-based covariates such as GD and EVS were measured in additional digit- and dice-RAN tasks; they were not used to compute the psychometric RAN scores. Subjects' digit-GD and digit-EVS were used as covariates for their psychometric digit-RAN; likewise their dice-GD and dice-EVS served as covariates for psychometric dice-RAN. Thus, there was an alignment between the levels of the within-subject factor 'condition' and two within-subject covariates. Taken together, six measures were included in the LMMs: two served as repeated measures of the dependent variable (psychometric digit-RAN, psychometric dice-RAN) and four served as covariates (digit-GD, digit-EVS, dice-GD, dice-EVS).

One drawback of LMM is that the error degrees of freedom for the  $t$ -values associated with fixed effects are not known. The sample size justifies the assumption that they are approximated by the normal distribution. Therefore, we report estimates larger than 2  $SE$  (i.e.  $t > 2$ ) as significant. In addition, we checked the significance of fixed effects with Markov Chain Monte Carlo methods. Specifically, we generated 10,000 samples from the posterior distribution of the fitted model parameters and constructed the highest posterior density (HPD) intervals which covered 95% of empirical cumulative density function for model parameters. Fixed effects with HPD intervals not including the value zero are judged to be significant.

Finally, analyses of LMM residual distributions strongly suggested that psychometric RAN scores and fixation durations needed to be log-transformed to meet statistical assumptions of these models. However, we also note that inferences did not substantially depend on the transformation.

## Results

Table 1 displays the scores of reading fluency, psychometric digit-RAN and dice-RAN (top block) and various eye-movement measures (i.e. gaze duration, eye-voice span, and saccade amplitude) for digit-RAN and dice-RAN versions of these tasks (bottom block) for both the dyslexic and the control groups. The two groups

differed significantly in reading fluency and psychometric digit-RAN and dice-RAN scores as well as in the eye-movement measures. Table 2 shows the correlations for the measures listed in Table 1. All correlations were significant; literacy skills tended to correlate higher with digit-RAN than dice-RAN. Whether these correlations and correlations within the condition (2)  $\times$  group (2) cells are significantly different will be assessed as part of an LMM.

### Crossed random-factor linear mixed models

We analyzed group and condition effects on various eye-movement measures with LMMs, specifying subjects and items as crossed random factors. Means (standard deviations) for eye movement variables (i.e. SFDs, FFDs, GDs, SA, LPs, and EVSs) are shown in Table 3A. The remaining parts of this table provide LMM-related results. In Table 3B, variance components of the random effects and residuals are reported, showing that the subject variance was much larger than the item variance. In Table 3C, estimates and  $t$ -values for main effects of group and condition and their interaction are reported. For all dependent measures, the interaction between group and condition was highly significant. Therefore, to test for which stimulus condition the group differences were largest, we also report statistics from additional LMMs in which we specified tests of the group differences (Control–Dyslexic) as nested within stimulus conditions, that is, separately for digit-RAN and dice-RAN conditions in Table 3D. Dyslexic and control groups differed significantly on all eye-movement measures in the digit-RAN, but only in GDs and EVSs in the dice-RAN condition. However, for the other measures numeric trends were always in the direction of less efficient processing for dyslexic than normal children, too. Nevertheless, the overall pattern is one of smaller group differences for dice-RAN than for digit-RAN,

**Table 2** Correlations among literacy skills and RAN measures

	1	2	3	4	5	6	7	8
1 Character recognition	–							
2 Reading fluency	.83	–						
3 Digit-RAN	–.63	–.56	–					
4 Dice-RAN	–.39	–.42	.68	–				
5 Digit-GAZE	–.53	–.48	.76	.61	–			
6 Dice-GAZE	–.34	–.39	.52	.64	.69	–		
7 Digit-EVS	.47	.31	–.57	–.45	–.69	–.55	–	
8 Dice-EVS	.34	.29	–.38	–.52	–.49	–.55	.76	–

Note: For all correlations:  $p < .05$ .

