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Research report

Dyslexia in a French–Spanish bilingual girl: Behavioural and neural modulations following a visual attention span intervention

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ABSTRACT

We report the case study of a French–Spanish bilingual dyslexic girl, MP, who exhibited a severe visual attention (VA) span deficit but preserved phonological skills. Behavioural investigation showed a severe reduction of reading speed for both single items (words and pseudo-words) and texts in the two languages. However, performance was more affected in French than in Spanish. MP was administered an intensive VA span intervention programme. Pre–post intervention comparison revealed a positive effect of intervention on her VA span abilities. The intervention further transferred to reading. It primarily resulted in faster identification of the regular and irregular words in French. The effect of intervention was rather modest in Spanish that only showed a tendency for faster word reading. Text reading improved in the two languages with a stronger effect in French but pseudo-word reading did not improve in either French or Spanish. The overall results suggest that VA span intervention may primarily enhance the fast global reading procedure, with stronger effects in French than in Spanish. MP underwent two fMRI sessions to explore her brain activations before and after VA span training. Prior to the intervention, fMRI assessment showed that the striate and extrastriate visual cortices alone were activated but none of the regions typically involved in VA span. Post-training fMRI revealed increased activation of the superior and inferior parietal cortices. Comparison of pre- and post-training activations revealed significant activation increase of the superior parietal lobes (BA 7) bilaterally. Thus, we show that a specific VA span intervention not only modulates reading performance but further results in increased brain activity within the superior parietal lobes known to housing VA span abilities. Furthermore, positive effects of VA span intervention on reading suggest that the ability to process multiple visual elements simultaneously is one cause of successful reading acquisition.

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1. Introduction

Although a phonological deficit is known to result in developmental dyslexia (Frith, 1997; Ramus et al., 2003; Snowling, 2001; Vellutino, Fletcher, Snowling, & Scanlon, 2004), some dyslexic children exhibit severe reading difficulties despite preserved phonological skills (Bouvier-Chaverot, Peiffer, N'Guyen Morel, & Valdois, 2012; Castles & Coltheart, 1996; Dubois, Lafaye de Micheaux, Noël, & Valdois, 2007; Hanley & Gard, 1995; Romani, Ward, & Olson, 1999; Valdois et al., 2003, 2011; Vidyasagar & Pammer, 2010). In particular, there are dyslexic children who have satisfactory phonological skills but show limitations in the number of visual elements they can process simultaneously (for alphanumeric elements: Hawelka & Wimmer, 2005; Valdois et al., 2011; Ziegler et al., 2011; for non alphanumeric elements: Lobier, Peyrin, et al., 2012; Lobier, Zoubrinetzky, & Valdois, 2012; Pammer, Lavis, Cooper, Hansen, & Cornelissen, 2005, 2004). These children exhibit a visual-attention (VA) span deficit (Bosse, Tainturier, & Valdois, 2007) that may explain their difficulties in reading (Valdois, Bosse, & Tainturier, 2004). The present research reports a case study of a French–Spanish bilingual dyslexic girl, MP, who exhibited a severe visual attention span deficit (VA span hereafter) but preserved oral language and phonological skills. Our purpose was first to explore the consequences of a VA span deficit on her reading performance as a function of the orthographic transparency of the language. Following the initial neuropsychological assessment, MP was administered an intensive VA span training. Our second purpose was to investigate whether such VA span training would result in reading performance improvement and whether training effect on performance would differ depending on language transparency. Finally, MP was administered before and after training fMRI assessments to explore whether and how intensive VA span remediation affected her brain activity. Overall, the current study provides new insights on the differential effects of a VA span disorder on reading performance according to language transparency. It further reports first evidence for brain activity modulation following a specific VA span remediation. The reported findings thus provide first behavioural and neurobiological evidence in support of a causal relationship between VA span disorder and developmental dyslexia.

1.1. *Dyslexia in French and Spanish speaking monolingual and bilingual individuals*

The study of developmental dyslexia has generally focussed on monolingual individuals and the study of bilingualism has tended to focus on reading learners who exhibited no specific reading disorder (Cline, 2000). Only a few cases of bilingual dyslexic individuals have been reported.

Cross-language studies on monolingual learners have shown differences in reading acquisition depending on language transparency (Landerl et al., 2013; Seymour, Aro, & Skine, 2003). In orthographically deep languages as French or English, the relationship between letters and phonemes can be extremely complex. In contrast, Spanish or Italian are considered as orthographically shallow languages because they have letter–sound relationships that are mostly unambiguous and very predictable. It follows that most Spanish words can be read accurately by applying one-to-one grapho-phonological correspondences (Davies, Cuetos, & Rodriguez-Ferrero, 2010). A number of cross-linguistic studies on monolingual children provided evidence indicating that children who learn to read orthographically deep languages consolidate reading skills at a later age than the children learning to read in languages with shallow orthographies (e.g., Thorstad, 1991; see Seymour et al., 2003 for a comparison of several European languages). Accordingly, near-to-ceiling accuracy performance in reading has been reported in Spanish speaking children after only one year of schooling while French readers still show a significant rate of reading errors after similar literacy exposure (Seymour et al., 2003). Differences in orthography transparencies are further expected to differently affect both the nature and degree of reading difficulties. It is well documented that in opaque orthographies dyslexic readers suffer from much more severe impairments in reading than the dyslexic children taught in more transparent orthographies (Bergmann & Wimmer, 2008; Landerl, Wimmer, & Frith, 1997). In particular, developmental dyslexia in deep languages typically results in both poor reading accuracy and slow reading speed while slowness in reading is the fundamental feature in transparent orthographies (for Spanish: Davies, Cuetos, & Glez-Seijas, 2007; Jiménez and Hernandez, 2000; Serrano & Defior, 2008; Suarez-Coalla & Cuetos, 2012). Despite differential transparency effects, accuracy-based and/or latency-based dissociations between word and pseudo-word reading have been described in developmental dyslexia in both opaque and transparent languages (Jiménez & Ramirez, 2002; Sprenger-Charolles, Siegel, Jiménez, & Ziegler, 2011). Some French dyslexic children show a selectively poor performance on pseudo-words but relatively preserved irregular word reading (Lallier, 2011). Other children show the reverse pattern characterized by selective impairment of irregular word reading (Valdois et al., 2003) while still others show poor performance on both words and pseudo-words (Valdois et al., 2011; see Sprenger-Charolles, Colé, Lacert, & Serniclaes, 2000, for regression-analyses-based subtyping). Similar dissociations between words and pseudo-words have been reported in Spanish dyslexic children (Jiménez, Rodriguez, & Ramirez, 2009). As word reading and pseudo-word reading rely on different reading procedures (Ans, Carbonnel, & Valdois, 1998; Coltheart, Rastle, Perry, Langdon, & Ziegler, 2001; but McClelland & Seidenberg, 1989), report of such dissociations in both languages suggests that each of the analytic (based on print-to-sound correspondences) and global (based on activation of specific word knowledge in long term memory) reading procedures can be selectively impaired in developmental dyslexia whatever the language transparency. However, the study of bilingual individuals is a far stronger case to assess orthographic transparency effects on reading performance. To our knowledge, no case of French–Spanish bilingual dyslexic child has previously been described. Similar low reading scores were reported in both languages in English–Portuguese bilinguals (Da Fontoura & Siegel, 1995) but some drastic dissociation may also exist. Indeed, the case study of an English–Japanese bilingual teenager reported by Wydell and Butterworth (1999) showed that the same individual can be a skilled reader in Japanese while showing severe difficulties in English. Lastly, bilingual individuals show some transfer from one language to the other and learning to read in a transparent language seems to affect processing in the more opaque one (in Arabic-English bilinguals: Abu-Rabia & Siegel, 2002; in English–Welsh bilinguals: Lallier, Carreiras, Tainturier, Savill, & Thierry, 2013). The analysis of reading and writing skills in a French–Spanish bilingual girl will provide the opportunity to assess how the reading disorder expresses itself in the transparent Spanish orthography as compared to the more opaque French orthography.

Well in line with the phonological theory of developmental dyslexia (Vellutino et al., 2004), cross-linguistic studies have shown evidence for a phonological awareness disorder in both opaque and transparent orthographies (English–Spanish–Chinese comparison: Goswami et al., 2011; French–English–Italian comparison: Paulesu et al., 2001; English–French–Spanish: Sprenger-Charolles et al., 2011; English–Japanese comparison: Wydell & Butterworth, 1999; English–Chinese: Chung & Ho, 2010). Such findings have led to a growing consensus that developmental dyslexia results in all languages from a failure to acquire phonological awareness. However, Bosse and Valdois (2009) have shown that the VA span component is also essential for the acquisition of reading skills and that a subset of French and English dyslexic children exhibits a VA span disorder (Bosse et al., 2007). Interestingly, this VA span disorder was found to dissociate from phonological problems in a non-trivial number of children, suggesting that it could independently affect reading performance in the two languages. However, this later study suffered limitations that prevented any straightforward conclusions on the effect of a VA span disorder in languages with different orthographic transparencies. The case study of a bilingual French–Spanish child offers the opportunity to assess whether a VA span disorder differently affects reading acquisition in a transparent (e.g., Spanish) versus more opaque (e.g., French) language.

1.2. VA span and differences in orthographic transparency

The VA Span is a notion theoretically motivated by the MultiTrace Memory model of reading (Ans et al., 1998; hereafter MTM model). The MTM model was the first reading model to implement a VA component, called the visual attentional window, as part of the reading system.[1] The visual attentional window is a critical component of the reading cognitive network as it delineates the amount of orthographic information that can be processed while reading. Actually, the visual attentional window – and its psychological counterpart, the VA span (Bosse et al., 2007) – defines the set of visual letters that are under the focus of attention. It is a multi-letter parallel processing device. The MTM model postulates that reading relies on two global (parallel) and analytic (serial) procedures that differ regarding the VA window size, and therefore, regarding VA Span skills (i.e., the quantity of VA devoted to processing). In global mode, the window spans over the whole input letter string whereas in analytic mode, it narrows down to focus attention on each orthographic subunit of the input in turn. Although these two procedures are *a priori* not devoted to reading specific item types, most familiar items (in particular previously learnt words) are processed in global mode whereas non-familiar items (most pseudo-words) are processed in analytic mode. Another key contribution of the MTM model is to suggest a critical role of VA span in reading acquisition (Valdois et al., 2004). Beginning readers have to attend successively to each word letter, but letter identification soon becomes automatic and gradually reading relies on larger and larger orthographic units (Laberge & Samuels, 1974). We claim that the processing and memorization of such larger units (multiple letter graphemes, syllables, morphemes or words) require a VA span large enough to simultaneously attend to all the letters of the corresponding units. As a consequence, a VA span reduction in developmental dyslexia is expected to primarily affect whole word letter string parallel processing. Such a reduction will have detrimental effects in regular (slow reading speed) and irregular word (poor accuracy and slow reading speed) reading, as reported in some cases of developmental dyslexia (Valdois et al. 2003). However, impaired multi-letter parallel processing may further affect the processing of multi-letter graphemes or syllables, then leading to reading problems on regular words and pseudo-words as well (Valdois et al., 2011; Zoubrinetzky , Bielle, & Valdois, submitted for publication). In other words, a VA span reduction is expected to affect the processing of multi-letter units –be they real words or long syllables or multi-letter graphemes, or contextual graphemes whose pronunciation depends on the surrounding context; the larger the unit the more severe the consequences of a VA span reduction. The consequences of a VA span disorder may thus differ from one language to the other as far as reading relies on orthographic units of different size in the different languages under concern. This should be the case for French and Spanish.

In French, there are one-to-one letter to sound correspondences like m = /m/ as in most alphabetical languages but there are a lot of multi-letter graphemes (Catach, 1995). Some graphemes correspond to two letters such as *ou* = /u/ in *pour* (/puR/, for) but some others may have three letters (*eau* = /o/, water) or even five, such as *aient* (/ɛ/) in *ils étaient* (/etɛ/, they were). This means that French graphemes' processing in reading typically requires several letters to be processed simultaneously. Furthermore, even the pronunciation of 1-letter graphemes typically requires surrounding letters to be taken into account (e.g., "a" *vs* "ai" or "au"; "s" pronounced /s/ in panse /pãs/ but /z/ in pause /poz/), as it is the case for many context dependent graphemes. For instance, the "an" bigram

[1] The CDP + model (Perry, Ziegler, & Zorzi, 2007) suggests that graphemic parsing (a component of the non lexical pathway) might be controlled by focused spatial attention but the attentional component was not implemented. Plaut (1999) implemented a refixation connectionist network that extended gradually from fixation rightward to larger and larger portions of input strings. This network might be assimilated to the VA span as involved in analytic processing. However, the VA window implemented in the MTM connectionist network remains unique as a key component of the reading system common to the global and analytic procedures.

will correspond to two graphemes "a" and "n" if followed by a vowel (like in the word ***an**alyse* /**an**aliz/, analyze) but to a single grapheme when followed by a consonant (like in ***an**tenne* (/ãtɛn/, antenna). Thus, to read *an* correctly, at least three letters have to be processed simultaneously, four for the "*ain*" string. With a large VA span, this is possible, but a small VA span necessarily leads to incorrect reading. Therefore, although 95% of French words can be read correctly using grapho-phonological correspondences (Gak, 1976), a child with a VA span deficiency will read many orthographically regular words and pseudo-words incorrectly. Finally, irregular words require their entire printed letter sequence to match word orthographic knowledge in long-term memory for being accurately named. These words require a VA span large enough to adapt to the word length in order to identify all the word constituent letters simultaneously.

