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Impact of orthographic transparency on typical and atypical reading development: Evidence in French-Spanish bilingual children

Marie Lallier [a,*], Sylviane Valdois [c,d], Delphine Lassus-Sangosse [g], Chloé Prado [b], Sonia Kandel [c,e,f]

[a] Basque Center on Cognition, Brain and Language, San Sebastian, Spain
[b] Centre Hospitalier Universitaire de Grenoble, France
[c] Université Grenoble Alpes, Laboratoire de Psychologie et NeuroCognition, Grenoble, France
[d] Centre National pour la Recherche Scientifique, France
[e] GIPSA-Lab, CNRS UMR 5216, Grenoble, France
[f] Institut Universitaire de France, Paris, France
[g] Centre de Diagnostic des troubles du langage et des apprentissages, Département de pédiatrie CHU Nord, Grenoble, France

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ABSTRACT

The present study aimed to quantify cross-linguistic modulations of the contribution of phonemic awareness skills and visual attention span (VA Span) skills (number of visual elements that can be processed simultaneously) to reading speed and accuracy in 18 Spanish-French balanced bilingual children with and without developmental dyslexia. The children were administered two similar reading batteries in French and Spanish. The deficits of the dyslexic children in reading accuracy were mainly visible in their opaque orthography (French) whereas difficulties indexed by reading speed were observed in both their opaque and transparent orthographies. Dyslexic children did not exhibit any phonemic awareness problems in French or in Spanish, but showed poor VA Span skills compared to their control peers. VA span skills correlated with reading accuracy and speed measures in both Spanish and French, whereas phonemic awareness correlated with reading accuracy only. Overall, the present results show that the VA Span is tightly related to reading speed regardless of orthographic transparency, and that it accounts for differences in reading performance between good and poor readers across languages. The present findings further suggest that VA Span skills may play a particularly important role in building-up specific word knowledge which is critical for lexical reading strategies.

1. Introduction

Literacy is a key determinant of a successful education and individuals' well-being. A large amount of studies have therefore investigated the nature of its neural and cognitive foundations (e.g., Carreiras et al., 2009). With both theoretical and applied perspectives in mind, some have taken on the challenge of establishing whether common bases support the

* Corresponding author at: Basque Center on Cognition, Brain and Language, Paseo Mikeletegi 69, Planta, 2, 20009 San Sebastián, Donostia, Spain. Tel.: +34 943 309 300; fax: +34 943 309 052.
E-mail address: m.lallier@bcbl.eu (M. Lallier).

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reading network across languages (e.g., Paulesu et al., 2000), and others have stressed the importance of taking into account the languages' specificities when studying reading (e.g., Share, 2008). In line with the latter point, Ziegler and Goswami (2005) proposed the psychological grain size theory which offers a theoretical framework allowing testing hypotheses about the impact of cross-linguistic differences linked to orthographic transparency on reading development. Orthographic transparency is the degree of the regularity of the correspondences between letter units (graphemes) and sound units (phonemes) in a given language. In transparent and consistent orthographies, such as Spanish, most letters equal one sound and most single sounds equal one letter, except for a very limited number of two letter clusters, such as "ch" in the word "ocho" (/otʃo/, "eight") and sounds that could be written in different ways (e.g., /x/ can be written with the letter "j" or "g"). It is therefore easy for children to learn the letter-sound conversion rules since they follow an almost "one letter = one sound" mapping pattern. Conversely, in non transparent (i.e., opaque) and inconsistent orthographies such as French, the same letter can be associated with more than one sound (e.g., "a" can be pronounced /a/ in "patin", /ɑ/ in "pantin", /o/ in "peau", or /ɛ/ in "paix"), and vice versa (e.g., the sound /e/ can be written "et", "er", "é", "ées", etc.) increasing the likelihood to mispronounce or misspell words.

The psychological grain size theory posits that the orthographic transparency of a certain language puts some constraints on the development of reading procedures (or reading strategies). More specifically, it postulates that the size of the units relevant for the build-up of lexical representations of this language is inversely proportional to the regularity of its grapheme-to-phoneme conversion rules. In opaque orthographies, children have to rely on multi-letter chunks in order to access the correct phonological form since the rules which permit to convert a letter into the correct sound are generally determined by the preceding and/or following context in the letter string. Conversely, learning to read in a transparent language favors strategies which rely on small units, because children can apply very regular grapheme-to-phoneme conversion rules to them. Regular letter-sound correspondences have been shown to accelerate the acquisition of both decoding and reading skills (Seymour, Aro, & Erskine, 2003) and enhance the ability to identify and manipulate consciously the sounds units of one's language (Goswami, Ziegler, & Richardson, 2005; Spencer & Hanley, 2003). This ability (i.e., phonemic awareness) is moreover critical for reading development (Snowling, 2000). Indeed, poor phonemic awareness skills have been repeatedly associated with developmental dyslexia (Vellutino, Fletcher, Snowling, & Scanlon, 2004 for a review), a neuro-cognitive disorder that specifically impedes reading acquisition, despite of normal intelligence and the absence of sensory or psychiatric disorders in individuals having received adequate education.

Although it could be assumed that dyslexic readers of transparent languages benefit from the nature of their orthography to compensate potential phonological disorders, some authors claimed that learning to read in a transparent orthography does not prevent dyslexia from manifesting through phonological difficulties (Caravolas, Volín, & Hulme, 2005; Jimenez, 2012; Landerl et al., 2013). Moreover, regardless of orthographic transparency, the contribution of phonological awareness to reading development was shown to remain the same across languages (Caravolas et al., 2012; Caravolas et al., 2005). A recent cross-linguistic study however showed that the contribution of phonological awareness to reading is less important in the most transparent languages (Ziegler et al., 2010), which might explain why a smaller proportion of individuals are diagnosed with dyslexia in these languages compared to in opaque orthographies (Lindgren et al., 1985). Nevertheless, this low prevalence rate of dyslexia may stem from difficulties at detecting obvious signs of reading problems rather than a real reduction of the dyslexic syndrome in populations with transparent languages. Because of the one-to-one very regular grapheme-to-phoneme mappings, reading accuracy generally plateaus at ceiling as soon as pupils reach the end of the first year of reading tuition in transparent orthographies (Seymour et al., 2003). Reading fluency, however, remains a good measure of reading performance in the most transparent languages (e.g., Aro & Wimmer, 2003; Kirby, Georgiou, Martinussen, & Parrila, 2010) but is of course more difficult to quantify in the classroom or at home.

Whether phonological awareness is or is not equally important for reading acquisition in transparent and opaque orthographies remains a challenging question for research. Work that looks at the developmental dynamics of orthographic transparency's impact on the contribution of phonological skills to reading shed light on it. For example, Vaessen et al. (2010) showed that changes in phonological awareness contribution to reading speed from Grade 1 to Grade 4 was qualitatively similar but quantitatively different across three languages varying in orthographic transparency (Hungarian, Dutch and Portuguese, from the most transparent to the most opaque). The authors found that phonological awareness contribution to reading speed declined with higher reading expertise in the three languages, but that its strength was weaker in the more transparent languages.

Moving away slightly from the role of phonological awareness in reading, Vaessen et al. (2010) also reported that the contribution of visual-to-phonology mappings skills to reading fluency, measured through rapid automatized naming, increased similarly across the three languages throughout development (see also Vaessen & Blomert, 2010). Data from other research groups also suggests that abilities tapping into visual processing contribute to reading acquisition in addition to, and independently from, phonological awareness. Like in Vaessen et al. (2010), Bosse and Valdois (2009) reported a decline in the contribution of phonological awareness to reading speed along Grades 1, 3 and 5 in French children, but a sustained constant contribution of specific visual skills, i.e., the visual attention (VA) span, to reading speed. The VA span is defined as the number of distinct visual elements that can be processed simultaneously in a multi-element array regardless of the verbal nature of the stimuli (Lobier, Zoubrinetzky, & Valdois, 2012). The VA span hypothesis proposes that a limit in simultaneous visual attention reduces the maximum amount of visual elements that can be processed at once in an orthographic sequence, and results in a subtype of developmental dyslexia independent from the phonological subtype

(Bosse, Tainturier, & Valdois, 2007). Accordingly, the neural dysfunctions associated to the VA span and the phonological dyslexic cognitive subtypes have been found to be independent (Peyrin et al., 2012).