**Table 3** (A) Means (standard deviations) of eye-movement and eye-voice span measures; number of observations; (B) variance components, (C) contrast estimates and associated *t*-values for main effects and interactions; (D) contrast estimates and associated *t*-values for simple effects for LMMs

		SFD (ms)	FFD (ms)	GD (ms)	SA (AOIs)	SLP (%AOI)	FLP (% AOI)	EVS (AOIs)							
(A)															
Digit	Dyslexic	322 (42)	296 (36)	386 (50)	.88 (.08)	50 (9)	46 (9)	.81 (.25)							
	Control	283 (30)	273 (30)	317 (34)	.93 (.06)	57 (9)	52 (8)	1.10 (.27)							
Dice	Dyslexic	378 (50)	332 (37)	472 (44)	.85 (.07)	45 (8)	41 (8)	.73 (.18)							
	Control	364 (47)	330 (43)	426 (42)	.88 (.07)	49 (8)	46 (9)	.88 (.21)							
<i>N</i> of obs.		15584	23958	23958	21532	15584	23958	21156							
(B)															
	Subject	.013	.128	.009	.005	.007	.006	.044							
	Item	.004	.004	.007	.000	.000	.001	.001							
	Residual	.168	.171	.180	.055	.024	.031	.357							
		SFD (ms)	FFD (ms)	GD (ms)	SA (AOIs)	SLP (%) AOI	FLP (%) AOI	EVS (AOIs)							
(C)															
Main effects	Group Stimuli	Est.	<i>t</i>	Est.	<i>t</i>	Est.	<i>t</i>	Est.	<i>t</i>	Est.	<i>t</i>	Est.	<i>t</i>	Est.	<i>t</i>
		-.058	-1.83	-.031	-1.00	-.137	-5.37	.040	2.12	.054	2.44	.056	2.59	.215	3.78
Interaction		-.197	-4.75	-.134	-3.38	-.254	-4.77	.036	4.69	.068	4.93	.062	4.31	.151	6.79
		-.052	-7.79	-.036	-6.71	-.050	-9.13	.009	2.85	.010	3.89	.013	5.60	.068	8.26
(D)															
Control–Dyslexic	Digit	Est.	<i>t</i>	Est.	<i>t</i>	Est.	<i>t</i>	Est.	<i>t</i>	Est.	<i>t</i>	Est.	<i>t</i>	Est.	<i>t</i>
	Dice	-.111	-3.34	-.066	-2.08	-.186	-6.04	.049	2.38	.063	2.65	.068	2.91	.287	4.16
		-.006	-.15	.005	.14	-.087	-3.27	.030	1.62	.044	1.99	.043	1.98	.143	2.74

*Note:* Means and standard deviations are based on subject means. SFD = single-fixation duration, FFD = first-fixation duration, GD = gaze duration, SA = saccade amplitude. SLP = single-fixation landing position (fraction of item), FLP = first-fixation landing position (fraction of item), EVS = eye-voice span.

with identical demands on articulation in both conditions.