In contrast, most Spanish words can be read by applying one-to-one grapho-phonological correspondences (Davies et al., 2010). Spanish only has three two-letter graphemes: *rr* (*perro* = /perro/, dog); *ch* (*pecho* = /petʃo/, chest); *ll* (*bello* = /bejo/, beautiful). Only a few letters (*c*, g, qu, gu) depend on context to be pronounced correctly and only two or three letters have to be simultaneously processed to solve any pronunciation ambiguity (*qu* + *e* or *i* (yields /ke/ or /ki/), *gu* + *e* or *i* (/ge/ or /gi/). Lastly, there are no irregular words in Spanish (note however that some borrowings have irregular pronunciations, e.g., "pub" pronounced /puv/ or /puf/). Accurate reading in Spanish might thus be achieved with a smaller VA span.

To summarize, 2 or 3 letters (and sometimes up to 5) have to be simultaneously processed for most French graphemes to be accurately identified whereas most Spanish graphemes are 1-letter long (and only 3 letters have to be simultaneously processed for the longest context sensitive graphemes). It follows that a VA span disorder that limits the number of letters simultaneously processed within strings should more strongly impair regular word and pseudo-word reading accuracy in French than in Spanish. A VA span disorder would further impact irregular word reading accuracy in French. Predictions may be different with respect to reading latency. Assuming that the high reading speed of proficient readers mainly reflects their capacity to process words as a whole whatever the language orthographic transparency (for French: Valdois et al., 2006; for Spanish: Suarez-Coalla & Cuetos, 2012), a VA span disorder should result in slower word reading in both French and Spanish.

1.3. *Brain activity modulations following remediation*

Only a few attempts have been made to explore the efficacy of remediation programmes through developmental dyslexia single case studies (Broom & Doctor, 1995; Brunsdon, Coltheart, & Nickels, 2005, 2006; Kipp & Mohr, 2008). In these studies, treatment programmes targeted specifically at a particular impairment. When irregular word reading (Brunsdon et al., 2005) or single letter processing (Brunsdon, Coltheart, & Nickels, 2006; Kipp & Mohr, 2008) was identified as the major functional difficulty of the child, a specific treatment was designed to primarily improve the processing of these particular items and in turn ameliorate reading performance more generally. In contrast, the large majority of group studies that explored the effect of remediation on reading performance in developmental dyslexia focused on phonology-based interventions. Training was expected to ameliorate phonological processing with a direct effect on reading ability, which was typically reported (Ehri et al., 2001; Gaab, Gabrielli, Deutsch, Tallal, & Temple, 2007; Torgesen, Alexander, Wagner, & Rashotte, 2001). Some studies examined how phonology-based remedial instruction modulated brain activations in developmental dyslexia. A consistent result is that the regions that were under-activated prior to remediation – typically left perisylvian regions as the inferior frontal gyrus, the inferior parietal lobe, the superior temporal gyrus or the left inferior temporo-occipital gyrus—became more active following remediation (Aylward et al., 2003; Eden et al., 2004; Shaywitz et al., 2004; Simos et al., 2002; Temple et al., 2003). Cross-language studies reported the same type of brain dysfunction, irrespective of language orthographic transparency (Paulesu et al., 2001; Silani et al., 2005; You et al., 2011). It is however noteworthy that previous neuroimaging studies assumed that developmental dyslexia is a cognitively homogeneous condition, i.e., all dyslexic children having the same type of underlying disorder, namely a phonological disorder. These studies largely ignored the varieties of developmental dyslexia (Hadzibeganovic et al. 2010 for a critical review) and the existence of dyslexic subtypes characterized by different cognitive disorders (Bosse et al., 2007; see however Lorusso, Facoetti, Paganoni, Pezzani, & Molteni, 2006). In particular, the existence of dyslexic children with a single VA span disorder was not taken into account.

Previous studies on normal-reading young adults (Peyrin, Lallier, & Valdois, 2008) and children (Peyrin, Démonet, N'guyen-Morel, Le Bas, & Valdois, 2011) helped identifying the neural underpinnings of the VA span. Participants showed increased activation of the superior parietal lobe bilaterally when asked to perform simultaneous multi-character processing under fMRI (for letters: Peyrin et al., 2008, 2011; for symbols: Lobier, Peyrin, et al., 2012). The dyslexic children with a VA span disorder have been reported to show under-activation of the superior parietal lobe bilaterally when they performed a VA span task (Peyrin et al., 2011, 2012; see Reilhac, Peyrin, Démonet, & Valdois, 2013 for similar findings from adult dyslexic individuals).

The interest in assessing the effect of a specific VA span remediation intervention in a bilingual participant is twofold. First, if as hypothesized above, a VA span disorder is expected to differentially impact reading performance in French and Spanish, then reading performance in French and Spanish should be differently impacted by a successful remediation of the VA span disorder. Pre–post-treatment comparison will thus provide good opportunity for better understanding the differential effects of VA span abilities in the two languages. Second, improved performance in report tasks and reading ability after specific VA span training should result in specific changes in brain activation. We hypothesize that after remediation, the superior parietal lobes would show increased activity during VA span processing.

2. Case report

MP was 7 years and 10 months old at the time of the first visit. She was 9 years 3 months old at the last visit, 10 months after the end of the remediation programme. MP is a French–Spanish bilingual. She was born in Mexico and speaks French and Spanish at home. She speaks both languages fluently. Her father is a bilingual French–Spanish speaker. Her mother is a native Spanish speaker who is relatively fluent in French. MP attended the Liceo Franco–Mexicano at Mexico City since she was two and a half years old. In this school, teaching is done in French by native French speakers educated in France, except for 3 h per week, in which reading and writing in Spanish is taught by a native Spanish-speaker. The French teachers reported that the reading method was mixed (global reading, syllabic reading and grapho-phonological conversion rules). In Spanish the teaching method is essentially based on grapho-phonological conversion rules. MP attended the Liceo Franco–Mexicano at the regular age until 2nd grade. School attendance was always regular. Because of her academic difficulties that occurred from the beginning of reading instruction, MP received some after-school help from native French-speaking teachers but she was never suspected of dyslexia and benefited no special therapy. When MP took part in this study, she was living in France for already five months and attended a public French school. When she arrived at the French school, she repeated the 2nd grade. The decision to make her repeat 2nd grade was taken at the Liceo Franco–Mexicano and is directly linked to her difficulties in the acquisition of written language.

MP is right-handed. She was born at term by caesarean and without any complications. She started walking when she was 12 months old. MP had no motor, neurological or psychiatric disorder. The parents reported that she had no problems in speech and oral language development neither in French nor Spanish. Audiometric and ophthalmologic evaluations revealed normal auditory and visual perception. There was no family history of learning disabilities or psychiatric illness.

MP's initial neuropsychological assessment is reported in the next section. Her intellectual capacities, executive functions and general attentional abilities were assessed in French during the initial clinical assessment. MP was further administered French and Spanish reading tests, together with tasks assessing her phonological and VA span abilities. Her performance on these tasks was compared to that of French–Spanish bilingual chronological age controls. Nine bilingual typical children were recruited at the Liceo Franco–Mexicano of Mexico City (mean RA = 7 years 11 months, SD = 13.2 months). All bilingual controls had an equivalent family environment as MP and the same contact with French and Spanish. In addition to the CA bilingual control group, MP's performance in phonological processing and VA span was further compared to that of two control groups of CA-matched and RA-matched monolingual French children. Comparison with these additional groups will allow assessing (a) sensitivity of the tasks (as shown by modulation of performance with age and reading level) and (b) whether MP's performance significantly differs from that of a younger group of children matched for RA; higher performance than RA controls will be taken as evidence of normal development of the function despite poor reading skills.

Following Crawford and Garthwaite (2002), comparison of MP's data with those of control samples was computed using a method based on the *t*-distribution (*t*-modified test). In the modified *t*-test, the individual person is treated as a sample of $N = 1$ and therefore does not contribute to the estimate of the within group variance. The use of modified *t*-test is recommended when the size of the normative sample is small (Crawford & Howell, 1998) as in the current study. Moreover, modified *t*-test is only minimally sensitive to departure from normal distribution (Crawford & Garthwaite, 2006), which was required here as a lot of measured abilities were largely within the competence of most non-dyslexic control children. Following Crawford, Garthwaite, and Porter (2010)'s recommendations, z-scores are further reported as an effect size index together with the interval estimates of the effect sizes for the difference between MP and the controls. Performance is thus expressed on a common metric whatever the task or language, which allows better identifying the relative strengths and weaknesses in MP's scores.

Table 1 – MP's performance in oral language tasks.

Verbal tasks	MP	Mean (SD) CA	z-score
Phonemic discrimination (/14)	13	13.47 (1.13)	−.42
Morpho-syntactic comprehension (/20)	14	16.47 (2.02)	−1.22
Verbal fluency			
Phoneme fluency	9	7.79 (3.18)	+.40
Semantic fluency	11	11.46 (3.87)	−.12

2.1. Initial neuropsychological assessment

Initial neuropsychological examination conducted in French included assessment of MP's intellectual efficiency and reading level. Administration of the Wechsler Intelligence Scale for Children (WISC IV) revealed that she had a full scale IQ of 92 with a similar average performance on verbal (ICV = 96) and performance (IRP = 94) subtests. Her score on the Raven Matrices (Raven, Court & Raven, 1998) revealed good reasoning abilities (raw score = 42; {75th–90th} percentile). MP's performance on the Alouette reading test – a standardized French reading text (Lefavrais, 1965) that required reading a 265 words text as quickly and as accurately as possible during 3 min – showed that she achieved a reading age of 6 years 7 months (15 months delay), corresponding to that of a very beginning reader with only 6 months of formal literacy instruction. Her performance on another standardized text reading task ("Petit monsieur" from the ODEDYS battery, Jacquier-Roux, Valdois, & Zorman, 2002) showed very slow reading (25 wpm) as compared to controls ($m = 107.2$ wpm, z-score = −2.62).

Clinical assessment further pointed to the absence of specific oral language disorder (Table 1). Her performance in phonemic discrimination, morpho-syntactic comprehension and verbal fluency on either semantic (requiring to produce as many animal names as possible within a minute) or phonemic criteria (produce as many words as possible beginning with /p/) was within the average of French children of similar chronological age.

To rule out any general attention deficit that could explain MP's difficulties in written language, we further evaluated her attentional abilities and executive functions (see Table 2). In

Table 2 – MP's performance in tasks of attention (NEPSY test) and executive functions (London Tower).

Tasks	MP	Standard score or percentile
Attention (NEPSY)		
Auditory attention	78	9/19
Visual attention	14	9/19
Statue	28	{26th–75th} percentile
Knock and Tap	29	{26th–75th} percentile
London Tower		
Success first trial	5	25th
Number of trials	26	25th
Mean planification time	3.6	>95th percentile

line with our clinical observations, the administration of the Conners questionnaire (Loney & Milich, 1985) did not reveal the presence of any behavioural deficit, hyperactivity, somatisation problems or anxiety. Her auditory and visual attentional capacities were assessed using the NEPSY Battery (Korkman, Kiri, & Kemp, 1988). MP's good performance in the auditory modality suggests good selective auditory attention skills. In the visual modality, she was able to cancel visual targets as accurately and as quickly as the controls, even when they were mixed with visually similar distractors. Her good performance on this later task suggested preserved selective VA, visual working memory and visual perception. MP further showed normal capacity to inhibit responses to auditory (statue test, NEPSY) and visual distractors (Knock & Tap test, NEPSY). We used the Tower of London Test (Lussier, Guerin, Dufresne, & Lassonde, 1998) to evaluate her executive functions and found efficient planning abilities. In sum, MP exhibited no attentional or executive functions deficit.

2.2. *Evaluation of reading abilities in French and Spanish*

2.2.1. *Method*

Regular word and pseudo-word reading performance was assessed in French and Spanish, using standardised tests in each language.