Interestingly, VA span skills are specifically critical for (i) processing simultaneously all the letters within whole-word visual forms, (ii) building-up lexical orthographic knowledge and (iii) enhancing the recognition of previously unfamiliar words (Bosse, Chaves, Largy, & Valdois, 2013; Bosse & Valdois, 2009). From a *visual processing* perspective of the psychological grain size theory, a sufficient amount of VA span resources (i.e., a large visual grain size) should be essential for coping with inconsistencies and irregularities present in opaque orthographies. Support for this idea is the study of Bosse and Valdois (2009), which showed that VA span skills explain more variance in irregular word reading accuracy than phonological awareness does.

The studies described above certainly help to sketch a (possible) universal framework of reading development in alphabetic languages. However, cross-linguistic comparisons which quantify the influence of orthographic transparency on reading acquisition are often vulnerable to uncontrollable factors such as the evaluation of reading in different groups and cultures, with different pools of items. A powerful approach to get around some of these methodological obstacles is to assess bilingual children who learn to read in both a transparent and an opaque language simultaneously. Studying this population should further bring unique insights on how reading develops in bilinguals, by clarifying whether the bilingual reading system is flexible and adapts to the orthography in which reading is performed. If this is the case as is argued by Das, Padakannaya, Pugh, and Singh (2011), measuring reading accuracy and speed in the two languages of bilinguals should result in similar patterns to those obtained in cross-linguistic monolingual studies, but with the additional benefit of avoiding inter-subject variability skewing the results. Consequently, evaluating bilinguals can also allow us to explore to what extent a specific brain dysfunction that causes developmental dyslexia in one language similarly affects reading in another language which differs in orthographic transparency. Assuming that orthographic transparency modulates the strength of the contribution of the independent cognitive factors that cause dyslexia (i.e., phonological awareness and VA span skills) to reading, the severity of the reading deficits observed should be modulated accordingly.

In the present study, bilingual children, with and without developmental dyslexia, who learned to read simultaneously in a transparent (Spanish) and an opaque (French) language were assessed. Based on assumptions relating to previous monolingual cross-linguistic studies, we predicted that children should be better readers in their transparent language, at least on accuracy measures (Seymour et al., 2003; Ziegler et al., 2010). We further expected dyslexic children to exhibit less severe reading deficits in their transparent language (Spanish) than in their opaque language (French): there would be a particularly noticeable difference on reading speed and less on reading accuracy (cf. Wimmer & Schurz, 2010).

Regarding cognitive reading sub-processes, a VA span disorder was predicted in our dyslexic sample (Bosse et al., 2007). As to phonological awareness skills, two hypotheses were plausible: (i) poorer phonological awareness skills regardless of the language of assessment were predicted in the dyslexic children compared to the control children (Caravolas et al., 2005) and (ii) a boost of phonological awareness development due to learning to read in a transparent language (e.g., Spencer & Hanley, 2003) was predicted to compensate for the phonological disorder of the dyslexic children in this language.

Lastly, within the whole group of children, compared to phonological awareness skills, VA span skills were expected to contribute more strongly to reading speed as well as to specific orthographic knowledge in both the opaque and transparent languages (Bosse & Valdois, 2009).

2. Method

2.1. Participants

Nine skilled bilingual readers and 9 matched dyslexic bilingual readers participated in the study. They were all pupils at the "Lycée Franco-Mexicain" of Coyoacan in Mexico City. All the children came from families in which at least one of the parents had French as their mother tongue and the other parent Spanish. Therefore, all children started being exposed to both languages from birth. They used both languages on a daily basis at home and at school: children mainly used Spanish during their daily life, but they followed a formal education in French since kindergarten. Based on parents' and teachers' reports, all children had comparable level of proficiency in the production and the comprehension of both languages. Most of the teaching in the school was done in French, except for one morning per week, in which reading and writing in Spanish was taught by a native Spanish speaker. Teachers reported that the reading method was mixed in French and essentially based on grapho-phonological conversion rules in Spanish. None of the participants were repeating or had skipped a grade, and all were therefore attending the expected grade for their age. Their school attendance was regular. All children had normal or corrected-to-normal vision and reported no hearing impairments.

The dyslexic children included in the study had previously received a formal diagnosis of developmental dyslexia either in French or Spanish, established after a complete interview and neuropsychological screening performed by neuropsychologists or speech and language therapists, and ruling out the presence of any co-morbid attentional disorders (e.g., ADHD). The diagnosis of developmental dyslexia was established using both inventories and testing procedures in accordance with the guidelines of the ICD-10 classification of Mental and Behavioral disorders. Each dyslexic child was paired with a skilled reader child. The two children in each pair were born on the same year, had the same gender and were attending the same course level. Furthermore, the control children had the same language background in their family as the dyslexic children. For example, if a dyslexic child had a French native mother and a Spanish native father, their paired control

Table 1
General abilities of the control and the dyslexic groups.

	Skilled readers		Dyslexics		*p*
	M (*SD*)	Range	*M* (*SD*)	Range	
Chronological age (months)	124.6(11.1)	108–140	124.8(11.2)	108–144	n.s.
Progressive matrices (score)	37.2(7.6)	22–46	35.5(8.9)	18–49	n.s.
Reading age (months)	124.0(18.8)	95–149	89.3(6.6)	78–98	<.001
Reading delay (months)	−0.55(13.6)	−20/19	−35(7.2)	−46/−24	<.001
Verbal fluency FR (words/min)	16.3(3.1)	12–23	14.3(4.3)	8–19	n.s.
Verbal fluency SP (words/min)	15.5(3.9)	8–23	14.7(4.5)	9–24	n.s.

child did too. The two groups of participants both included two children attending Grade 3, two attending Grade 4, four attending Grade 5 and one attending Grade 6.

2.2. Neuropsychological battery

Each child was administered French and Spanish batteries that assessed their reading skills and their cognitive underpinnings. The two batteries were as similar as possible in French and Spanish regarding the material used and the instructions given. Each battery lasted about two hours and was split in two sessions of 1 hour each. The experimental sessions took place at the "Lycée Franco-Mexicain" of Coyoacan in a quiet room. All children were randomly assigned to two groups: one starting with the French battery and the other starting with the Spanish battery. Before a more detailed evaluation of reading and cognitive skills, and in order to confirm the previous diagnosis of the children assigned to the dyslexic group, and the absence of any significant reading deficit in the children assigned to the control group, children were given a task measuring their non verbal IQ (progressive matrices; Raven, Raven, & Court, 1990), and the French Alouette reading test (Lefavrais, 1967) which gives a index of the general reading level of the child. All children obtained a score above the 10th centile on the progressive matrices compared to the chronological age norm, and all dyslexic children obtained a reading age of at least 24 months younger than their chronological age, whether skilled reader did not exhibit any delay on this task (cf. Table 1). A semantic fluency task was also administered to the children in order to measure how fast they were at accessing lexical items. In this task, children were asked to say as many "animals" (French) and "aliments" (Spanish) as possible in 1 minute. The latter task allowed getting a measure of Spanish and French verbal proficiency and vocabulary as well as a measure of the degree of bilingualism of the two groups since slow lexical access skills have been related to bilingualism (Poulin-Dubois, Bialystok, Blaye, Polonia, & Yott, 2013).