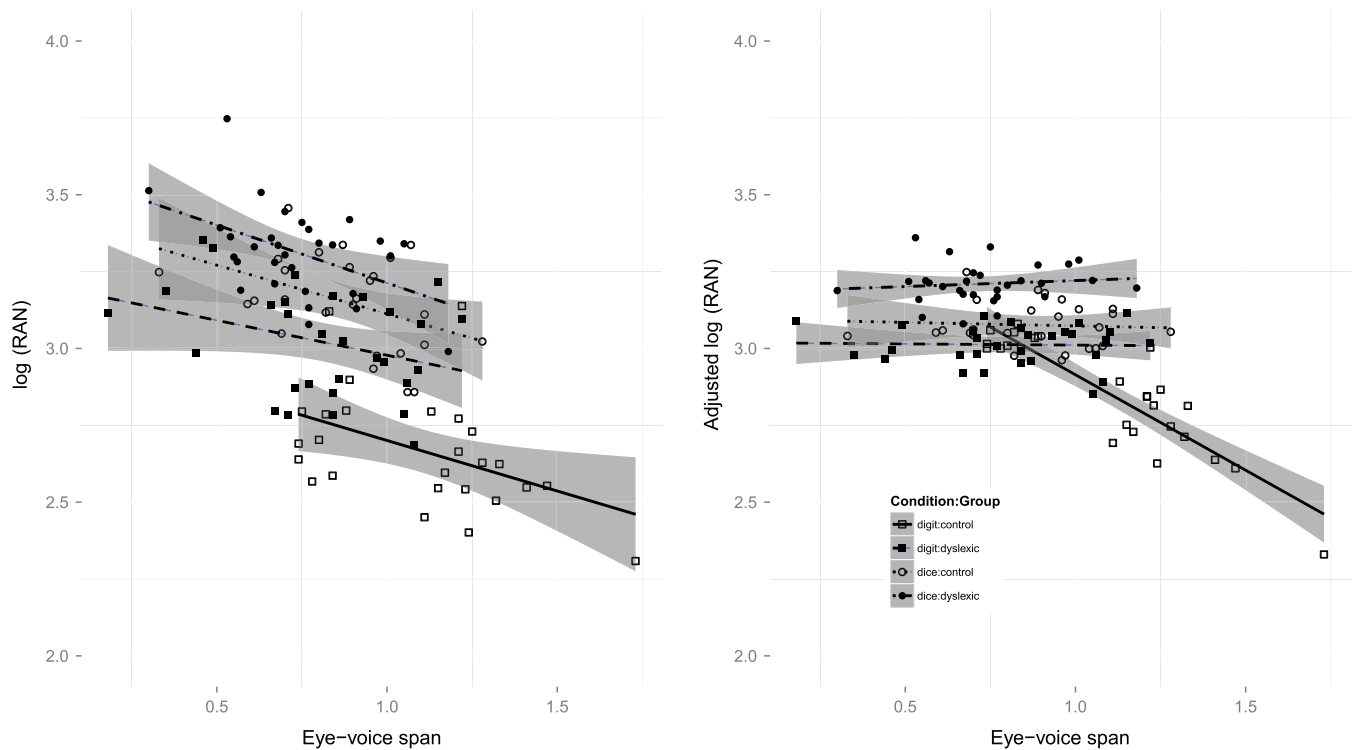
#### *Predicting differential RAN scores with GDs and EVSs*

In a final LMM we uncovered two group- and condition-specific interactions that might have gone unnoticed with conventional analyses. Let us first look at one such set of conventional analyses.

The left panel of Figure 1 shows the regression of psychometric digit- or dice- RAN on digit-RAN EVS or dice-RAN EVS separately for normal and dyslexic readers. Regression lines look roughly parallel. Indeed, the four zero-order correlations were  $-.40$ ,  $-.34$ ,  $-.41$ , and  $-.46$  for digit-control, digit-dyslexic, dice-control, and dice-dyslexic, respectively. Psychometric RAN is weakly (negatively) correlated with EVS, indicating faster RAN performance with greater EVS. Thus, on the basis of simple regressions we might conclude that individual differences in EVS do not relate differentially to psychometric digit- and dice-RAN in normal and dyslexic readers. The interaction between condition and group for psychometric RAN reported above (i.e. larger group difference for digit- than dice-RAN) appears to be independent of the eye-movement-based covariates.

The LMM tells a different story. In this model we take into account the correlations between all variables as well as individual differences in GD and EVS to predict psychometric RAN. As shown in Table 4, the fixed effect part of the LMM comprises the two design factors condition and group, the two covariates GD and EVS, and eight interactions between these independent variables. Interactions including both GD and EVS covariates did not significantly improve the goodness of fit of the model and were dropped from the final model; sample size was not sufficient for a meaningful test of the four-factor interaction. The middle part of Table 4 gives estimates for variance components associated with subjects and model residuals. The bottom part lists goodness-of-fit statistics.