- We used the ODEDYS battery (Jacquier-Roux et al., 2002) to assess regular word and pseudo-word reading abilities in French. MP was asked to read aloud 40 regular words and 40 pseudo-words. The 40 pseudo-words were matched in length with the regular words (4–8 letters, 1–3 syllables long) and had no orthographic neighbour. Words and pseudo-words were presented in different lists. MP was informed of the nature of the items and asked to read them aloud as quickly and accurately as possible. The words and pseudo-words were written in lower case, Times 14, and presented in columns on a white sheet. Both accuracy and reading speed were collected for each list.
- MP was further administered the irregular word list of the ODEDYS battery in French. The list comprised 40 words matched on frequency, word length and grammatical class to the regular words. Because of the absence of letter-to-phonology inconsistencies in reading, no equivalent list was designed in Spanish.
- We used the PROLEC battery to evaluate MP's word reading accuracy and speed in Spanish (Cuetos, Rodríguez, & Ruano, 2000). There were 30 real words (one or two syllables long) and 30 pseudo-words that were derived from the words by changing one or two letters (e.g., the pseudo-word "tiella" was constructed from the word "tierra" prairie). The list of mixed words and pseudo-words was further administered. It was composed of 40 words (20 HF and 20 LF) and 20 pseudo-words (1–5 syllable long). In all lists, items were written in lower case, Times 14, and presented in columns on a white sheet.
- MP's text reading abilities were further assessed in the two languages. We used a text extracted from St. Exupéry's *The little prince* that had been used in a previous study to compare reading skills in French–Spanish monolingual and bilingual 1st and 2nd graders (Kandel and Valdois, 2006). The text in French was the original 1946 text and the text in Spanish was a professional translation (both texts have 104 words, see Appendix A). We measured reading speed and the number of errors. If the child made an error but corrected him/herself, it was not counted as an error.

2.2.2. *Results*

Table 3 reports scores on the different tasks for MP and for the bilingual control group. As Table 3 shows, MP's accuracy performance in French (regular and irregular) word and pseudo-word reading was in the lower range of bilingual CA controls. She read half as many irregular words as the controls but her lower performance did not reach significance. Her reading speed was significantly slowed relative to controls for all types of items. The number of words (regular and irregular) and pseudo-words accurately read per minute tended to be lower than for controls. We further computed the rate of regularisation errors on irregular words (e.g., "femme" read /fam/) and the rate of phonological errors (i.e., voiced–voiceless confusions) on regular words and pseudo-words in MP and CA bilingual controls. The rate of regularisation errors in MP (76.7%) was well within the normal range of the controls [$m = 75.39\%$ SD = 13.36; $t(7) = -.09$, $p = .465$]. She produced no voiced/voiceless confusion whereas 8.19% (SD = 5.52; range 0%–14%; median: 9.37%) such errors occurred on average in bilingual controls [$t(7) = -1.399$, $p = .102$]. Similar rates of contextual errors (i.e., c, g, s) were observed in MP and the controls: 38.46% *vs* 33.41% [SD = 18.89; $t(7) = .252$, $p = .404$]. Lastly, despite a higher rate of parsing errors (e.g., animé → an-imé instead of a-ni-mé), her performance did not differ significantly from that of the controls [MP = 17.95% *vs* 7.15% (SD = 8.66); $t(7) = 1.176$, $p = .139$; range: 0%–26% with 86% of the normal population falling below MP's score].

In Spanish, word and pseudo-word reading (PROLEC) was slow. Although she made only a few errors on words, MP's score on regular words was significantly poorer than for the controls. She read less regular words per minute than the controls but as many pseudo-words. It can be seen from the effect sizes that the deficit is severe for reading speed in the two languages. The revised standardized difference test (Crawford & Garthwaite, 2005) was used to compare MP's performance in French and Spanish. Results showed that her reading speed was slower for the pseudo-words in French than in Spanish [$t(8) = 5.878$, $p = .0004$] but equivalent for the

Table 3 – MP's reading performance at the initial assessment (T0) in French and Spanish as compared to chronological age (CA)-matched bilingual controls. Information is provided on MP's raw scores for the different tasks, the mean and standard deviation for controls the number of control children (*n*), the modified *t*-value and its probability (*p*), the point estimate of the effect size and its 95% confidence interval. Performance is reported for the regular, irregular words and pseudo-words of the ODEDYS battery in French; for the high frequency (HF) and low frequency (LF) words and pseudo-words of the PROLEC battery in Spanish.

	MP	CA bilingual controls			Significance tests		Estimated effect size	
	Scores	*n*	Mean	SD	*t*	*p*	Point	95% CI
Word reading								
French								
Regular words								
Score (/40)	22	9	32.13	7.47	−1.28	.117	−1.356	−2.259 to −.412
Time (sec)	148	9	59.62	20.23	4.14	.002	4.369	2.167 to 6.557
Wpm	8.92	9	36.76	17.76	−1.49	.087	−1.568	−2.546 to −.550
Pseudo-words								
Score (/40)	20	9	28.25	5.65	−1.38	.102	−1.460	−2.400 to −.481
Time (sec)	226	9	74.38	24.34	5.91	.0002	6.229	3.171 to 9.285
PWpm	5.31	9	25.38	10.49	−1.81	.053	−1.913	−3.023 to −.767
Irregular words								
Score (/40)	10	9	20.25	8.17	−1.19	.134	−1.255	−2.124 to −.345
Time (sec)	218	9	71.00	20.86	+6.68	.0001	7.047	3.607 to 10.489
IWpm	2.75	9	19.34	10.9	−1.44	.093	−1.522	−2.484 to −.521
Spanish								
Blocked lists								
Words								
Score (/30)	26	9	29.00	.93	−3.06	.008	−3.226	−4.895 to −1.534
Time (sec)	90	9	39.50	11.11	+4.32	.001	4.545	2.263 to 6.815
Wpm	17.33	9	47.37	14.69	−1.94	.044	−2.045	−3.207 to −.847
Pseudowords								
Score (/30)	24	9	28.00	2.27	−1.67	.071	−1.762	−2.813 to −.673
Time (sec)	96	9	57.12	16.63	−2.21	.029	2.338	1.022 to 3.621
PWpm	15	9	31.99	11.50	−1.40	.100	−1.477	−2.423 to −.492
Mixed lists								
HF words (/20)	17	9	19.43	.79	−2.92	.010	−3.076	−4.678 to −1.449
LF words (/20)	16	9	18.14	1.46	−1.37	.105	−1.438	−2.370 to −.467
Pseudo-words (/20)	14	9	17.14	3.02	−.99	.176	−1.040	−1.843 to −.197
Items per min	12.26	9	33.30	7.52	−2.65	.014	−2.798	−4.278 to −1.290
Text reading								
French								
Nb of errors	20	9	10.22	5.85	+1.58	.076	1.672	.616 to 2.688
Time (sec)	293	9	84.78	20.81	+9.49	.00001	10.006	5.172 to 14.853
Wpm	17.20	9	71.32	19.58	−2.62	.015	−2.764	−4.229 to −1.271
Spanish								
Nb of errors	14	9	5.44	3.38	+2.40	.022	2.533	1.137 to 3.898
Time (sec)	281	9	101.67	23.41	+7.26	.00004	7.660	3.932 to 11.392
Wpm	19.22	9	62.44	17.38	−2.35	.023	−2.487	−3.833 to −1.110

regular words in the two languages [$t(8) = .601$, $p = .564$]. No other observed difference was significant.

The reading difficulties highlighted through single word reading in French and Spanish extended to text reading. In both languages, texts were read more slowly and with more errors than for the controls. The number of words accurately read per minute was significantly lower in MP than in typical French–Spanish bilingual readers. The effect sizes are large in the two languages. Direct comparison between French and Spanish showed that text reading speed was significantly slower in French [$t(8) = 2.428$, $p = .041$].

2.2.3. Summary

In sum, MP shows severe reading difficulties in the context of good intellectual efficiency and in the absence of any specific language disorder, general attention or executive function disorder. She exhibits a developmental dyslexia in both French and Spanish mainly characterized by slow reading speed on all types of items. Her impairment more strongly affects reading speed performance in French than in Spanish for the pseudo-words and texts. The qualitative analysis of her reading errors provides no support for a phonological problem. The high proportion of regularisation errors in irregular word reading suggests preserved ability to parse the input word into phonemes and associate each phoneme with the corresponding grapheme. The absence of voiced/voiceless confusions suggests preserved phoneme discrimination abilities. The next section explores whether her reading disorder is associated with phonological or visual processing disorders.

Table 4 – MP's phonological and VA span skills at the initial assessment; Comparison with the CA bilingual control group for French and Spanish and with two monolingual CA and RA control groups for French. Information is provided for MP's raw scores for the different tasks, the mean and standard deviation for controls the number of control children (*n*), the modified t-value and its probability (*p*), the point estimate of the effect size and its 95% confidence interval.

Tasks	MP	CA Bilingual controls			Significance test		Estimated effect size		CA monolinguals	RA monolinguals
	Scores	*n*	Mean	SD	t	*p*	Point	95% CI	Mean (SD)	Mean (SD)
French										
Phonological assessment										
Forward digit span	4	9	5.22	.83	−1.394	.101	−1.470	−2.413 to −.487	4.6 (.57)^{ns}	
Backward digit span	3	9	3.44	.52	−.803	.223	−.846	−1.598 to −.058	3.2 (.92)^{ns}	
Phoneme deletion (/20)	19	9	14.44	5.17	.837	.214	.882	.084 to 1.643	14.4 (4.74)^{ns}	5.9 (4.41)**
Phoneme segmentation (15)	11	9	8.33	4.5	.563	.295	.593	−.135 to 1.291	8.27 (4.43)^{ns}	4.7 (4.41)*
Acronyms (/10)	8	9	8.56	1.33	.399	.350	−.421	−1.093 to .275	7.64 (2.16)^{ns}	5.9 (3.31)^{ns}
VA span assessment										
Global report (letters; /100)	44	8	77.5	10.47	−3.017	.009	−3.200	−4.965 to −1.411	74.5 (10.3)**	49.7 (8.87) ^{ns}
Partial report (letters; /50)	22	8	41.75	5.51	−3.579	.006	−3.584	−5.534 to −1.615	39.6 (7.21)*	30.5 (7.89) ^{ns}
Spanish										
Phonological assessment										
Phoneme deletion (/20)	19	9	17.55	4.30	.320	.379	.337	−.346 to 1.001		
Phoneme segmentation (28)	25	9	24.22	5.72	.129	.450	.136	−.524 to .789		
Acronyms (/10)	10	9	9.71	.76	.362	.363	.382	−.308 to 1.049		
VA span assessment										
Global report (digits; /100)	64	7	82.42	5.56	−3.099	.011	−3.313	−5.269 to −1.335		
Partial report (digits; /50)	31	7	38.57	7.32	−.967	.185	−1.03	−1.944 to −.073		

* = $p < .05$; ** = $p < .01$.

2.3. *Phonological and VA span processing in French and Spanish*

2.3.1. *Phonological assessment*

MP's phonological abilities were explored through phonemic fluency, phoneme awareness and verbal short-term memory tasks.

2.3.1.1. Method. In French, the phoneme awareness tasks (Phoneme deletion, phoneme segmentation and acronyms) were taken from Bosse and Valdois (2009). In addition to the CA bilingual control group, MP's performance was compared to that of two CA-matched (N = 40; mean CA = 92.70, SD = 2.93; mean RA = 94.76, SD = 3.48) and RA-matched (N = 40; mean CA = 79.11, SD = 1.65; mean RA = 80.4, SD = 2.59) monolingual control groups. We designed similar materials in Spanish and compared MP's performance to that of the bilingual CA matched controls

Verbal short-term memory was further assessed though the digit span report task (forward and backward) of the WISC IV but only in French. The phoneme awareness tasks are described below (Items are listed in Appendix B for the handmade tasks in Spanish).

- *Phoneme deletion*: MP had to delete the first sound of a word and produce the resulting pseudo-word (e.g., French: *frite* (French fries) /fRit/ → /Rit/; Spanish: *grapa* (staple) /grapa/ → /rapa/). The task comprised 20 trials in both French and Spanish.
- *Phoneme segmentation*: MP had to successively sound out each phoneme of the word [e.g., French: *cadeau* (gift) /k/–/a/–/d/–/o/; Spanish: *gato* (cat)/g/–/a/–/t/–/o/]. A set of 15 words was presented auditorily in French (28 in Spanish).
- *Acronyms*: Two words were presented auditorily with a 1 sec interval and MP had to extract the first phoneme of each and blend them together to produce a new syllable (e.g., French: *chien* /ʃjɛ̂/ "dog" then *accroupi* /aKRupi/ "squat) → /ʃa/; Spanish: *color* (colour) then *hechizo* → /ke/). In French, there were 10 word pairs extracted from the « BELEC » battery (Mousty, Leybaert, Alegria, Content, & Morais, 1994). Ten pairs were also presented in Spanish.