2.2.1. Literacy skills

2.2.1.1. Text reading. In both French and Spanish, participants were presented with the same passage of the novel "The little prince" ("El principito", "Le petit Prince" written by Saint Exupéry). The text in French was the original text and the text in Spanish was a professional translation. Both versions were matched for the number of words ($n = 104$) and lines ($n = 8$). The French text counted 614 characters (spaces included) and the Spanish text 587. The number of errors and the overall time taken to read the text were recorded.

2.2.1.2. Single item reading. In French, two lists of regular words ($n = 20$) and pseudowords ($n = 40$) from the ODEDYS-2 battery (Jacquier-Roux, Valdois, & Zorman, 2002) were administered. Younger children (Grade 3) were presented with the high frequency regular word and irregular word lists whereas older children (from Grade 4) were presented with the low frequency regular word list. In Spanish, children of Grade 3 and Grade 4 were presented with the regular words ($n = 30$) and pseudowords ($n = 30$) reading lists of the PROLEC battery (Cuetos, Rodríguez, & Ruano, 1996), whereas children in Grades 5 and 6 were presented with the reading lists of the PROLEC-SE battery (Ramos & Cuetos, 1999). For each language, the length of the words were between 3 and 8 letters, and pseudoword accuracy and time measures were transformed into percentages of accuracy and second per item reading speed measures.

2.2.1.3. Specific orthographic knowledge. In French, the list of irregular words ($n = 20$) from the ODEDYS-2 battery (Jacquier-Roux et al., 2002) was presented to the children. In Spanish, they had to perform an orthographic choice task similar to the one used by Serrano and Defior (2008): children had to read 18 sentences where the last word was missing without time pressure. They were instructed to complete each sentence by choosing the appropriate written word between two homophones characterized by a different spelling and meaning (e.g., botas, votas; max = 18).

2.2.2. Cognitive contributors to reading

2.2.2.1. Phonemic awareness. Omission of the initial phoneme. For each language, 20 words (1 to 4 syllables in French and 2 to 4 syllables in Spanish) were presented to the children orally one by one. Children had to repeat the items removing the first phoneme (e.g., /piko/ → /iko/; /viRgyl/ → /iRgyl/). Before the test phase, the child was presented with an example. For both the French and the Spanish versions of the task, the number of errors was recorded and converted into percentage of accuracy.

Acronyms. For each language, 10 pairs of words (2 to 3 syllables in French and 2 to 4 syllables in Spanish) were presented orally to the child. The first word always started with a consonant and the second word of the pair with a vowel. The children had to remove the first phoneme of the two words, blend them and produce the resulting syllable (e.g., bébé + ourson → /bu/; camion + uva → /ku/). Before the test phase, the child was presented with an example. For both the French and the Spanish versions of the task, the number of errors was recorded and converted into percentage of accuracy.

2.2.2.2. VA span. Since the assessment of VA span skills requires the presentation of consonant strings (consonants used were part of both the French and the Spanish alphabet), it was measured only once and was part of the French battery.

Control task: letter identification task. Children were presented with single letters in the center of the screen during varying durations (10 items for each presentation time of 33 ms, 50 ms, 67 ms, 84 ms and 101 ms) and immediately followed by a mask. They were asked to name the letter immediately after being presented. Scores corresponded to the number of letter correctly reported (max = 50).

Whole report task. The whole report task included 20 black consonant strings (upper-case Arial font, 18 pt). The center-to-center distance between each adjacent consonant was 1.2° so that lateral masking effects were minimized. Stimuli did not include the same letter twice and were not French or Spanish word skeletons (e.g., C M P T R for "compter"). At the start of each trial, a central fixation point was displayed for 1000 ms followed by a blank screen for 50 ms. Consonant strings were presented horizontally during 200 ms at the center of the screen and immediately after, participants had to recall as many letters as possible (identity not location). They started naming letters at the end of the 5-consonant string display. The experimental trials were preceded by 10 training trials for which participants received feedback. No feedback was given during the 20 test trials. The number of letters accurately reported was recorded (identity not location; max = 100).

Partial report task. The participants were required to orally report a single cued letter among the 5 letters of each briefly presented string. Fifty random 5-letter strings (e.g., T H F R D) were built up from the same 10 consonants used in the whole report condition (with no repeated letter). At the start of each trial, a central fixation point was presented for 1000 ms followed by a blank screen for 50 ms. A 5-letter string was then presented at the center of the screen for 200 ms. At the offset of the letter string, the bar probe appeared for 50 ms. Participants were asked to report the cued letter only. The experimental trials were preceded by 10 training trials for which participants received feedback. No feedback was given during the 50 test trials. The score was the number of letters accurately reported (max = 50).

2.3. Data analysis

For the tasks conducted in one language only (non verbal IQ and VA span tasks), group effects were measured by means of independent ANOVA on performance with group (control, dyslexic) as the between-subject factor. For tasks conducted in both French and Spanish (single item reading and phonological awareness), ANOVAs were conducted with group (control, dyslexic) as the between-subject factor and orthography (French, Spanish) as the within-subject factor. For single item reading, lexicality was entered as an additional within-subject factor in the analyses (i.e., regular word, pseudoword). Bonferroni post hoc tests were used to assess further multiple comparisons. Non parametric independent *U*-tests or Wilcoxon matched pairs test were used when the homogeneity of variance was violated even after data transformation (log or reciprocals) and Greenhouse–Geisser adjustment was applied when the assumption of sphericity was not respected.

We also determined the cognitive subtype of each dyslexic bilingual child (VA Span, phonological, both or none). For the VA span tasks and the two French phonological tasks, individual deficits were assessed using *z*-scores computed according to the age-matched corresponding norms (Bosse & Valdois, 2009). For the two Spanish phonological tasks that were created for the propose of the present study, we used the *t* distribution method (t_{modified}, Crawford & Howell, 1998) to establish the presence of significant deficit for each dyslexic child as compared to the control group ($n = 9$, $p < .05$ for $t < 1.83$, one-tailed; note that such test has been shown robust in the case of small control groups; Crawford, Garthwaite, Azzalini, Howell, & Laws, 2006).

Lastly, partial correlation analyses controlling for chronological age were conducted in the whole sample of children ($n = 18$) between reading and both phonological and VA span skills, for French as well as Spanish tasks. All correlations coefficients (unless specified) will be presented with the one-tailed *p* value since the direction of the correlation was a priori expected: the poorer (slower and less accurate) the reading, the lower the VA span and phonological skills.

3. Results

The skilled reader children and the dyslexic children were matched for non verbal IQ ($t < 1$, $p > .5$). They significantly differed on reading age level ($t(16) = 4.9$, $p < .001$) with the dyslexic children exhibiting a younger reading age than the control children. No group or language effect was observed on the semantic fluency ($Fs < 1$), nor an interaction between group and language on this task ($F < 1$) reflecting similar semantic lexical access across groups and languages (Table 1).

Table 2
Performance of the two groups on reading skills and reading related skills. Group differences are presented: ">" and "<" indicates significant differences and ">=" indicates marginal differences.