The critical LMM result relates to the significant interaction between group  $\times$  condition  $\times$  EVS ( $t = -2.5$ ). The interaction between group, condition, and EVS is visualized in the right panel of Figure 1: Digit-RAN EVS is a significant predictor for digit-RAN psychometric score, but only for control children. Conversely, the other three slopes do not exhibit a dependency on EVS. The difference between the two panels highlights the advantage of LMMs. In the adjusted log (RAN) score the fixed and random effects are not



**Figure 1** Regression of  $\log(\text{RAN})$  scores on eye-voice span for each of the group  $\times$  condition combinations. Left: Regressions for observed scores. Right: Regression with scores adjusted for other fixed effects and between-subject differences as estimated in the linear mixed model. The eye-voice span  $\times$  group  $\times$  condition interaction was significant ( $t = -2.5$ ; Table 4). Error bars show 95% confidence intervals.

contributing to the interaction because they are statistically controlled for (i.e. fixed effects of GD and its interactions with group and condition as well as random effects due to subjects) and are removed from the observed  $\log(\text{RAN})$  score.

The left panel of Figure 2 displays results analogous to the right panel of Figure 1, but substituting GD for EVS as covariate, again showing the effects of the adjusted psychometric RAN scores. In this case, adjustment concerned effects of EVS and its interactions with group and condition. There was a highly significant positive effect of GD ( $t = 5.3$ ), but the interaction between group, condition, and GD was very far from being significant ( $t = 0.1$ ; see Table 4). The figure does, however, provide the source for the significant group  $\times$  GD interaction ( $t = 2.2$ ): Regression lines for the control group are steeper than those for the dyslexics. This interaction, however, was not significant according to MCMC-based HPD intervals (see Table 4).

Finally, the right panel of Figure 2 traces the source of the strong interaction of GD and EVS as predictors of RAN ( $t = -3.2$ ). The relationship between GD and RAN is stronger for participants or conditions with small EVSs, or to put it another way, that after adjusting

for all other effects, when EVS is large, GD does not play a major role in determining RAN, whereas it does when EVS is small. This suggests that visual processing and translation of visual input into phonological output is more effortful for readers/conditions with smaller EVS. In this respect, GD does not play a major role in the prediction of RAN for children/conditions with large working memory capacity (large EVS), but it does for children/conditions with small working memory capacity (small EVS). However, note that this explanation is based on post-hoc analyses; different explanations might be needed for different patterns of the post-hoc analyses.

In summary, individual differences in digit-RAN EVS are predictive of psychometric digit-RAN. This relation, however, was only significant for control children. GD was a significant predictor across conditions and reader groups. There was also a non-significant trend suggesting that this effect may be stronger for normal than dyslexic readers. Finally, GD and EVS interacted in predicting RAN, with GD determining RAN performance only in participants and conditions in which EVS was small.

Based on these results, in order to further test to what extent the RAN-reading relationship could be influenced by EVS, we tested the contribution of RAN to

**Table 4** LMM of psychometric RAN with gaze duration and eye-voice span as covariates

	LMM			
	Estimate	SE	<i>t</i> -value	HPD interval (95%)
<b>Fixed effects</b>				
Mean log(RAN)	3.075	.024	127.4	3.016 3.115
Group (Grp)	-.079	.049	-1.6	-.212 -.006
Condition (Cnd)	-.143	.044	-3.3	-.258 -.058
Grp × Cnd	.122	.104	1.2	-.216 .226
Gaze (GD)	.0020	.0003	5.3	.0013 .0028
EVS	-.153	.074	-2.1	-.250 .026
GD × EVS	-.005	.0016	-3.2	-.0066 -.0003
GD × Grp	.0018	.0008	2.2	-.0008 .0025
GD × Cnd	.0012	.0006	1.9	-.0005 .003
GD × Grp × Cnd	.0001	.0012	0.1	-.0038 .0022
EVS × Grp	-.337	.167	-2.0	-.624 .037
EVS × Cnd	-.323	.164	-2.0	-.545 .204
EVS × Grp × Cnd	-.551	.217	-2.5	-1.205 -.056
<b>Variance components</b>				
	Var	SD		
Subjects ( <i>N</i> = 56)	.0102	.101		
Residual	.0087	.0933		
<b>Goodness of fit</b>				
Log Likelihood		31.5		
REML deviance		-62.9		

*Note:* Grp: control-dyslexic; Cnd: digit-dice RAN; GD: gaze duration (centered); EVS: eye-voice span (centered); HPD interval (95%): highest posterior density intervals for model parameters; covers 95% of empirical cumulative density function generated from a sample (*N* = 10,000) from the posterior distribution of the fitted model parameters using Markov Chain Monte Carlo methods. A faster RAN score indicates better performance.