2.3.1.2. Results. MP's scores and CA bilingual controls' on the phoneme awareness and verbal short-term memory tasks are presented on Table 4. MP showed good phoneme awareness skills and good verbal short-term memory in French. Her performance was well within the normal range of CA-matched bilingual children. It was further similar to that of CA French monolinguals, showing that the absence of disorder in the comparison with the bilingual control group was not just due to poorer performance of bilingual children. Furthermore, MP's phonological performance outperformed that of RA-matched French monolingual controls. This finding suggests first that the phonological tasks were sensitive enough to point difficulties if any; second, that MP developed normal phonological processing skills in French despite her poor reading abilities. MP further exhibited good phonemic fluency skills in French (see Table 1). In Spanish as in French, phoneme awareness tasks were performed at the level of bilingual controls. The investigation conducted in Spanish thus confirms preserved phoneme awareness skills in MP. The effect sizes are fairly modest (and mainly positive) in both French and Spanish.

2.3.2. *VA span assessment in French and Spanish*

2.3.2.1. Method. We administered MP two tasks of global and partial report that were designed to estimate the number of distinct elements that could be extracted in parallel from a brief visual display. Letters were used as stimuli in French, digits in Spanish. Letter-report tasks have been widely used to evaluate VA span capacities in previous studies (see Bosse et al., 2007; Bosse & Valdois, 2009; Dubois et al., 2007; Lobier, Zoubrinetzky, et al., 2012; Prado, Dubois, & Valdois, 2007; Valdois et al., 2003). The rational for using digits in Spanish and letters in French is twofold. First, our purpose was to avoid repetition of the same tasks using identical material during the same session once in French, once in Spanish; Second, previous findings showed that performance was impaired in dyslexic children with a VA span disorder either using letters or digits (Valdois, Lassus-Sangosse, & Lobier, 2012; Ziegler, Pech-Georgel, Dufau, & Grainger, 2010) and that the two tasks highly correlated ($r = .79$) in French children (Valdois et al., 2012).

The letter report tasks were administered first, asking MP to report letter names in French. Digits were used in Spanish, so that MP was not administered exactly the same tasks twice. A control single letter identification threshold task was further administered to control for single letter processing rate.

- *Global and Partial Report Tasks*: The VA Span of participants was estimated using global and partial report tasks. In these tasks, strings of five letters/digits were displayed for 200 msec at the centre of the computer screen. The strings built up from 10 consonants (BPTFLMDSRH) or 10 digits (from 0 to 9) contained no repeated item. Letter strings never matched the skeleton of a real word (e.g., R H S D M). Letters/digits were presented in upper case (Geneva) in black on a white background; each letter/digit subtended a visual angle of .7°. The distance between adjacent items was of .57 cm in order to minimize crowding. The whole line subtended an angle of approximately 5.4°. In both the global and partial report conditions, the task began with 10 training trials, for which MP received feedback. She did not receive any feedback on the experimental trials.

At the beginning of each trial, a central fixation point was presented for 1000 msec followed by a blank screen for 50 msec. Then, the letter/digit string was presented at the centre of the display for 200 msec. In the Global report condition, 20 experimental trials were displayed. Each letter/digit was used 10 times and appeared twice in each position. MP had to report verbally (identification not location) all the letters/digits she could, immediately after they disappeared. In the partial report condition, a cue –a vertical bar– was presented for 50 msec, 1.1° below the target letter/digit, at the offset of the string. The cue indicated the position of the letter/digit to be reported. There were 50 successive trials. Each item occurred 25 times and appeared 5 times in each position. Each was used as target once in each position, so that 10 target letters/digits could be reported in each position at the end of the task. In global report, we measured the number of items accurately reported, irrespective of location, across the 20 experimental trials (maximum score = 100). In partial report, the number of cued items accurately identified across the 50 trials (max = 50) was recorded.

- *Letter identification threshold*: To control for the processing rate of single letters, each of the 10 letters used in report tasks was randomly presented (5 times each) at the centre of the screen at 5 different display durations (33, 50, 67, 84 or 101 msec). The letters had the same physical features as in the report tasks. Each of the 50 experimental trials began with a central fixation point for 1000 msec followed by a letter, then a mask (a series of ***). The mask was displayed for 150 msec at the offset of the letter. The experimental trials were preceded by 10 training trials using other letters (2 at each duration). The task consisted of naming the letter immediately after its presentation. The letter identification threshold was estimated as the shortest display duration leading to at least 80% accurate naming. This task was only administered in French.

MP's performance on the VA span tasks was compared to that of bilingual CA matched and monolingual French CA- and RA-matched control children. We used the same monolingual control groups as for the phonological processing assessment.

2.3.2.2. Results. MP accurately identified 80% isolated letters when presented for only 50 msec. On average, 2nd grade French monolingual controls identified 66% letters at this short presentation time. Further, MP's single letter identification skills were within the normal range of bilingual CA controls (mean = 77.14, SD = 23.60; $t(8) = .115$; $p = .45$) and well above RA French monolinguals' performance (mean = 41.6, SD = 17.28; $t(39) = 2.20$, $p = .017$). Younger reading age controls only reached 80% accuracy on average when single letters were displayed for 100 msec on the screen.

Table 4 reports MP's and CA-matched bilingual controls' performance for (French) letters and (Spanish) digits in global and partial report. In letter global report (French), MP reported 44 letters out of 100, a score well below the average of bilingual CA controls. Her score was also abnormally low in letter partial report. Comparison with the French monolingual groups showed that MP performed lower than CA matched controls but at the level of RA matched monolingual French children in both global and partial report. In Spanish digit global report, MP performed significantly lower than bilingual controls in global report; her low performance in partial report did not reach significance (estimated 18% control scores falling below MP's scores). The effect sizes are large for global report in both French and Spanish but only moderate for partial report in Spanish. Direct comparison showed a similarly poor performance in global report for both French and Spanish ($t(6) = .157$, $p = .88$) but better performance in partial report for Spanish ($t(6) = 3.056$, $p = .02$).

Fig. 1 shows the response patterns of MP and CA-matched bilingual controls for (French) letters and (Spanish) digits in global and partial report as a function of letter position within strings. Very similar curve shapes characterize MP's response patterns in French and Spanish. Performance in letter global report for French was mainly characterized by a significant linear function in MP [$F(1,3) = 30.26$, $p = .012$] and the controls [$F(1,3) = 89.31$, $p = .003$] that accounted for 91% and 97% of the variance respectively. Interestingly, the slope of the function was steeper for MP [$t(7) = -2.488$, $p = .021$] suggesting a sharper drop of performance across positions. For digits in Spanish, there was a significant linear effect [$F(1,3) = 11.81$, $p = .041$] that accounted for 80% of variance in MP. The effect

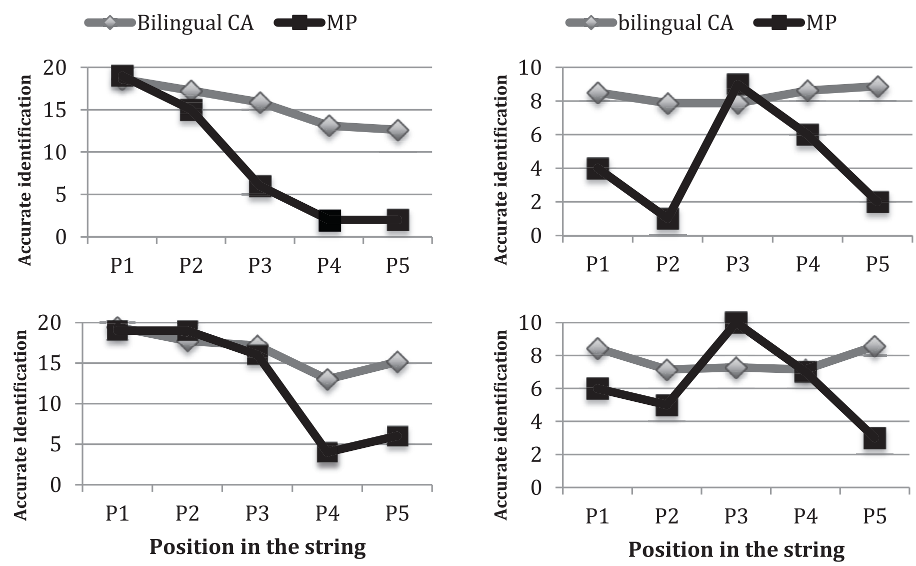

Fig. 1 – MP's accurate identification of items according to their position in the string in global (left) and partial report (right) for letters in French (top) and digits in Spanish (bottom), comparison with CA bilingual controls.

was close to significance in the controls [$F(1,3) = 7.68$, $p = .07$] and explained 82% of the variance. As previously for letters, the slope of the function was steeper in MP than the controls [$t(6) = -4.025$, $p = .003$]. In line with her response pattern curve shape analysis, variability of performance across positions was found higher in MP than the controls for both French [MP = 7.791 *vs* CA = 3.955 (SD = 1.51), $t(8) = 2.395$, $p = .024$] and Spanish [MP = 7.259 *vs* CA = 2.832 (SD = .89), $t(7) = 4.690$, $p = .001$]. Overall, her performance showed a stronger left bias than the controls and problems for identifying the rightmost letters/digits within strings (all $ps < .05$). In partial report, MP's response profiles are very atypical in the two languages. As previously for global report, MP showed higher variability of performance across positions than the controls in both French [MP = 3.21 *vs* CA = 1.146 (SD = .685); $t(8) = 2.841$, $p = .013$] and Spanish [MP = 2.588 *vs* CA = 1.3 (SD = .478); $t(7) = 2.521$, $p = .023$]. Thus, although MP identified on average as many digits as the controls in Spanish partial report, the particular shape of her identification function and higher variability of performance across positions suggests an atypical distribution of attention while performing the task.

2.3.2.3. Summary. Investigation of the cognitive abilities known to affect reading acquisition revealed preserved phonological skills in MP. She showed preserved phoneme awareness skills in both French and Spanish. Her phoneme awareness developed at the expected level for her age and well above that of younger children of the same reading level. In the same way, MP's verbal short-term memory skills were well within the normal range of CA matched controls. Assessment of her visual processing skills revealed very good single letter identification skills, well above those of RA matched controls. She however showed poor performance in global and partial report tasks either using letter strings in French or digit strings in Spanish. Poor performance on the report tasks assessing simultaneous processing skills in vision but good single letter identification suggests that MP suffers from a reduced VA span regardless of the item category (letter or digit) or language (French or Spanish). For letters in French, her performance was in the low average of RA matched children but did not differ significantly from performance of the younger children group. However, similar results may have different origins. In particular, the RA group's VA span abilities may primarily reflect their slow identification of individual letters, a limitation that cannot account for MP's result on VA span tasks. Her slightly better performance in digits partial report may have resulted from the limited number of possible digits (10 digits against 26 letters) and lesser visual confusability between digits than letters.

A remediation programme aimed at improving her VA span abilities was administered to MP. Behavioural and neuroimaging data from pre–post training assessment are reported in the next section.

3. Behavioural and neural effects of VA span training

3.1. Method

3.1.1. The training phase

MP was administered a VA span training programme[2] during two periods of 3 consecutive weeks with 2 weeks of therapy interruption (which corresponded to school breaks) between

[2] The VA span intervention programme COREVA (Valdois, Bosse, & Peyrin, in press) is available for clinicians together with EVADYS, the diagnostic tool for assessment of VA span abilities (Valdois, Guinet & Embs, in press). They are distributed by ORTHO-Edition (Isbergues: France).

them. She received VA span training exercises on a daily basis for 6 consecutive days with a 1-day interruption per week. The exercises were administered in a pre-defined order so that the progression was from non-verbal material (drawings, shapes, symbols) to verbal material (letters) and from the processing of single visual elements to multiple-element (from 1 to 5) strings.

The exercises consisted of visual search and discrimination tasks, visual matching and visual parsing tasks. Previous evidence suggests that these tasks require multi-element simultaneous processing (thus relying on VA span abilities). Visual search tasks (and the discrimination task variant version) were administered because visual search performance was found to relate with VA span abilities (Lallier, Donnadieu, & Valdois, 2013). Visual matching was found to activate the brain regions (superior parietal lobe) that house VA span and a problem on these tasks was found in children with a VA span disorder (Reilhac et al., 2013). Other tasks required grapheme or short word parsing. Indeed, we found that dyslexic children with a VA span disorder produced a higher rate of parsing errors than dyslexic children with preserved VA span abilities (Zoubrinetzky et al., submitted for publication), well in line with our theoretical hypothesis that multi-letter grapheme analysis relies on VA span large enough to hold the whole unit letter string. We thus inferred that these tasks were good candidates for training VA span abilities.