	Skilled readers		Dyslexic readers		Group effect	
	M (SD)	Range	M (SD)	Range		p
Reading processes						
Text reading						
Acc (number of errors) – FR	3.8 (4.9)	0–17	13.0(7.9)	3–30	D > C	.01
Acc (number of errors) – SP	3.6(3.6)	1–13	5.1(2.6)	1–10	D = C	n.s.
Speed (total time in s) – FR	47.6(13.9)	33–74	163.2(150.9)	64–546	D > C	<.01
Speed (total time in s) – SP	57.3(18.6)	41–97	118.4(56.8)	63–225	D >= C	.052
Regular word reading list						
Acc (%) – FR	92.8(5.3)	85–100	73.3(14.9)	45–95	D < C	<.001
Acc (%) – SP	98.2(2.1)	95–100	90.4(5.6)	80–97	D = C	n.s.
Speed (s/item) – FR	0.9(0.2)	0.6–1.2	2.1(1.1)	0.8–3.8	D > C	<.01
Speed (s/item) – SP	1.0(0.2)	0.7–1.3	2.0(0.8)	0.9–3.1	D > C	<.01
Pseudoword reading list						
Acc (%) – FR	81.4(11.4)	67–100	57.8(11.7)	42–75	D < C	<.001
Acc (%) – SP	95.6(5.0)	83–100	86.7(6.8)	80–100	D = C	n.s.
Speed (s/item) – FR	1.3(0.3)	0.9–2.0	2.5(1.5)	1.1–5.6	D >= C	.06
Speed (s/item) – SP	1.3(0.3)	1.0–1.8	2.3(0.7)	1.3–3.5	D >= C	.06
Specific orthographic knowledge						
Irregular word reading – FR						
Acc (%)	73.3(14.3)	60–100	33.3(17.0)	10–70	D < C	<.001
Speed (s/item)	1.1(0.3)	0.8–1.6	2.5(1.5)	0.9–5.6	D > C	<.005
Orthographic choice – SP						
Acc (/18)	14.1(2.0)	9–16	11.5(2.2)	8–14	D < C	.027
Cognitive reading underpinnings						
Phonemic awareness						
Acronyms Acc (%) – FR	83.3(13.3)	60–100	74.4(19.5)	30–100	D = C	n.s.
Acronyms Acc (%) – SP	97.7(6.3)	80–100	91.1(14.5)	60–100	D = C	n.s.
Phonemic omission Acc (%) – FR	83.8(27.6)	30–100	80.6(16.9)	55–100	D = C	n.s.
Phonemic omission Acc (%) – SP	92.8(15.5)	50–100	87.8(16.5)	45–100	D = C	n.s.
VA Span skills						
Control task: Letter identification (/50)	48.4(1.5)	46–50	46.0(3.5)	40–50	D = < C	.09
Whole report task (/100)	88.1(7.8)	73–97	66.9(9.4)	44–79	D < C	< .001
Partial report task (/50)	46.1(2.5)	42–50	38.8(7.7)	22–48	D < C	.021

3.1. Literacy skills

3.1.1. Text reading (cf Table 2)

On accuracy, main effects of orthography ($F(1,16) = 7.5$, $p = .014$, $\eta_p^2 = .32$) and group ($F(1,16) = 6.4$, $p = .022$, $\eta_p^2 = .29$) were found. A significant interaction between these two factors ($F(1,16) = 6.7$, $p = .020$, $\eta_p^2 = .30$) showed that skilled reader children made as many mistakes in their transparent language as in their opaque language (post hoc, $p > .9$), whereas dyslexic children text reading was better in Spanish than in French (post hoc, $p = .01$). Moreover, dyslexic children made more mistakes compared to their peers when reading the French text(post hoc, $p < .01$) but not the Spanish text (post hoc, $p > .9$).

On text reading speed, no main effect of orthography was found ($F < 1$). A main group effect showed slower reading speed for dyslexic children compared to skilled readers ($F(1,16) = 14.5$, $p < .005$, $\eta_p^2 = .48$). Orthography modulated the expression of this deficit ($F(1,16) = 4.8$, $p = .043$, $\eta_p^2 = .23$), which was significant in French (post hoc, $p < .01$) and marginal in Spanish (post hoc, $p = .052$).

3.1.2. Single item reading: regular word and pseudoword reading (Table 2)

Children were overall more accurate when reading single items in Spanish than in French ($F(1,16) = 62.7$, $p < .001$, $\eta_p^2 = .80$), whereas they were as fast at reading items in the two languages ($F(1,16) = 1.9$, $p = .18$, $\eta_p^2 = .11$). Moreover, in both orthographies, children were faster ($F(1,16) = 37.2$, $p < .001$, $\eta_p^2 = .70$) and more accurate ($F(1,16) = 21.9$, $p < .001$, $\eta_p^2 = .58$) at reading regular words than pseudowords. The lexical effect on item reading was modulated by orthography for accuracy ($F(1,16) = 8.2$, $p = .01$. $\eta_p^2 = .34$) but not for speed ($F < 1$): in Spanish, children could read regular words as well as pseudowords (post hoc, $p > .9$), whereas in French, they were better at reading words than pseudowords (post hoc, $p < .001$).

On both item reading accuracy and speed, we observed a main group effect that showed that dyslexic children exhibited slower ($F(1,16) = 14.1$, $p < .005$, $\eta_p^2 = .47$) and less accurate ($F(1,16) = 25.5$, $p < .001$, $\eta_p^2 = .62$) performance than skilled readers. A significant group by orthography interaction ($F(1,16) = 10.0$, $p < .01$, $\eta_p^2 = .38$) modulated the main group effect (but not the main orthography effect) reported on accuracy: post hoc analyses showed that dyslexic children made more mistakes than control children in French ($p < .001$) but not in Spanish ($p > .05$). Group differences on accuracy were not modulated by the lexical status of items ($F < 1$). Inversely, the group effect on speed was not influenced by orthography

($F < 1$) but by the lexical status of items ($F(1,16) = 7.1$, $p = .017$, $\eta_p^2 = .31$). Post hoc analyses showed that dyslexic children were slower than control children at reading words ($p < .01$), and tended to be slower at reading pseudowords ($p = .06$). Furthermore, dyslexic children showed similar speed at reading both words and pseudowords (post hoc, $p > .1$) whereas skilled readers read words faster than pseudowords (post hoc, $p < .001$).

Lastly, no group by orthography by lexicality interaction was found, neither on reading accuracy, nor on reading speed ($Fs < 1$).

3.1.3. Specific orthographic knowledge

Compared to the skilled readers, the dyslexic children were impaired on French irregular word reading accuracy ($F(1,16) = 25.9$, $p < .001$, $\eta_p^2 = .62$) and speed ($F(1,16) = 10.9$, $p < .005$, $\eta_p^2 = .41$). Dyslexic children were also less accurate in choosing the right word between the two options proposed to complete the sentence in the homophone choice task in Spanish ($F(1,16) = 6.0$, $p = .027$, $\eta_p^2 = .27$).

3.2. Cognitive underpinnings

3.2.1. Phonemic awareness

On the phonemic omission task, no main group effect was observed ($F < 1$), and this was not influenced by orthography ($F < 1$). A marginally significant benefit at performing the task in Spanish as compared to French was observed in the whole sample ($F(1,16) = 3.7$, $p = .072$, $\eta_p^2 = .19$). On the acronym task, no group difference was found neither in French nor in Spanish (for all Us, $ps > .2$). A main effect of orthography was found on the acronym task performance, indicating that all children were better in the Spanish than the French version of the task ($z = 2.8$, $p < .01$). Overall, no deficit in phonemic awareness was found in the group of dyslexic children.

3.2.2. VA span skills

First, no group difference was found on the control task ($F(1,16) = 3.3$, $p = .09$, n.s., $\eta_p^2 = .17$ at all presentation times, $ps > .05$, n.s.), suggesting that the dyslexic participants were as good as the skilled readers at identifying the consonants presented in isolation. On both the whole and the partial report tasks, the dyslexic children reported significantly less letters than the skilled readers ($F(1,16) = 24.6$, $p < .001$, $\eta_p^2 = .60$ and $F(1,16) = 6.5$, $p = .021$, $\eta_p^2 = .30$, respectively).

3.2.3. Cognitive profile of the dyslexic children: phonological awareness and VA Span

Analysis of the cognitive profile of each dyslexic child revealed that six children had a significant deficit on at least one VA Span task (i.e., whole report or partial report), and three children had a significant deficit on at least one phonological awareness task in Spanish or French. As shown in Table 3, three children exhibited a significant impairment only on their VA Span skill (child 2, child 6 and child 8), one only on their phonological awareness skills (child 5), and 2 on both their phonological awareness and VA Span skills (child 1 and child 4). Lastly, 2 dyslexic children did not exhibit any deficit on the tasks administered (child 3 and child 7).