character recognition without and with statistically controlling for EVS in digit and dice conditions, respectively. The direct contributions of RAN to character recognition were significant in both conditions (digit:  $t = -6.02$ ,  $p < .001$ ,  $\Delta R^2 = .40$ ; dice:  $t = -3.10$ ,  $p < .01$ ,  $\Delta R^2 = .15$ ); they were still significant with statistical control of EVS (digit:  $t = -4.27$ ,  $p < .001$ ,  $\Delta R^2 = .20$ ; dice:  $t = -1.97$ ,  $p < .10$ ,  $\Delta R^2 = .06$ ). All together, these results suggested that EVS should be viewed as a correlated indicator of the RAN-reading relationship rather than the cause of this relationship.

## Discussion

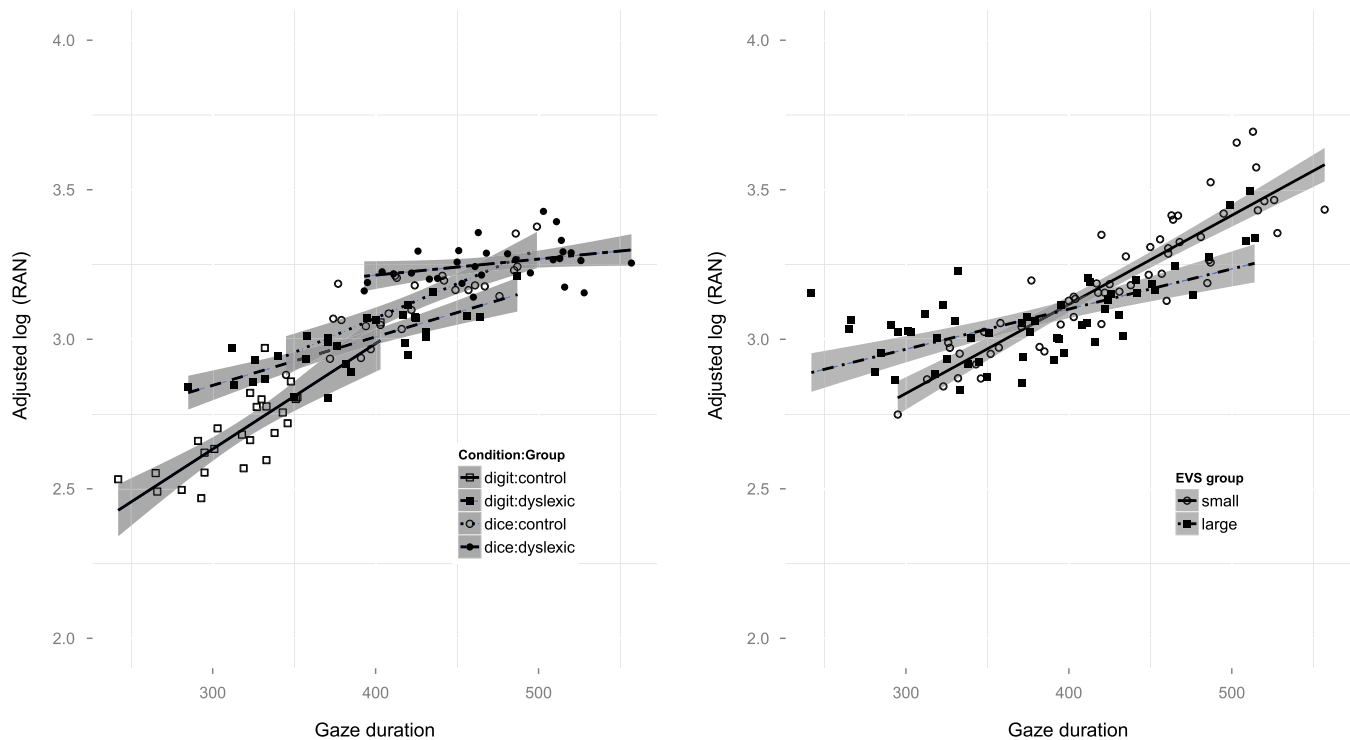
We followed up the well-documented result of larger differences between dyslexic and control children in alphanumeric RAN than in symbolic RAN (e.g. Ho & Lai, 1999; Wolf, Bally & Morris, 1986) with measures of eye movements. Although RAN is easy to administer and a potent predictor of reading ability and impairment, it is itself a very complex task, sharing many basic processes with regular oral reading. During efficient oral reading the eyes are usually ahead of the voice and the larger this distance measured in the EVS the better. Therefore, we tested to what degree the predictive value of RAN can be reduced to this measure capturing a core