In the visual search tasks, a target (made of single or multiple elements) was presented at the top of the sheet and MP was asked to retrieve its different tokens among visually similar distracters. She could also be engaged in discrimination tasks that required crossing the items that differed from a repeated target. The distracters and targets were mixed. Their visual similarity was typically high. Items were either aligned or randomly located on the sheet; their number could vary as well as their proximity so that task difficulty progressively increased. Visual matching required deciding as fast as possible whether two strings of letters, drawings or symbols were identical or not. The child had to relate the identical strings. Visual parsing tasks required retrieving target strings that were embedded among items of the same category (e.g., retrieve all the "est" triplets in "casfinestcaletradeston"). Targets were frequent bigrams or trigrams, some of which corresponded to French graphemes or short words. For all the exercises, MP was asked to respond as accurately and as quickly as possible. Emphasis was made on speed of processing to induce parallel processing. The instructions were always the same for the different exercises within a given category (search, discrimination, matching, parsing…). MP was asked to search for (discriminate, match, parse) targets that were visually presented. Even verbal targets (letters, graphemes, syllables or short words) were never named, so that grapheme–phoneme correspondences were not simultaneously trained. The exercises were organized in six workbooks, one a week. MP had to do around 15 exercises daily during the afternoon. Each training session lasted 15 min. The training was done under the supervision of MP's mother. Her mother followed an initial training session during which she was given the examiner's book that provided information on the instructions, how to conduct the tasks, and how to correct the child at the end of each exercise. Once a week, a research assistant checked that the exercises of the previous week had been done. She provided a brief summary of the exercises to be done the next week and answered questions if any.

3.1.2. *Assessment*

The effect of training was assessed at the behavioural and at the neurobiological levels. Apart from the initial assessment (T0) previously reported, MP was administered a pre-training assessment at T1, followed by a post-training assessment at T2 and a long-term assessment at T3. The pre-training neuropsychological assessment was performed in February 2008 (T1), followed by a post-training assessment in April 2008 (T2). A fourth visit occurred 10 months later in March 2009 (T3) for long-term evaluation of the training effects. Neuropsychological assessments were carried out at T0, T1, T2 and T3. Remediation exercises were administered between T1 and T2. Neurobiological investigation under fMRI was carried out at T1 and again at T2 to evaluate whether training resulted in neural activity modulations.

3.2. Results

3.2.1. *Remediation effects on cognitive abilities*

3.2.1.1. Method. VA span abilities were assessed before (T0) and after (T2) training in both French and Spanish. They were again measured at T3, but only the letter report tasks in French were used. We expected performance in VA span to improve as an effect of training and to at least remain at a comparable level at T3 as compared to T2.

Reading performance was assessed pre- and post-training in both French and Spanish, since improvement in reading was in particular expected following remediation. An overview of the different tasks that were administered at each assessment session is provided in Appendix C.

The Alouette reading Test (Lefavrais, 1965) was repeated at T0, T1, T2 and T3. We expected performance to improve between T1 and T2. The same tests of single word and pseudoword reading as described in the previous section for T0 assessment were again administered in French (ODEDYS Battery) and in Spanish (PROLEC battery) at T1 and T2. The use of identical tests at T0 and T1 provides a baseline for comparison with T2 performance. However, repeating the same reading tasks with the same items three times can induce learning effects. We therefore designed new lists of items to be used at T1, T2 and T3 (computer-based reading assessment). The three different lists of each item type (regular words, irregular words and pseudo-words) were strictly matched (for frequency and length for words; for length and syllabic structure for PWs). The items of each list (e.g., regular words in List 1, 2 and 3) were further matched on their initial phoneme, in order to compare latency times at T1, T2 and T3. The pseudo-words were constructed from the regular words by substituting some word letters while keeping the graphemic and syllabic structure similar (e.g., festin → fustan; confetti → canfelli). They had no word neighbours. Words (25 regular, 25 irregular) and pseudo-words ($N = 25$) were displayed at the centre of the computer screen (maximum letter-string length = 5° at a distance of 57 cm) using the DMDX software (Forster & Forster, 2003). The lists were displayed by

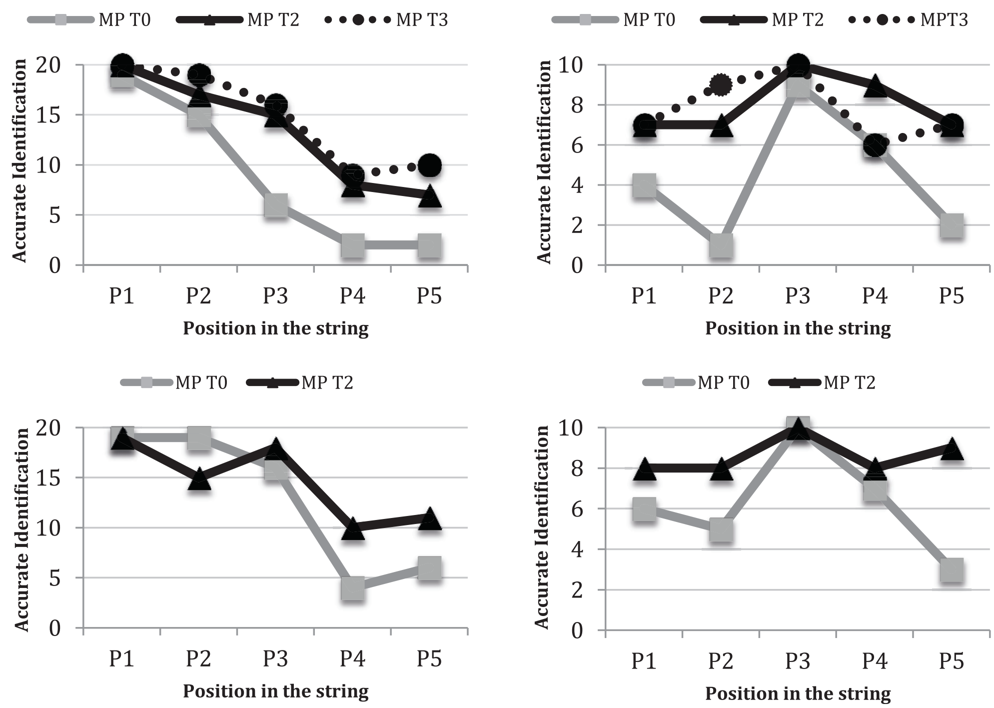

Fig. 2 – Evolution of MP's performance in global (left) and partial report (right) for letters in French (top) and digits in Spanish (bottom). T0 = initial assessment, T2 = post-intervention, T3 = long-term follow-up.

blocks, beginning with the pseudo-words, then the irregular words and last the regular words. Children were asked to orally pronounce each item as quickly and as accurately as possible. The items disappeared at the onset of oral production. Latency times were recorded through a vocal key. The examiner wrote the child responses and then started the next trial. Performance improvement was expected between T1 and T2, with potential sustained performance at T3.

Lastly, her text reading performance was assessed at T0, T1 and T2 in both French and Spanish using the "Little Prince" text.

The phoneme awareness tasks of deletion, segmentation and acronyms and the digit span task of verbal short-term memory first administered at T0 were again administered at T2. Results on these later tasks are not further discussed below as ceiling effects were observed at both T0 and T2.

3.2.2. *Remediation effect on the VA span*

MP's VA span performance before and after remediation (T0–T2) is provided on Fig. 2 for the global and partial letter report tasks in both French (letters) and Spanish (digits). Performance at long-term follow-up (T3) is further reported for French.

Results show that MP's performance for letters in French strongly improved between T0 and T2 (44 *vs* 67 in global report, z-scores = −3.199 *vs* −1.003; 22 *vs* 40 in partial report, z-score = −3.584 *vs* −.318). Whereas MP's performance in global report significantly differed from CA bilingual children's performance at T0, her performance was brought into the normal range after remediation (T2) in both global [$t(7) = -.946$, $p = .188$] and partial [$t(7) = -.299$, $p = .387$] report. Long-term follow-up in French showed that MP's performance (Global report = 74, z-score = .334; Partial report = 39, z-score = .499) remained at the level of the controls 10 months after the end of the VA span intervention. In line with the French data, her performance for (Spanish) digits strongly increased between T0 and T2 in both global (64 *vs* 73; z-score = −4.938 *vs* −2.716) and partial report (31 *vs* 43; z-scores = −1.049 *vs* .462). Her global report performance was found within the normal range of bilingual controls [$t(6) = -1.585$; $p = .082$] after the intervention, as was her performance in partial report [$t(6) = .566$, $p = .296$]. Fig. 2 shows that MP's response pattern in Global report was characterized by less steep slopes after than before the intervention in both French and Spanish. The slope of the linear function no longer differed in MP and the controls at T2 for both French [$t(7) = -1.523$, $p = .086$] and Spanish [$t(6) = -1.11$, $p = .153$]. As expected, variability of performance across positions no longer differed in MP and the controls in both Global [French: $t(8) = .939$, $p = .189$; Spanish: $t(7)1.276$, $p = .121$] and Partial report [French: $t(8) = .369$, $p = .362$; Spanish: $t(7) = -795$, $p = .229$], thus suggesting that her attention more smoothly spread over the whole string. The overall findings suggest a positive effect of remediation on MP's VA span abilities. We then explored whether improvement in VA span modulated reading performance in French and/or Spanish.

3.2.3. *Remediation effect on reading*

3.2.3.1. Reading age improvement. In French, MP's reading age as assessed through the Alouette reading test remained unchanged during the two months interval – between T0 and T1 (RA = 6:7 at both T0 and T1) – that preceded remediation. Her reading age improved after training with a 4 months gain during the 2 months interval between T1 and T2 (RA = 6:11 at

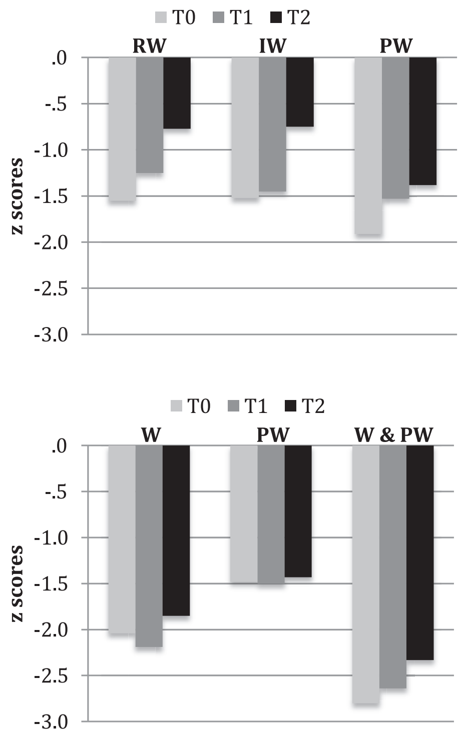

Fig. 3 – Number of items accurately read per minute (z-scores) at the initial assessment (T0), pre- (T1) and post- (T2) intervention in French (top; RW = regular words; IW = irregular words and PW = pseudo-words) and Spanish (down; W = words, W&PW = mixed lists).

T2). The advantage due to remediation remained 10 months later (RA = 7:2 at T3).

3.2.3.2. Single word and pseudo-word reading in French and in Spanish. In French, MP was administered the same ODEDYS reading lists of regular words, irregular words and pseudo-words three times, at the initial assessment (T0), pre-(T1) and post-(T2) intervention. The PROLEC battery was used to assess her reading performance on words and pseudo-words in Spanish. Her performance was expected to improve between T1 and T2, if reflecting a positive effect of the intervention on reading performance. Computerized reading tasks were further administered in French using different but matched lists of regular words, irregular words and pseudo-words at T1, T2 and T3. As for the ODEDYS test, we expected reading performance to improve between T1 and T2. Significant improvement on both the ODEDYS and the computerized tasks would suggest a specific effect of the intervention while minimizing any interpretation of better performance on the ODEDYS tasks at T2 as compared to T1 as reflecting a test–retest effect.

MP's scores (in wpm) were transformed to z-scores by reference to the CA bilingual control group. Fig. 3 illustrates how her reading performance evolved in French and Spanish between T0, T1 and T2.

As shown on Fig. 3, MP's word reading performance in French (ODEDYS test) only slightly improved between T0 and T1. Stronger improvement was observed between T1 and T2 on both the regular and the irregular words, thus suggesting positive effects of the remediation on single word reading in French. In contrast, her performance only slightly improved for words in Spanish (PROLEC) and for pseudo-words in the two languages.