3.2.4. Correlations: reading in French and Spanish and cognitive underpinnings

For correlation purposes, we computed two global phonemic awareness scores for French and Spanish, resulting from the average performance obtained on the two phonemic awareness tasks, and a general VA span score computed as the average performance on the whole and partial report tasks.

The two phonological scores correlated with each other ($r = .54$, $p = .02$). As predicted by the VA span hypothesis, no correlation was found between the VA span score and the phonological score neither in French ($r = .23$, $p > .4$, two-tailed) nor

Table 3
Individual deficits of the nine dyslexic children on the phonemic awareness and VA Span tasks. Bold underlined numbers indicate a significant deficit.

	French PA		Spanish PA		VA Span	
	Acronyms	Phonemic omission	Acronyms	Phonemic omission	Whole report	Partial report
Child 1	−0.48	**−1.41**$	**−4.19***	**−2.92***	**−2.26***	−0.47
Child 2	−0.48	−0.89	−1.17	0.44	**−1.34**$	−0.70
Child 3	0.38	0.93	0.33	0.14	−1.03	−0.47
Child 4	**−2.20***	0.41	0.33	0.44	**−2.05***	**−2.56***
Child 5	−0.05	0.41	**−5.70***	−0.17	−0.62	0.23
Child 6	−0.91	−1.15	0.33	−0.78	**−1.54**$	**−2.79***
Child 7	0.63	−0.18	0.33	−0.48	−0.97	0.52
Child 8	0.17	0.89	0.33	0.13	**−3.13***	**−2.71***
Child 9	0.81	0.93	0.33	0.44	**−1.95***	0.96

PA: phonological awareness. z-Scores are presented for the French PA tasks and the VA Span tasks (age-matched norms of Bosse & Valdois, 2009) and $t_{modified}$ scores computed based on average of the control group are presented for the Spanish PA tasks.

* z-score or $t_{modified}$ score $< .05$ (one-tailed).

$ z-score or $t_{modified}$ score $< .10$ (one tailed).

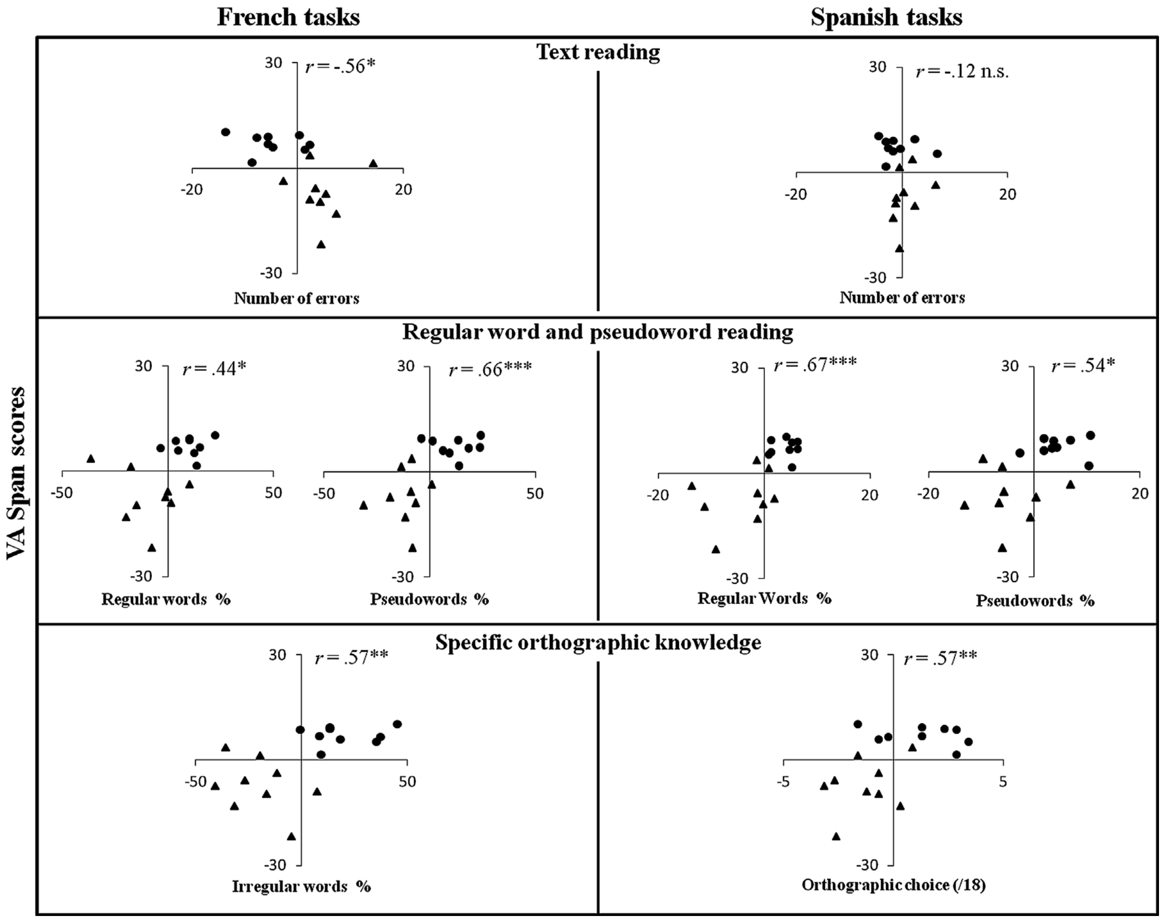

Fig. 1. Scatterplots depicting the partial correlations between VA Span scores (y axes) and visual French and Spanish reading accuracy measures (x axes) among the whole group of children ($n = 18$). For each panel, individual residual scores are represented, which stem from the correlations between the factor(s) controlled for and (i) VA Span scores, as well as (ii) reading accuracy measures. Dots represent the control children and triangles represent the dyslexic children.

in Spanish ($r = .11$, $p = .6$, two-tailed). Reading age correlated with VA span, indicating that the poorer reading skills, the poorer VA span skills ($r = .67$, $p < .01$). Reading age did not correlated with the two phonological scores (French: $r = .08$, $p > .3$; Spanish: $r = .02$, $p > .4$).

3.2.4.1. VA span skills and reading accuracy (see Fig. 1). In French, VA span skills correlated with the number of errors made in text reading, as well as with regular word, pseudoword, and irregular word reading accuracy ($r = -.56$, $p = .01$; $r = .44$, $p = .03$; $r = .66$, $p < .005$; $r = .57$, $p < .01$; respectively). In Spanish, VA span skills correlated with word and pseudoword reading accuracy ($r = .67$, $p < .005$; $r = .54$, $p = .013$; respectively), with performance on the orthographic choice task ($r = .57$, $p < .01$), but not with the number of errors in text reading($r = -.12$, $p > .3$).

3.2.4.2. VA span skills and reading speed (see Fig. 2). In French, VA span skills correlated with the total time for reading the text, as well as with regular word, pseudoword, and irregular word reading speed (in French: $r = -.74$, $p < .005$; $r = -.70$, $p < .005$; $r = -.67$, $p < .005$; $r = -.76$, $p < .001$, respectively). In Spanish, VA span skills also correlated with all speed measures(text: $r = -.77$, $p < .001$; words: $r = -.75$, $p < .001$; pseudowords: $r = -.67$, $p < .005$).

3.2.4.3. Phonemic awareness and reading accuracy (see Fig. 3). In French, phonological awareness scores correlated with the number of errors made on reading the text and with pseudoword reading accuracy ($r = -.47$, $p = .02$; $r = .52$, $p = .015$, respectively), but not with regular or irregular word reading accuracy ($ps > .10$). In Spanish, phonological awareness scores also correlated with both the number of errors in text reading ($r = -.62$, $p < .005$) and pseudoword reading accuracy ($r = .65$, $p < .005$).The correlation was marginal with word reading ($r = .40$, $p = .06$) and non significant with the orthographic choice task performance ($p > .5$).