quality of the dynamics of reading. The expectation was that, at least in perspective, an understanding of the dynamics of dyslexic RAN will shed new light on current explanations of dyslexic reading. Several potentially complementary factors have been nominated as contributors to this impairment. Some of them are probably the consequence of others, but the precise ordering and possible redundancies define much of the current theoretical debate in the field. Our results speak to two potentially dyslexia-related deficits: phonological processing and automaticity.

### Phonological deficit

Initially, RAN deficit was considered as a phonological deficit believed to be associated with poor, unspecified phonological representations (for a review, see Ramus & Szenkovits, 2008). Conceivably, poor phonological representations could have led to group differences in both digit-RAN and dice-RAN. However, in our experiment, we established critical group (dyslexic vs. control) × condition (digit-RAN vs. dice-RAN) interactions for the psychometric RAN scores as well as for independently measured eye movements in these tasks. Moreover, group differences were not consistently significant in the dice condition. Since identical phonological representations were required in both conditions, the interactions





**Figure 2** Left: Regression of  $\log(\text{RAN})$  scores on gaze duration for each of the group  $\times$  condition combinations. The gaze-duration  $\times$  group  $\times$  condition interactions was not significant ( $t = 0.1$ ; Table 4). Right: Regression of  $\log(\text{RAN})$  scores on EVS and GD (grouped for visualization purposes), illustrating the significant interaction of the two covariates ( $t = -3.2$ , Table 4). In both panels, scores are adjusted for other fixed effects and between-subject differences as estimated in the linear mixed model. Error bars show 95% confidence intervals.

between group and stimulus type do not support the role of phonological output processing *per se* as a critical determinant of the RAN-reading relationship.

Contrary to the account in terms of poor phonological representations, Ramus and Szenkovits (2008) suggested that dyslexics' lexical-phonological representations may actually be intact; rather, naming deficits may reflect a problem of fast access of these representations. The access deficit may indicate a general access deficit of dyslexia that could express itself in different domains (Jones *et al.*, 2010). However, naming dice activates concepts before retrieving phonological representations (Roelofs, 2006), while naming digits activates the lexical-phonological codes directly from the visual input. Therefore, if slow naming is due to a general access deficit, a larger difference would be expected in dice-RAN than in digit-RAN since retrieving the lexical-phonological representation of dice requires access to two representations (i.e. of concept and phonological representations) than digit (only phonological representations). Our results are exactly the opposite.

Another alternative is that dyslexics are less efficient in the naming process that involves arbitrary print-to-

sound conversion (Manis, Seidenberg & Doi, 1999). In the digit-RAN task, phonological codes are directly derived from visual input, thus the print-to-sound conversion is highly arbitrary. However, in the dice-RAN task, visual information non-arbitrarily activates semantic information first rather than phonological codes. It has been speculated that semantic activation may bootstrap the naming process in object RAN (Jones *et al.*, 2010). It is likely that dyslexic and control children have about the same amount of practice in naming semantic concepts, thus differential automaticity should not play a role in this. Although our results suggest that a phonological deficit could partly account for a naming deficit in dice-RAN, it was digit-RAN rather than dice-RAN (judging by response speed) that afforded direct conversion from print to sound and led to larger group differences and a better prediction of reading ability (see also Hawelka *et al.*, 2010, for a tentative proposal to link RAN of dyslexic adults to the lexical route). On the other hand, this result is also in agreement with a recent hypothesis about a deficit of orthographic-phonological connectivity as a core reason for dyslexia (Wimmer & Schurz, 2010).