Direct comparison of reading speed performance in MP and the controls for French showed that her reading speed remained abnormally low at T1 as compared to bilingual controls: 139 sec for the regular words [$t(8) = 3.723$; $p = .00293$], 187 sec for the irregular words [$t(8) = 5.276$; $p = .0004$] and 155 sec for the pseudo-words [$t(8) = 3.142$; $p = .007$]. The same lists were read significantly faster following the intervention. Reading speed no longer differed significantly from that of bilingual controls for the regular words [85 sec, $t(8) = 1.190$; $p = .134$] and only tended to be lower for the irregular words [107 sec, $t(8) = 1.637$; $p = .07$] and pseudo-words [122 sec, $t(8) = 1.856$; $p = .0503$]. In Spanish, MP's reading performance remained significantly lower than for the controls at both T1 and T2 for words and pseudo-words (accuracy and speed). However, the number of Spanish words accurately read per minute just reached the level of controls' performance at T2 [$t(8) = -1.753$, $p = .059$], suggesting some improvement of MP's word reading performance following remediation. The overall results suggest a more specific effect on word than pseudo-word processing in the two languages and a larger impact of intervention in French than in Spanish.

Fig. 4 illustrates MP's performance on the computerized reading task when using different lists of each category of items (regular words, irregular words and pseudo-words) at T1, T2 and T3. Only reading accuracy is reported as MP's reading speed data were lost due to a technical problem with the vocal key.

MP accurately read no more than 25 per cent irregular words and pseudo-words at T1. Her performance tended to improve between T1 and T2 on all types of items but improvement was only significant for the regular words [$\chi^2(1) = 3.95$, $p = .047$] and close to significance for the pseudo-words [$\chi^2(1) = 3.57$; $p = .059$]. No significant improvement was found between T2 and T3 (all $ps < .05$), but reading accuracy

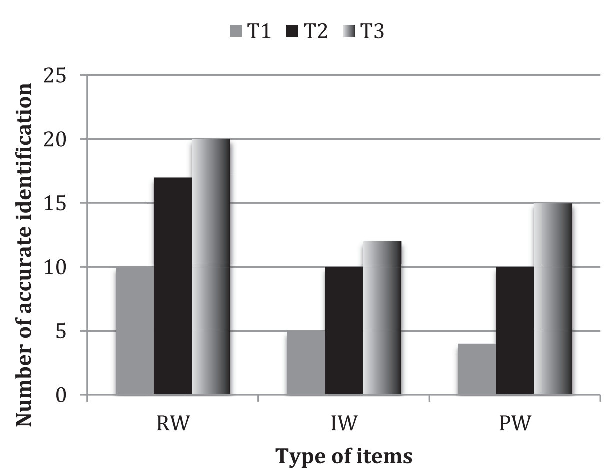

Fig. 4 – Number of regular words (RW), irregular words (IW) and pseudo-words (PW) accurately read in French (computerized lists) before (T1) and after (T2) the intervention and 10 months later (T3).

significantly improved between T1 and T3 whatever the type of items [regular words: $\chi^2(1) = 8.33$, $p = .004$; irregular words: $\chi^2(1) = 4.37$, $p = .037$; pseudo-words: $\chi^2(1) = 10.3$, $p = .001$].

3.2.3.3. Text reading in French and Spanish. Lastly, MP's performance in text reading (The little prince) was compared for T0, T1 and T2 in both French and Spanish (see Fig. 5). Her reading speed (in wpm) slightly improved from T0 to T1 in both French and Spanish. However, her performance remained significantly lower than expected at T1 in the two languages [$t(8) = -2.179$, $p = .03$ for French and $t(8) = -1.980$, $p = .042$ for Spanish]. Following the intervention, her performance no longer differed from that of CA bilingual readers for either French [MP's RT = 46.62; $t(8) = -1.197$, $p = .132$] or Spanish [mean RT = 33.81; $t(8) = -1.563$, $p = .078$] with a larger effect in French. Results again suggest a positive effect of VA span training on MP's reading performance with a larger impact in French.

In conclusion, behavioural data suggests that VA span improved following remediation, as illustrated by better performance at T2 than T1 on the report tasks in both French and Spanish. Reading performance on single words further improved after intervention but mainly in French and improvement remained 10 months later. MP read short texts more accurately and faster following the intervention in both French and Spanish, but here again the effect of treatment seems stronger for French than for Spanish. A T1–T2 increase in reading speed was also found when different lists of items were used in French, thus suggesting that improvement on the repeated tasks was not just due to familiarisation with the items to be read. The absence of significant improvement between T2 and T3 on the different lists also speaks against such an interpretation. It is further worth noting that similar reading performance improvement would have been expected in both French and Spanish if just reflecting a test–retest effect, which was not found.

However, performance improvement cannot be straightforwardly interpreted as resulting from the specific VA span intervention in the absence of data showing that similar improvements would not have occurred following a placebo programme. We thus collected neuroimaging data before and after remediation, reasoning that evidence for specific brain activation modulations following intervention would provide converging evidence in support of a specific remediation effect. The following section presents the neurological evaluation of VA span training effects.

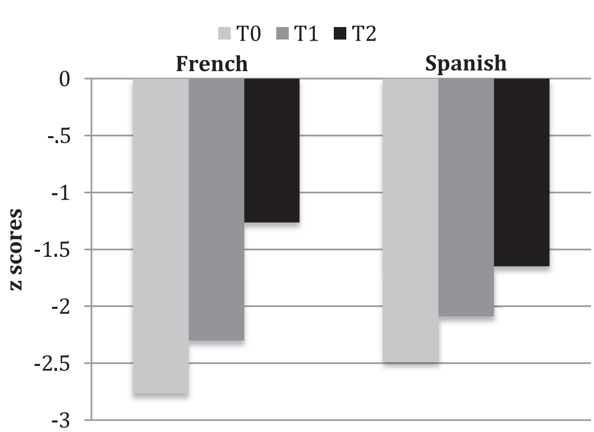

Fig. 5 – Effects of intervention on "The little prince" text reading speed (in z-scores) in French and Spanish. T0 = initial assessment, T1 = pre-intervention; T2 = post-intervention.

4. Examining MP's cerebral activation patterns before and after VA span training

We carried out two fMRI sessions before (T1) and after (T2) the remediation programme. The first fMRI assessment (pre-training fMRI hereafter) investigated whether MP's severe VA span disorder was associated with underactivation of the superior parietal lobes as previously demonstrated in both group (Peyrin et al., 2011; Reilhac et al., 2013) and case studies (Peyrin et al., 2012) carried out on dyslexic individuals with a single VA span disorder. The second fMRI session assessment (post-training fMRI hereafter) was conducted after the end of the VA span training period to explore potential brain activity modulations, more specifically in the parietal regions, following training. In both fMRI sessions, MP was administered a flanked letter categorisation task (taken from Pernet, Valdois, Celsis, & Démonet, 2006). This task has proven useful for the selective identification of the neural network of the VA span (Peyrin et al., 2011). Previous neuroimaging studies suggest that parietal regions are involved in VA span in skilled readers and that a failure of the superior parietal cortex to function properly characterises a subtype of dyslexic individuals with a VA span impairment (Lobier, Peyrin, et al., 2012; Peyrin et al., 2011, 2012; Reilhac et al., 2013). We thus expected that a parietal activation disorder, mainly affecting the superior parietal lobes, may characterize MP's brain activity before training. MP's brain activity pattern collected during pre-training fMRI was compared to the cerebral activations of chronological age controls. The post-training fMRI experiment was conducted to assess the effect of VA span training on MP's cerebral activity. We expected an increase in parietal activity when comparing fMRI post- and pre-training activations during the flanked letter categorisation task.

4.1. *Method*

4.1.1. *Participants*

MP and twelve chronological age matched controls (6 boys; mean chronological age = 9 years 3 ± 18 months) participated in this fMRI study. All control participants were native French speakers living in the Grenoble urban area. They had normal or corrected-to-normal visual acuity, a normal hearing level and no history of neurological or psychiatric disorders. They attended school regularly and were free from neurological or psychiatric illness, or any medical treatment. None of the controls reported any learning impairment for reading or spelling. All participants gave their informed written consent for participating in the study that was approved by the local ethic committee.

4.1.2. *Stimuli*

The stimuli used in the categorisation task were twelve uppercase Latin letters (A, E, F, G, H, M, N, P, Q, W, Y, Z) and four drawings of geometrical figures (rectangle, trapezium, pentagon, parallelogram) sized approximately .8° of visual angle. The stimuli were displayed by pairs, made up either of two letters (matched pair) or of a letter and a geometrical figure (unmatched pair). For each pair, one stimulus was displayed centrally and the other peripherally at 3° of eccentricity in either the right (RVF) or left visual field (LVF). The peripheral stimulus was closely flanked by two 'X' letters (flanked stimuli). Each pair was displayed for only 180 msec in order to avoid useful ocular saccades. Fig. 2A provides a schematic representation of the experimental design. The stimuli were written in white and displayed on a black screen, by using E-prime software (E-prime Psychology Software Tools Inc., Pittsburgh, USA) on a PC computer. They were transmitted into the scanner by means of a video projector (Epson EMP 8200), a projection screen situated behind the scanner and a mirror centered above the participant's eyes.

4.1.3. *Task*

Participants had to perform a categorical matching task. They were instructed to fixate the central stimuli and press a response key with the index finger of the dominant hand, each time and only when they detected an *unmatched* stimulus pair (e.g., a centrally displayed letter and a lateralized geometrical figure, or vice-versa). Participants performed 2 ER-fMRI sessions.

4.1.4. *Event-related fMRI experimental design*

Pseudo-randomized Event-Related (ER) fMRI paradigms were used optimizing the onset of each type of stimuli (Friston, Zarahn, Josephs, Henson, & Dale, 1999). Each participant performed 2 ER-fMRI consecutive sessions. The order of fMRI sessions was counterbalanced across participants. For each session, 28 pairs of stimuli were displayed: 12 matched letter pairs in the LVF, 12 matched letter pairs in the RVF, 2 target unmatched pairs in the LVF and 2 target unmatched pairs in the RVF. In addition, 22 null-events (ten of them at the end of the session) were included in each session in order to provide an appropriate baseline measure (Friston et al., 1999). Null-events were composed of a black screen and a white fixation dot sized .1° of visual angle displayed at the centre of the screen. This central fixation dot was also displayed between stimuli in order to encourage participants to fixate the centre of the screen. For each functional session, six initial dummy scans were performed in order to stabilize the magnetic field. After dummies, 60 functional volumes were acquired during each session of the categorization task. The averaged inter-stimulus interval was 3 sec. The total duration of each functional session was 2 min 30 sec. The number of items requiring a motor response was minimized (4 items only per functional session) and brain activity was only considered for the no go trials. The few trials with a motor response play the role of catch trials in allowing an estimation of the participants' vigilance all along the tasks. Response accuracy and reaction times (RT) in milliseconds were recorded. Before the experiments, participants underwent a training session outside the scanner, with stimuli that differed from those used in functional sessions.

4.1.5. *MR Acquisition*

MRI acquisitions were performed at the Grenoble Hospital University Center (IrMaGe Unit) using a whole-body 3T MR scanner (MedSpec S300 system; Bruker, Ettligen, Germany) with 40 mT/m maximum gradient strength and 120 mT/m/sec maximum slew rate equipped with Transmit/Receive quadrature head coil. For functional scans, the manufacturer-provided gradient-echo/T2* weighted EPI method was used. Forty-one adjacent axial slices parallel to the bi-commissural plane were acquired in interleaved mode. Slice thickness was 3.5 mm. The in-plane voxel size was 3 × 3 mm (216 × 216 mm field of view acquired with a 72 × 72 pixels data matrix; reconstructed with zero filling to 128 × 128 pixels). The main sequence parameters were: TR = 2.5 sec, TE = 30 msec, flip angle = 80°. A T1-weighted high-resolution three-dimensional anatomical volume was acquired, by using a sagittal magnetization-prepared rapid acquisition gradient echo (MP-RAGE) sequence (field of view = 256 × 224 × 176 mm; resolution: 1.333 × 1.750 × 1.375 mm; acquisition matrix: 192 × 128 × 128 pixels; reconstruction matrix: 256 × 128 × 128 pixels).

4.1.6. *Data processing*

Data analysis was performed by using the general linear model (Friston et al., 1995) as implemented in SPM (Welcome Department of Imaging Neuroscience, London, UK, www.fil.ion.ucl.ac.uk/spm) where each event is modelled using a haemodynamic function model. Data analysis started by applying several spatial pre-processing steps. First, functional volumes were time-corrected with the twentieth slice as reference, in order to correct effects caused by the different acquisition time of each slice. Subsequently, all volumes were realigned to correct head motion using rigid body transformations. The first volume of the first ER-fMRI session was taken as reference volume. T1-weighted anatomical volume was co-registered to mean images created by the realignment procedure and was normalized to the MNI space using a trilinear interpolation. The anatomical normalization parameters were subsequently used for the normalization of functional volumes. Finally, each functional volume was smoothed by an 8-mm FWHM (Full Width at Half Maximum) Gaussian kernel. Time series for each voxel were high-pass filtered (1/128 Hz cut-off) to remove low-frequency noise and signal drift.