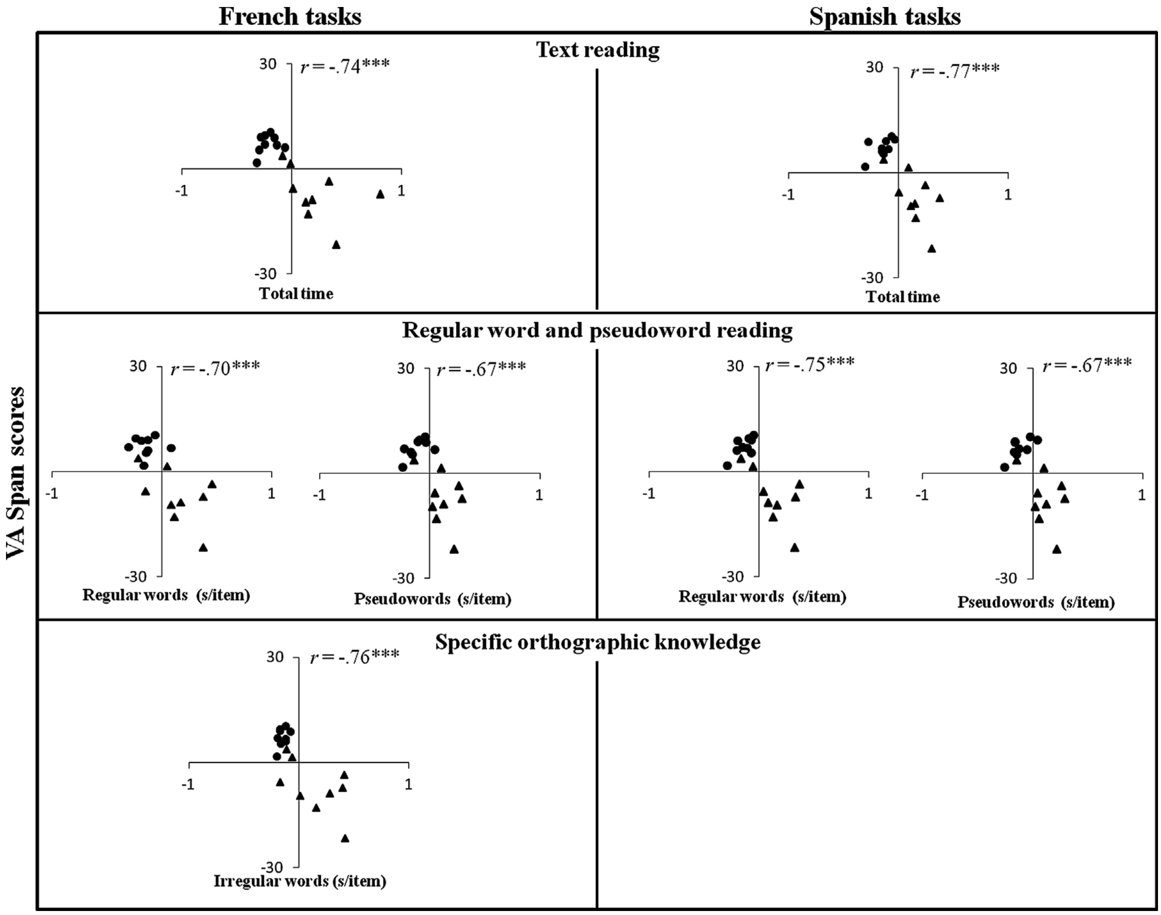

Fig. 2. Scatterplots depicting the partial correlations between VA Span scores (*y* axes) and visual French and Spanish reading speed measures (*x* axes) among the whole group of children ($n = 18$). For each panel, individual residual scores are represented, which stem from the correlations between the factor(s) controlled for and (i) VA Span scores, as well as (ii) reading speed measures. Dots represent the control children and triangles represent the dyslexic children.

3.2.4.4. Phonemic awareness and reading speed (see Fig. 4). None of the speed measures correlated with phonological awareness scores, neither in French,nor in Spanish (all *ps* > .30).

4. Discussion

The present study examined the impact of orthographic transparency on typical and atypical reading acquisition in bilingual children. We evaluated reading performance on similar tasks in both an opaque (French) and a transparent (Spanish) orthography within the same group of bilingual children who are proficient and have learned to read in both languages. In line with previous cross-linguistic studies conducted within monolingual groups (Ellis et al., 2004; Kandel & Valdois, 2006; Seymour et al., 2003; Ziegler et al., 2010), bilingual children were generally more accurate at reading in their transparent language (i.e., regular word and pseudoword reading). The control children made also more errors when reading the French than the Spanish version of the text replicating the findings of Kandel and Valdois (2006) in non dyslexic French-Spanish bilingual first and second graders. These results support the few neuroimaging studies showing that orthography modulates brain activity during reading in bilinguals (Das et al., 2011; Jamal, Piche, Napoliello, Perfetti, & Eden, 2012; Meschyan & Hernandez, 2006). Our results further showed that reading accuracy deficits did not manifest when the bilingual dyslexic children read in Spanish, including preserved performance on text reading, regular word, and pseudoword reading. On all these tasks in French, however, the bilingual dyslexic children exhibited significant reading accuracy deficits. Our findings therefore echo earlier research that showed that dyslexic symptoms are exacerbated in opaque compared to transparent orthographies (Landerl et al., 2013; Landerl, Wimmer, & Frith, 1997). Such cross-linguistic differences highlighted within the same children show that the language of assessment modulates the manifestation of reading (accuracy) disorders in bilinguals, and are in line with previous studies conducted in balanced bilingual dyslexic individuals. Wydell and Butterworth (1999) indeed showed that the dyslexic symptoms of a Japanese-English balanced bilingual adult, which were evident in English, disappeared when reading was assessed in the transparent Japanese Kana. More recently,