### *Automaticity deficit*

Thus, our results are more compatible with an explanation that focuses on the degree of automaticity achieved in critical component processes (LaBerge & Samuels, 1974; see Norton & Wolf, 2012, for a review). The double-deficit hypothesis suggests that alphanumeric RAN tasks predict reading better than non-alphanumeric RAN tasks because alphanumeric stimuli are more automatically processed after about 6 years of age (Meyer, Wood, Hart & Felton, 1998; Wolf *et al.*, 1986). Thus, the major share of reading efficiency tapped by the RAN task may be the degree of automaticity in print-to-sound conversion for various materials, i.e. the relative ease of directly accessing phonological representations from print. This explanation adds the assumption that symbol-to-sound conversion is initially a resource-demanding process that is automatized with practice.

Our results are compatible with such group-differential automatization (Norton & Wolf, 2012) because it is safe to assume that longer psychometric RAN times and associated eye-movement measures during dice-RAN than digit-RAN reflect primarily that dice-to-phonology translation is less well practiced than digits-to-phonology translation. In agreement with this expectation, both groups performed better in the digit-RAN; retrieval of phonological representations given digits as input dominates retrieval of the same phonological representations given dice. A higher degree of automaticity could indicate the development of a direct route from visual to phonological codes with practice. The smaller group differences for dice-RAN than digit-RAN may simply reflect the differences in retrieval frequencies and, consequently, in practice opportunities.

In summary, if reading speed is linked to automaticity of naming, digit-RAN should be a better predictor of normal reading. Controls did not achieve the same degree of automaticity for dice naming as for digit naming; dyslexics did not achieve the same degree of automaticity of naming digits as controls. As argued in the next section, this interpretation is also supported by analyses of eye movements during RAN.

### *EVS and perceptual span*

RAN resembles normal oral reading in the need to move the eyes from left to right across several rows. One characteristic of oral reading is that the EVS increases with reading competence, with the eyes further ahead of the voice during fluent and skilled reading (Buswell, 1920). Our non-reading RAN-condition by reader-group design was compatible with expectations: larger EVS for digit-RAN than dice-RAN, a larger EVS for normal than dyslexic children, and the group difference was

larger for alphanumeric than symbolic RAN. As far as individual differences in EVS and psychometric RAN are concerned, only control children's digit-EVS was related to psychometric digit-RAN: a large EVS was predictive of fast RAN (see Figure 1, right panel). This suggests that control children can buffer more phonological information when initial print-to-sound conversion is relatively easy. Moreover, the profile of how far the eyes landed toward the center of the item mirrored the EVS profile.

We propose that this pattern of eye movements implicates an effect of processing difficulty on the perceptual span, as documented in studies of reading (Inhoff, Pollatsek, Posner & Rayner, 1989; Rayner, 1986; Yan, Kliegl, Shu, Pan & Zhou, 2010). EVS was larger for digit naming than dice naming for control children, suggesting that when the material is easy to process, the eyes tend to take in more parafoveal information. The perceptual span widens when reading/naming is largely driven by automatic processing. Thus, group and condition differences in RAN could be a consequence of such reduced parafoveal processing.

There is already some research on this topic. Rayner, Murphy, Henderson, and Pollatsek (1989) reported a smaller perceptual span for two adult dyslexic readers than for normal readers in text reading. They argued that lower reading ability requires more attentional resources, inducing a reduction in the perceptual span (Rayner, 1986). In the present experiment we did not directly test the parafoveal processing efficiency of dyslexic children, but reduced parafoveal processing in RAN tasks has already been documented for adult dyslexics (Jones *et al.*, 2008) and beginning readers (Logan, 2009). We also found such a group difference in a recent study with the gaze-contingent display-change paradigm, where control children suffered more from a denial of parafoveal preview than dyslexic children, but only with digits which were automatized material (Yan, Pan, Laubrock, Kliegl & Shu, 2013). Note, however, that in that study dyslexic children still benefited from intact parafoveal preview in digit-RAN, just not as much as controls. Our findings with Chinese dyslexic children are in accord with previous findings in British dyslexic adults, that dyslexic readers' parafoveal processing abilities are more severely impaired in alphanumeric than symbolic naming (Jones *et al.*, 2008, 2010). Further, in line with former studies (e.g. Hutzler *et al.*, 2006; Olson, Kliegl & Davidson, 1983), the interaction between group and stimulus type suggested that dyslexic readers were not characterized by oculomotor control problems.