After pre-processing steps, statistical analysis was performed on functional images. For controls, four conditions (Flanked-LVF matched, Flanked-LVF unmatched, Flanked-RVF matched, Flanked-RVF unmatched) were modelled as 4 regressors convolved with a canonical haemodynamic response function (HRF). Movement parameters derived from realignment corrections (3 translations and 3 rotations) were also entered in the design matrix of each experiment as additional factors. The general linear model was then used to generate parameter estimates of activity at each voxel, for each condition, and each participant. Statistical parametric maps were generated from linear contrasts between the HRF parameter estimates for the different experimental conditions. At the individual level, we assessed the whole network of cerebral areas involved in VA processes by contrasting the flanked condition to the baseline (crosshair fixation). Then, we

Table 5 – Cerebral regions activated during the lateral masking task for controls and MP before and after training. The statistical significance threshold for individual voxels was set at uncorrected $p < .001$. For each cluster, the Talairach coordinates (x, y, z) of the peak and the spatial extent (k) are indicated. All peaks $p < .001$ uncorrected, except $^{*}p < .005$. Abbreviations: BA = Brodmann area; k = number of voxels in the cluster.

	Controls		MP before training		MP after training	
	x, y, z	k	x, y, z	k	x, y, z	k
[Flanked > baseline]						
Temporal cortex						
Left inferior temporal gyrus/fusiform gyrus (BA 37)	−36, −44, −13	59				
Right inferior temporal gyrus/fusiform gyrus (BA 37)	42, −50, −12	34				
Parietal cortex						
Right precuneus/superior parietal lobule (BA 7)	27, −56, 48	150			39, −37, 66	68
Right inferior parietal lobule (BA 40)	45, −39, 41	32				
Left inferior parietal lobule (BA 40)	−36, −39, 44	30			−33, −47, 44	41
Left precuneus/superior parietal lobule (BA 7)	−33, −59, 48	41			−39, −49, −63*	
Bilateral central parietal lobule (BA 5)					−9, −31, 79	163
Occipital cortex						
Bilateral cuneus (BA 17/18/19)	3, −69, 10	36	15, −77, 33	32	−3, −67, −3*	32*
			−6, −77, 33		24, −93, 5*	39*
			−3, −78, 17*			
Frontal cortex						
Left middle frontal gyrus/SMA (BA 9/6)	−39, 25, 28	40				
Supplementary motor area/cingulate gyrus (BA 6/32)	15, 9, 61	39				
	0, 22, 38					
Left cerebellum						
Posterior Cingulate Gyrus (BA 29)	−12, −71, −17	53			3, −40, 18	49

performed a random-effect group analysis on the contrast images from the individual analyses (Friston et al., 1998), using one-sample t tests. Clusters of activated voxels were then identified, based on the intensity of the individual responses ($P < .001$ uncorrected, $T > 4.02$, extended threshold of 30 voxels). For MP, eight conditions (Before Training-Flanked-LVF matched, Before Training-Flanked-LVF unmatched, Before Training-Flanked-RVF matched, Before Training-Flanked-RVF unmatched, After Training-Flanked-LVF matched, After Training-Flanked-LVF unmatched, After Training-Flanked-RVF matched, After Training-Flanked-RVF unmatched) were modelled as 8 regressors convolved with a canonical haemodynamic response function (HRF). Movement parameters derived from realignment corrections (3 translations and 3 rotations) were also entered in the design matrix of each experiment as additional factors. The general linear model was then used to generate parameter estimates of activity at each voxel, for each condition. At the individual level, we assessed first the whole network of cerebral areas involved in VA processes before and after training by contrasting the flanked condition to the baseline (crosshair fixation) before and after training, respectively. Then, we directly compared the activation elicited by the flanked condition before and after training. Clusters of activated voxels were then identified, based on the intensity of the individual responses ($P < .001$ uncorrected, $T > 3.13$). Brain regions were reported according to the stereotaxic atlas of Talairach and Tournoux (1988).

Analysis was finally completed by statistically comparing MP's data with the data of controls within regions of interest (ROIs). The regions specifically involved in normal VA processing were defined as ROIs. Parameter estimates of event-related responses were then extracted from these ROIs for each participant. Finally, modified t-test analyses (Crawford & Howell, 1998) were carried out to compare the mean parameter estimates of MP with that of the control group.

4.2. *FMRI results*

Results of the contrasts between relevant conditions are presented in Table 5.

4.2.1. *Behavioural results under fMRI*

Behavioural data recorded during the visual categorisation task under fMRI showed that mean error rate (mER) was low before training for both MP (Flanked/LVF: 0%, Flanked/RVF: 3.57%), and the Controls (Flanked/LVF: 4.76% ± 5.13, Flanked/RVF: 1.49% ± 2.83). In the pre-training fMRI session, response times on correct responses were slightly delayed in MP (Flanked/LVF: 992 msec, Flanked/RVF: 980 msec) relative to controls (Flanked/LVF: 962 msec ± 126, Flanked/RVF: 917 msec ± 120). However, Modified t-test analysis (Crawford & Howell, 1998) showed no significant difference between MP and controls for either accuracy (Flanked/LVF: $t = -.89$, $p = .80$; Flanked/RVF: $t = .71$, $p = .25$) or reaction times (Flanked/LVF: $t = .23$, $p = .41$; Flanked/RVF: $t = -.50$, $p = .31$).

After training, MP no longer made errors (Flanked/LVF: 0%, Flanked/RVF: 0%) and performed as CA-matched controls (Accuracy: Flanked/LVF: t-value = −.89, $p = .80$; Flanked/RVF: t-value = −.50, $p = .69$; RTs for correct responses: Flanked/LVF: t-value = .45, $p = .33$; Flanked/RVF: t-value = −.12, $p = .55$).

4.2.2. *Cerebral reorganisation after VA span training*

FMRI data acquired from controls (Fig. 6B and Table 5) showed that the flanked stimulus condition (relative to baseline; [Flanked/LVF + Flanked/RVF > crosshair fixation]) activated a

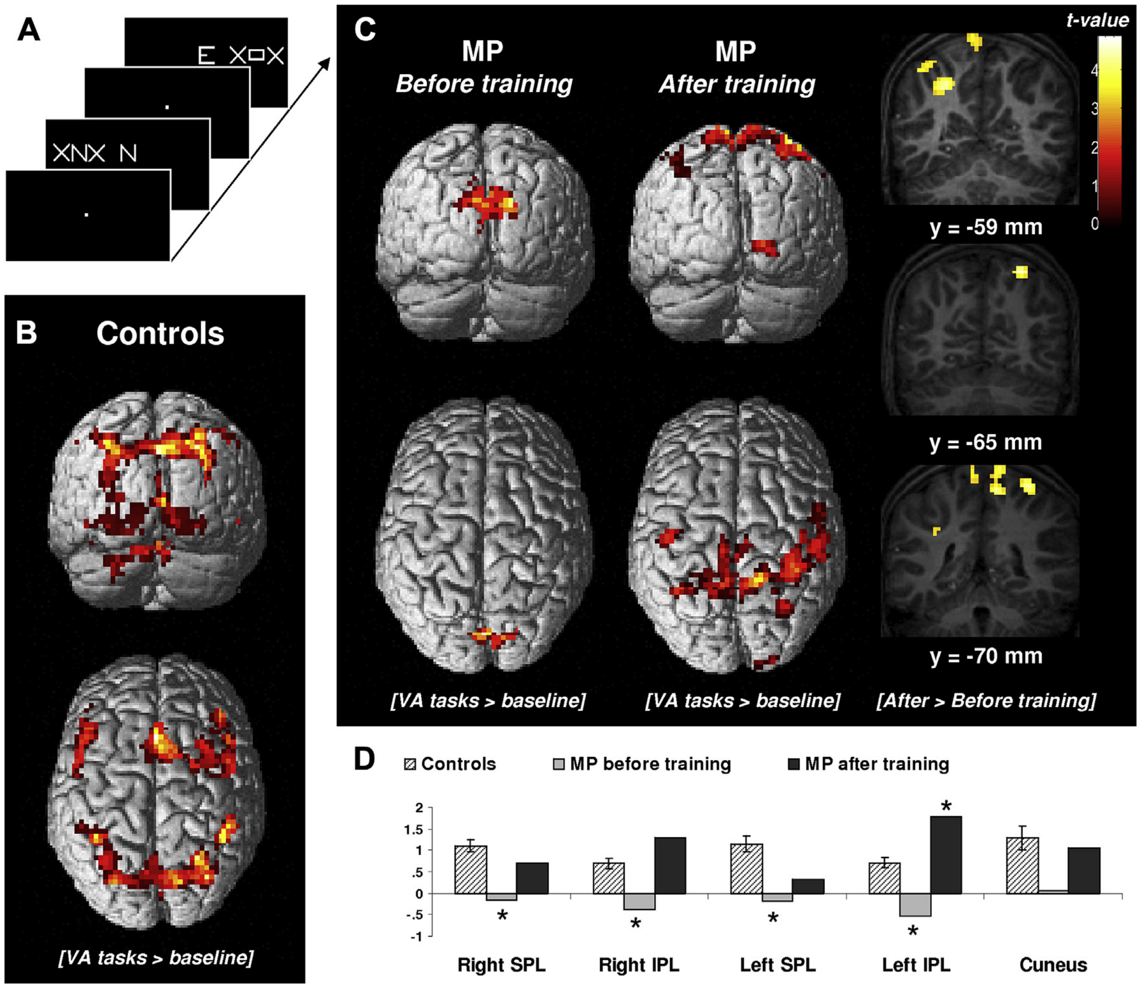

Fig. 6 – (A) Example of the stimuli used in the flanked condition of the visual categorisation task. Parafoveal stimuli were lateralized in either the right or left visual field. They were flanked with two Xs in the flanked condition. Cerebral regions activated [(flanked > baseline) contrast] for (B) Controls and (C) MP before and after training. Before intervention, MP showed significant activation within bilateral striate and extrastriate areas (BA 17/18/19). After intervention, she showed an activation of the superior and inferior parietal cortex similar to controls. Direct pre-post training comparison revealed significant increase of the superior parietal lobes bilaterally, the left inferior parietal lobe and central parietal lobe. For illustrative purpose, the statistical maps were generated for active pixels with $p < .005$. (D) Difference between the average parameter of activity (% change relative to the global mean intensity of signal) calculated for Controls and MP confirmed that the right and left superior parietal lobes (SPL), and right and left inferior parietal lobes (IPL) were less activated for MP than controls before training, but not anymore after training. The asterisk (*) means that the difference between Controls and MP is significant (modified *t*-tests; Crawford & Howell, 1998).

large cortical network comprising bilaterally the superior and inferior parietal lobes (SPL, BA 7 and IPL, BA 40), the inferior temporal gyri (ITG, BA 37), the striate and extrastriate visual cortices (BA 17/18/19) and the frontal cortex including the supplementary motor area (BA 9/6), anterior cingulate cortex (BA 32) and cerebellum. For MP (Fig. 6C and Table 5), fMRI data acquired before training only showed activation of the striate and extrastriate visual cortex (BA 17/18/19) for the same contrast. After training, the bilateral SPL (BA 7) and the left IPL (BA 40) were found activated in MP who further activated the central parietal lobe (BA 5). The striate and extrastriate visual cortices were found activated at a less restrictive threshold ($P < .005$).

More interestingly, direct comparison between post- and pre-training fMRI sessions revealed a significant bilateral activation increase within the left SPL (BA 7, 19 voxels, −45x 50y 54z, $T = 3.62$), the left IPL (BA 40, 48 voxels, peak co-ordinates −27x −50y 44z, $T = 4.27$), the right SPL (BA7, 24 voxels, 33x −58y 61z, $T = 4.87$ and a cluster of 56 voxels extending to the central parietal lobe and the postcentral gyrus, 39x −37y 66z, $T = 4.73$) and within the central parietal lobe bilaterally (BA 5, 114 voxels, 12x −41y 63z, $T = 4.24$ and −6x −46y 80z, $T = 3.80$).

Finally, an ROI based analysis was performed to compare MP's activation to controls'. Based on control readers' and MP's brain activation pattern during the visual categorization task, the following posterior cortical ROIs were specifically investigated: right SPL, right IPL, left SPL, left IPL and cuneus. We extracted parameter estimates from these clusters for each participant (ROI-based analysis) and modified *t*-test analyses (Crawford & Howell, 1998) were carried out to compare the mean parameter estimates of MP and the controls. The ROI analyses (see Fig. 6D) confirmed significantly lower activation before training for MP than controls within the right SPL (t-value $= -2.62$, $p < .05$), right IPL (t-value $= -2.72$, $p < .05$), left SPL (t-value $= -3.25$, $p < .05$) and left IPL (t-value $= -2.12$, $p < .05$), but not within the cuneus (t-value $= -1.35$, $p = .10$). After training, the analysis confirmed similar brain activation patterns in MP as in the controls for the right SPL (t-value $= -.84$, $p = .50$), right IPL (t-value $= 1.54$, $p = .83$), left SPL (t-value $= -1.34$, $p = .17$) and cuneus (t-value $= -.26$, $p = .50$) and a significant greater activation within the left IPL (t-value $= 2.80$, $p < .05$).