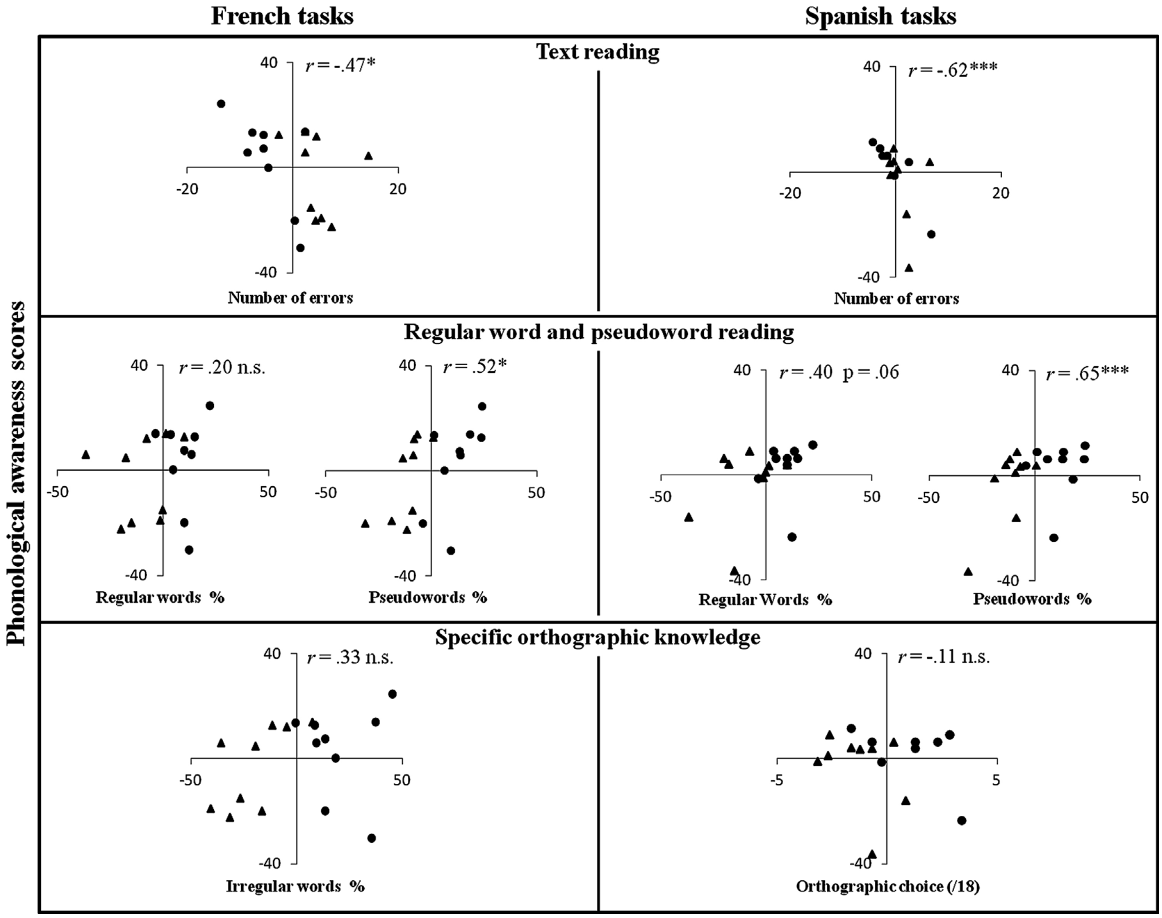

Fig. 3. Scatterplots depicting the partial correlations between phonological scores (y axes) and visual French and Spanish reading accuracy measures (x axes) among the whole group of children ($n = 18$). For each panel, individual residual scores are represented, which stem from the correlations between the factor(s) controlled for and (i) phonological scores, as well as (ii) reading accuracy measures. Dots represent the control children and triangles represent the dyslexic children.

Gupta and Jamal (2006) evaluated a group of Hindi-English balanced bilingual dyslexic children and showed that they made less reading errors in their transparent (Hindi) than their opaque (English) language (see also Gupta & Jamal, 2007).

Interestingly, high reading accuracy in Spanish was also accompanied by an overall better level of phonemic awareness in this language compared to French. This possibly stems from the previously reported boost in phonemic awareness skills which learning to read in transparent orthographies favors since they make salient the units important for building-up the representations of linguistic sounds (Anthony & Francis, 2005; Caravolas & Bruck, 1993; Goswami, 1999). Still, phonemic awareness differences between Spanish and French in the whole bilingual group could be due to the children living in a Spanish speaking country, and hence being more exposed to the Spanish than the French phonological system. According to the Lexical Restructuring Model (e.g., Metsala & Walley, 1998) vocabulary skills – the quality of phonological representations – are the bases for phonological awareness acquisition in a particular language. Better Spanish vocabulary could therefore yield better phonemic awareness in this language than in French (see Russak & Saiegh-Haddad, 2011; Scarpino, Lawrence, Davison, & Hammer, 2011 for support of this hypothesis in un-balanced bilinguals), regardless of the influence of the transparency of the written language. However, we found no difference between French and Spanish on the semantic fluency tasks, which provides an index of the richness of children's vocabulary, in line with the fact that the children in our study were balanced bilinguals.[1] Moreover, both phonemic awareness scores correlated with each other suggesting that poor French phonemic awareness skills were associated with poor Spanish phonemic awareness skills. The Lexical Restructuring Model would not have predicted this correlation if differences in phonological word knowledge had driven the cross-

[1] In favor of a high proficiency level in French of the bilingual control children for written language skills, we found that the skilled readers performed well within the monolingual French children's age norms (Bosse & Valdois, 2009) on the three items reading lists in French (average z-scores for the six accuracy and speed measures between −0.39 and 0.03). The deficit of the dyslexic bilingual children was not more severe than the typical deficit exhibited by dyslexic French monolingual children on these lists (average z-scores for the six accuracy and speed measures between −2.94 and −2.26).

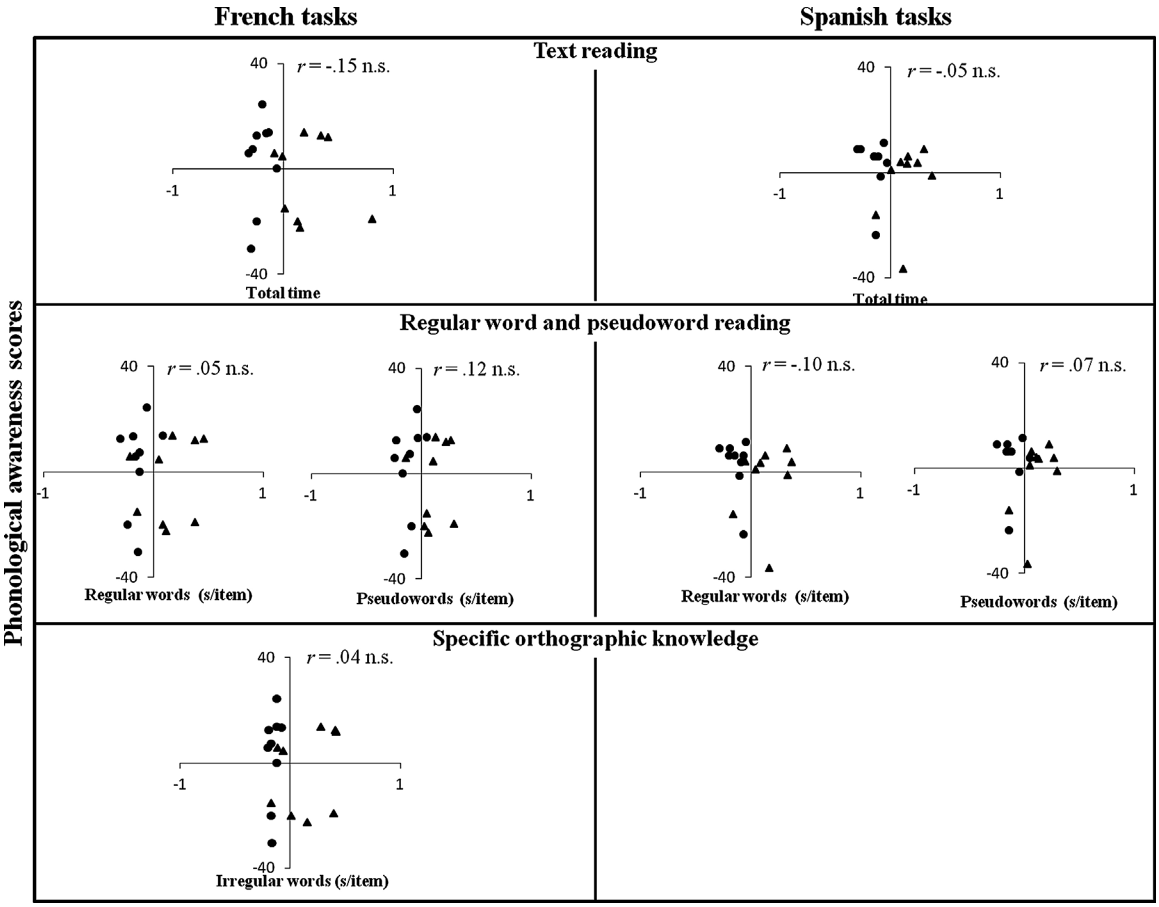

Fig. 4. Scatterplots depicting the partial correlations between phonological scores (*y* axes) and visual French and Spanish reading speed measures (*x* axes) among the whole group of children ($n = 18$). For each panel, individual residual scores are represented, which stem from the correlations between the factor(s) controlled for and (i) phonological scores, as well as (ii) reading speed measures. Dots represent the control children and triangles represent the dyslexic children.