There is much previous research showing small or no dyslexic effects in naming visual symbols which do not map to sound directly (Valdois, Lassus-Sangosse &

Lobier, 2012; Ziegler, Pech-Georgel, Dufau & Grainger, 2010). We suspect that our comparatively small group difference for dice-RAN belongs in this category as well. When naming is sufficiently automatized, as in control children's digit-RAN, then sufficient visual attentional resources are freed up to permit a wide perceptual span and to trigger their fast digit-naming times. Basically, lack of automaticity in naming and need for foveal visual attention may refer to the same process, which might well involve a phonological buffer in the case of efficient performance. The EVS, although it cannot fully account for the RAN-reading relationship, dynamically mirrored how the automaticity in translating visual symbols to their oral names modulates the naming process.

### Limitations

There are at least two limitations of the present study that should be addressed in future research. First, replacing the age-matched with a reading-level (RL)-matched control group might help us to understand whether the poor performance of the dyslexic group in the digit-RAN task is linked to reading level. If the RL-matched control children perform like age-matched control children in the present study, the automaticity deficit would be highly specific to the reading-like context of the RAN task. If the RL group performs worse or equal to the dyslexic group, the interpretation of results will be difficult. Obviously, an RL control group will be younger than the two groups in our experiment and differences could be due to age-related correlations with the efficiency of the oculomotor system.

A second limitation of the present study is that our tasks always required oral responses to visual stimuli. There are arguments about whether deficits of dyslexia originate from the visual attention domain. In this case, our results might be linked to the visual attention span (VAS) deficit hypothesis (Bosse, Tainture & Valdois, 2007; Prado *et al.*, 2007; Stenneken, Egetemeier, Schulte-Körner, Müller, Schneider & Finke, 2011), if differences in the size of the EVS are systematically related to foveal processing load via a reduced perceptual span. Bosse and Valdois (2009) discuss the differences between perceptual span and VAS. Despite the similarity between RAN and VAS with respect to demand to name items in strings, VAS tasks require the extraction and storage of information in visual short-term memory whereas this information is available all the time during RAN. Nevertheless, even in RAN there is a need for temporary storage between processing of visual input and production of phonological output, and the EVS results suggest that more items can be temporarily stored with automatized material. Of course, perceptual span is different from VAS, but we would argue that foveal processing

deficiencies such as those uncovered in VAS may trigger the kind of reduction of perceptual span that we witnessed in the EVS in our studies. Thus, reductions of perceptual span may ride on foveal processing difficulties. However, others argue that the VAS deficit is unlikely to be due to a deficit in visual attention, citing the dependence of the effect on the naming response (Ziegler *et al.*, 2010; Hawelka & Wimmer, 2008). Thus, comparison between verbal and non-verbal tasks, for example in the context of a visual search using the same stimulus material, is likely to open new perspectives on the processes underlying RAN tasks.

### Conclusion

The present study is the first to trace alphanumeric and symbolic RAN deficits in Chinese dyslexic children to measures of eye movements and, in particular, digits. Despite being the easier task, digit-RAN is a better predictor of dyslexic status than dice-RAN, presumably because for digit naming, much more so than for dice naming, the efficacy of the pathways connecting printed digits with sound (Klein, 2002) is higher for control but not (or much less efficiently so) for dyslexic children. The efficiency or automaticity of this print-to-sound translation is also reflected in a larger eye-voice span group difference for digit-RAN than dice-RAN. Finally, for control children individual differences in digit-RAN EVS were predictive of individual differences in psychometric digit-RAN. Given current hypotheses on dyslexia, our findings suggest that besides phonological representation *per se*, print-to-sound translation which reading acquisition importantly relies on is important for understanding reading development and dyslexia.

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