linguistic differences on phonemic awareness in the children. Our results suggest that rather than being influenced by oral proficiency and vocabulary, phonemic awareness may be more prone to be subject to written language influences, as soon as it is taught and acquired (Castles & Coltheart, 2004; Morais, Cary, Alegria, & Bertelson, 1979). Lastly, the Lexical Restructuring Model would have also predicted stronger phonological deficits of the bilingual dyslexic children in their weakest language. Contrary to this hypothesis, as a group, the dyslexic children did not present any phonemic awareness deficit in either French or Spanish. At the individual level, only three participants out of nine exhibited a significant deficit in at least one of the phonemic awareness tasks, which also reflects well-known heterogeneity of the dyslexic population (Lallier, Thierry, & Tainturier, 2013; Protopapas, 2014). It is furthermore unlikely that our phonemic awareness tasks did not capture processes critical for reading development since within both languages, phonological scores positively correlated with text and pseudoword reading accuracy. The absence of phonemic awareness deficit seems therefore genuine in our bilingual dyslexic children since the lack of variance that generally characterizes these skills in transparent languages (and hides the deficits) is less likely to have occurred in the opaque French orthography (Landerl et al., 2013). Although our results go against the hypothesis of the phonological core deficit hypothesis of developmental dyslexia (Snowling, 2000), Laurent and Martinot (2010) showed that, from Grade 4 on, children undergoing a bilingual tuition exhibit better phonological awareness skills than their monolingual peers. Most of the children in the present study (14 out of 18) were beyond Grade 4. It is therefore possible that dyslexic bilingual children exposed to two languages for sufficiently long enough somehow compensate for potential phonological awareness impairments.

The aforementioned results overall stress the importance of finding visible markers of developmental dyslexia in bilingual children in a transparent language. In Spanish, reading disorders may indeed manifest themselves through more subtle measures. For example, the orthographic transparency of the two languages known by our bilingual participants *did not* modulate the reading speed deficit exhibited by dyslexic children. This result fits well with studies showing that reading speed is a critical measure for reading evaluation in transparent languages since it accounts for reading variance which is often not captured by accuracy measures (Kirby et al., 2010). Interestingly, whereas the orthographic transparency did not influence the reading speed deficits of the dyslexic children, the lexical status of items did. Bilingual skilled readers were faster at reading words than pseudowords, independently of the orthography, which suggests that they use two reading procedures in both French and Spanish: word traces encoded in orthographic memory led to a faster retrieval than pseudowords for which slower decoding skills were required. Interestingly, this lexical effect was absent in the dyslexic children. This suggests the use of a unique strategy to decode known or unknown items in these children, possibly because they still have not developed lexical orthographic memory skills in either of their languages. This hypothesis was supported by the particularly severe speed deficit of the bilingual dyslexic children in reading real words, as well as in tasks that required the use of specific whole word knowledge in French (irregular word reading accuracy and speed) and Spanish (orthographic choice).

Related to this point, VA span skills that are critical for building-up such whole word knowledge (Bosse et al., 2007; Bosse & Valdois, 2009) were severely impaired in the dyslexic bilingual children. Indeed, a high number of dyslexic participants presented a significant deficit of at least one of the VA Span tasks (six out of nine), leading to a poorer performance on the two visual report tasks in the dyslexic children as a group compared to the skilled readers.[2] Accordingly, in addition to correlating with French and Spanish reading accuracy, VA span skills correlated with reading speed in the two orthographies. This is in line with Lobier, Dubois, and Valdois (2013) who demonstrated the critical role of VA span skills in reading speed. VA span skills may therefore determine the reading speed deficits observed across languages in the bilingual dyslexic children who were similarly slow at reading in French and Spanish, as well as words and pseudowords. This indicates the use of a constant speed to screen any type of letter string in any language in these children. As shown in Fig. 2, a limitation in the amount of visual elements that can be processed simultaneously, such as a VA span deficit, is likely to contribute to this constant reading speed. Conversely, the modulation of reading speed by the lexical status of the item in skilled readers fits well with the predictions of the Multi-Trace Memory model about typical reading (Ans, Carbonnel, & Valdois, 1998; hereafter MTM model): The MTM model was the first reading model to implement a visual attention component, called the visual attentional window (the VA span in humans). It postulates that reading relies on two procedures (one global and one analytic) that differ regarding the visual attention window size, therefore regarding the amount of VA span skills devoted to processing. In global mode, the window opens over the whole letter string facilitating fast access to orthographic and phonological lexical traces. In analytic mode, the window narrows down to focus attention serially on each orthographic sub-unit of the input, constraining the processing speed of the letter string. Although these two procedures are a priori not devoted to specific types of item, familiar items (known words) are mainly processed in global mode whereas non-familiar items (pseudowords) are processed in analytic mode, which may have been the case for the skilled reader children in the present study.

Consequently, dyslexic children with VA span deficits (like our bilingual dyslexic group) may exclusively use the analytic reading procedure (i.e., a small grain of processing), whereas skilled readers are flexible and adapt the size of their attentional window to the type of item to be read. This would result in relatively preserved pseudoword reading speed in Spanish, as indeed shown by the bilingual dyslexic children (only a marginal deficit on this measure was observed) who further demonstrated preserved Spanish pseudoword reading accuracy. Unlike French, the high regularity of Spanish grapheme-to-phoneme conversion rules may prompt the use of small grain size decoding skills since they are sufficient to yield very high accuracy. Accordingly, both dyslexic and control bilingual children reached similar very high accuracy levels for Spanish words and pseudowords reading, suggesting the use of a unique and efficient (sublexical) reading procedure for all items. Conversely, in the opaque French, they were more accurate to read words than pseudowords, suggesting the use of two strategies. Hence, since sublexical strategies may be overused in Spanish, the development of Spanish lexical representations may be slowed down (Share, 1995, 1999). This would be especially detrimental for the dyslexic children who showed deficits on the Spanish reading tasks requiring whole word orthographic knowledge (word reading speed and orthographic choice task). Along the same lines, Jimenez and Ramirez (2002) reported that, out of 89 dyslexic children, 48 (54%) Spanish dyslexic children were assigned to a surface dyslexia subgroup (i.e., lexical procedure deficit) whereas only 20 (22%) to a phonological dyslexia subgroup (i.e., sublexical procedure deficit).

5. Conclusion

In the present study, we highlighted cross-linguistic modulations of the contribution of phonemic awareness skills and VA span skills to reading speed and accuracy in French-Spanish bilingual children. Mirroring the findings of previous studies conducted between groups of monolingual individuals (Landerl et al., 2013; Landerl et al., 1997), reading accuracy deficits of bilingual dyslexic children were mainly visible in their opaque orthography whereas impairments on reading speed was significant in both their opaque and transparent orthographies. Importantly, we could rule out the potential influence of inter-individual differences on our cross-linguistic effects, since Spanish and French reading abilities were assessed within

[2] One could assume that learning to read in an opaque orthography enhances lexical reading strategies (i.e., processing items ''as a whole'') since it has been shown that learning to read in a transparent orthography enhances sub-lexical reading strategies in bilinguals (Seymour et al., 2003). Skilled reader children may have been able to take advantage of being taught to read in an opaque orthography to boost the acquisition of whole word orthographic knowledge whereas the reading difficulties of the dyslexic children may have prevented them to do so. Being taught to read in French may therefore have exacerbated the gap between skilled readers and dyslexic readers' performance on tasks tapping into whole word orthographic knowledge.

the same individuals. Our results suggest that the VA span may be a good candidate to account for reading variance and for variations between reading performance of good and poor readers, in both transparent and opaque orthographies, by playing a particular role in specific word knowledge acquisition. Future studies should investigate the link between VA span and rapid automatized naming skills since the latter have been proposed to contribute to reading speed in transparent orthographies (van den Boer, de Jong, & Haentjens-van Meeteren, 2013). Research on reading in bilingual individuals with other language/orthography pair is needed in order to pin down the impact of orthographic transparency on dyslexic symptoms in bilinguals, and better predict whether and how (e.g., through speed or accuracy measures) reading difficulties in one language will persist in the other.

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