5. General discussion

Although developmental dyslexia has been mainly viewed during the last decades as resulting from a phonological deficit (Vellutino et al., 2004), there is growing evidence that some dyslexic children do exhibit a single VA span disorder in the absence of phonological problems (Bouvier-Chaverot et al., 2012; Dubois et al., 2010; Peyrin et al., 2012; Valdois et al., 2003, 2011 for single case reports; or Bosse et al., 2007; Zoubrinetzky et al., submitted for publication, for group studies). MP is such a case. Neuropsychological investigation (at T0) indeed revealed good phoneme awareness and good verbal short-term memory in MP together with the absence of oral language problems (i.e., good phoneme discrimination, normal verbal fluency and preserved oral comprehension). Further evidence of her good phonological skills comes from the inspection of her reading errors that were phonologically motivated for most of them. In sharp contrast with her good phonological skills, MP demonstrated very poor VA span abilities. She could only identify 2 letters out of a string of five at the expected level for her age but could identify single letters as efficiently as her peers. The overall findings thus suggest that MP does not suffer from a general visual disorder or letter identification problem but from a specific parallel visual processing disorder, namely a VA span disorder. In preventing visual multi-element parallel processing, the VA span disorder is in particular detrimental for reading. Although some cases of developmental dyslexia with a single VA span disorder have already been reported, the relevance of MP's case is twofold. First MP is the youngest case ever described, well in line with evidence that VA span abilities modulate reading performance from the beginning of reading acquisition (Bosse & Valdois, 2009). Second, MP case study provides the first report of a single VA span disorder but normal phonological processing in a bilingual child with developmental dyslexia. This case study thus provides the opportunity to explore the effect of a single VA span disorder on reading performance in two languages, French and Spanish that differ in orthographic transparency. MP was engaged in an intensive remediation programme whose aim was to improve her VA span skills. Post-intervention assessment showed that her VA span abilities did improve following training, thus giving us the opportunity to examine whether post-training VA span improvement differently affected her reading performance in French and Spanish. Post-training specific modulation of brain activity was lastly explored under fMRI in order to track any evidence that successful VA span training resulted in specific increase of activation of the brain regions specifically involved in VA span, thus suggesting a causal relationship between VA span improvement and increased reading performance.

5.1. *A VA span disorder but no phonological problem in MP*

As previously reported in subgroups of monolingual French and English dyslexic children (Bosse et al., 2007), MP exhibits poor performance on report tasks that require multi-letter/digit string simultaneous processing. Previous findings have already shown that poor performance on the VA span tasks in developmental dyslexia is not specific to letters. As in MP, very similar findings are typically reported either using letters or digits (Valdois et al., 2012; Ziegler et al., 2010). Although they necessitate a verbal response and use alphanumeric stimuli, it has been shown that performance on these tasks is not sensitive to verbal short-term memory (Lassus-Sangosse, N'Guyen-Morel, & Valdois, 2008) and does not reflect a visual-to-phonological code mapping disorder (Valdois et al., 2012). As further evidence against a phonological account of poor letter/digit string processing in developmental dyslexia, the VA span disability was found to extend to non-verbal tasks (Reilhac et al., 2013) and non-verbal material (Lobier, et al., 2012). Otherwise, although MP performed at the level of RA matched controls on VA span tasks, her poor performance cannot be viewed as just reflecting a general delay in reading acquisition. First against the delay hypothesis, her phoneme awareness skills and oral language abilities were at the expected level for her age, well above those of RA controls. Second MP's individual letter identification skills were at the expected level for her age while single letter identification threshold was far higher in (RA matched) beginning readers. As multi-letter parallel processing is sensitive not only to the amount of VA resources that can be allocated to processing but also to letters' discriminability (Bundesen, 1990; Dubois et al., 2010), a limitation in single letter processing might have affected beginning readers' performance on report tasks, which cannot account for MP's performance level on these tasks. Accordingly, MP's poor performance on letter/digit report tasks can be reasonably ascribed to a VA span disorder, i.e., a limitation in the amount of VA resources that can be allocated to multi-letter simultaneous processing within strings.

The VA span disorder in MP was found in the absence of phonological problems (i.e., good phoneme awareness and verbal short-term memory, good oral language abilities). Available data suggests that such a dissociation between phonological and VA span abilities is relatively frequent in the dyslexic population (Bosse et al., 2007; Zoubrinetzky, et al., submitted for publication; see also Valdois et al., 2003; Lallier, Donnadieu, Berger, & Valdois, 2010 for dissociation evidence through single case studies). However, evidence for a single VA span disorder in MP was reported when she was only 7 years old, thus suggesting that severe VA span disorders can occur very early during reading acquisition. The dissociation between preserved phonological skills but impaired VA span was further observed while MP never benefited from any phonological remediation, well in line with the hypothesis that phonological skills and the VA span act as distinct underpinnings of reading acquisition (Bosse & Valdois, 2009).

5.2. *Effect of a single VA span disorder on reading performance in French and Spanish*

The consequences of a phonological disorder on reading acquisition are well documented in French and Spanish monolingual, or bilingual individuals (Goswami et al., 2011; Jiménez, 1997; Jiménez & Hernandez-Valle, 2000; Sprenger-Charolles et al., 2011). In the same way, more and more studies have explored how VA span abilities affect reading performance in French monolinguals (Bosse et al., 2007; Bosse & Valdois, 2009; Dubois et al., 2010; Lobier, Dubois, & Valdois, 2013; Prado et al., 2007; Valdois et al., 2011). However for the first time, MP's case study provided the opportunity to explore the consequences of a single VA span disorder on the acquisition of reading in two languages that differ in orthographic transparency.

In French, MP's VA span disorder was associated with a reading speed disorder whatever the type of stimuli to be read (regular and irregular words or pseudo-words) and a low but not significant (as compared to bilingual children) accuracy performance. MP further showed a severe text reading speed reduction. It has previously been shown that VA span abilities modulate both reading accuracy and reading speed in French normal readers, and so from the beginning of reading acquisition (Bosse & Valdois, 2009). The link between VA span and reading speed performance has also been highlighted in French and English monolingual dyslexic children (Bosse et al., 2007). In a recent study on French typically developing children, Lobier et al. (2013) showed that text reading speed development is constrained by VA capacity. This finding is well in agreement with previous evidence from eye movements that VA span abilities constrain the number of letters accurately processed at each fixation during text reading in French (Prado et al., 2007). A large VA span ensures that more letters are processed and identified simultaneously, favouring a fast global reading procedure. In contrast, a small VA span in MP limits the amount of visual information available for word identification, favouring a slower analytic procedure based on sublexical units' processing.

Reliance on parallel processing for fluent reading is well documented in opaque languages like French (Aghababian & Nazir, 2000) or English (Adelman, Marquis, & Sabatos de Vito, 2010; New, Ferrand, Pallier, & Brysbaert, 2006) but a parallel/whole word procedure is also effective in transparent languages as Spanish (Davies, Barbon and Cuetos, 2013; Davies, Rodriguez-Ferreiro, Suarez, & Cuetos, 2013; Jiménez et al., 2009; Suarez-Coalla & Cuetos, 2012). Accordingly, a VA span disorder preventing global processing of words was expected to result in slower reading speed in Spanish, like in French. As typically reported in dyslexic individuals from transparent orthographies and well in agreement with the VA span disorder's prediction, MP indeed showed an abnormally slow reading speed in Spanish. Her reading speed disorder was severe and affected both single word and text reading. Both the current findings and recent evidence that VA span predicts reading latencies in Dutch (van den Boer, de Jong & Kaentjens-van Meeteren, 2013) suggest that VA span abilities may affect the fast global reading procedure in transparent as in more opaque languages.

Moreover, impaired global processing and reliance on the analytic procedure of reading should have resulted in poor irregular word reading accuracy and the predominance of regularisation errors. MP's performance partly conforms to this prediction. Although her performance did not reach significance due to large variability of performance in the bilingual control group, she only read half as many irregular words as the controls accurately. She however read the irregular words very slowly and mainly produced regularisation errors, thus showing that irregular words were analytically processed thanks to MP's good orthographic-to-phonological mapping knowledge and good phonological skills.

Although a VA span disorder is expected to primarily impact word reading, theoretical and empirical evidence suggests that pseudo-word reading can further be affected. At the theoretical level, a VA span disorder – if severe enough to prevent simultaneous processing of multi-letter graphemes or syllables—is expected to disturb sublexical orthographic units processing, thus resulting in poor pseudo-word reading (Ans et al., 1998; Valdois et al., 2004). At the empirical level, we already found that VA span abilities contribute to pseudo-word reading performance in dyslexic (Bosse et al., 2007) and non-dyslexic children (Bosse & Valdois, 2009). The case study of a French monolingual child (Valdois et al., 2011) has been previously reported showing that poor accuracy and slow pseudo-word reading can be found in the context of impaired VA span but preserved phonological skills. Note that poor (regular and irregular) word and pseudo-word reading is here interpreted as following from the same inability to process the whole string of multi-letter units (words, syllables or graphemes) in parallel. Accordingly, MP's VA span disorder was expected to affect pseudo-word reading performance in both French and Spanish, which was found. As for words, pseudo-word reading was slowed in the two languages and reading speed more affected than reading accuracy.

Direct comparison between French and Spanish showed a similar impact of the VA span disorder on regular word reading speed in both French and Spanish while reading speed was more affected in French than in Spanish for the pseudo-words. In the same line, text reading speed was slower in French than in Spanish. As expected the overall results suggest a higher impact of the VA span disorder on the language characterized by longer graphemes and longer syllables. A difficulty to process multi-letter strings should primarily impact whole word letter string processing, thus resulting in slow reading speed for words whatever the language transparency, which was found. A failure to process words as wholes would lead to shift to the analytic reading procedure which relies on parallel processing of sublexical units. A VA span disorder would then be all the more detrimental that the units to be processed are longer in number of letters, thus affecting processing in French more than in Spanish. Future studies are required to more directly explore differential effects of a single VA span disorder on reading performance in French and Spanish. Assuming that the larger the unit to be processed the more severe the consequences of a VA span reduction, a stronger impact on word and pseudo-word reading speed should be expected in French as compared to Spanish provided that French (pseudo) words include multi-letter graphemes (or longer syllables).

5.3. *Modulation of French/Spanish reading performance following VA span training*

Neuropsychological assessment revealed that MP's poor reading performance was associated with a specific VA span disorder but no phonological problem. As intensive interventions focused on dyslexic children underlying phonological disorders have proven useful to improve reading performance (Gaab et al., 2007; Temple et al., 2003; see Castles & Coltheart, 2004 or Griffiths & Stuart, 2013, for a review), a new intervention programme was elaborated with the aim to improve MP's VA span abilities. The exercises were designed to require more and more visual elements to be simultaneously processed across sessions and children were encouraged to reduce their processing time from one session to the other. MP was trained on these exercises for 20 min a day, 6 days a week during 6 weeks. The key point here is that only VA span was trained. Several exercises used non-verbal material and when letters were used, letter names or letter sounds were never pronounced to ensure that grapheme–phoneme correspondences were not simultaneously reinforced.

It is moreover worth noting that the exercises used to train the VA span were not just the mirror of the report tasks used to assess the intervention efficacy. To the contrary, although the training and assessment tasks both involved VA span abilities, better performance at post-test assessment can in no way be viewed as just resulting from the repetition of or higher familiarity with the assessment's paradigm. After the intervention, we first checked whether the training exercises had been effective to improve MP's VA span. Pre–post training comparison on the report tasks revealed a positive effect of intervention on MP's VA span abilities. While she showed a very severe VA span deficit before training, the improvement raised MP's scores into the normal range after training.

We then reasoned that improvement of MP's VA span abilities should have resulted in enhanced reading skills, as VA span is thought to directly influence reading acquisition (Ans et al., 1998; Bosse & Valdois, 2009; Valdois et al., 2004). After 6 weeks of remediation focused on VA span abilities, MP did show significant reading improvements in French. Improvement was observed not only in single word reading – using the same ODEDYS lists before and after intervention or different lists (computerized tasks) – but also in text reading – as assessed through the little prince reading text or the Alouette Test used to estimate MP's reading age at the initial assessment. In particular, although MP's performance on the Alouette Test remained stable during the two months that preceded the intervention, her reading age put up by 4 months during the 2 months intervention period. Long-term assessment suggested that the advantage due to intervention remained 10 months later. Reading speed on the Little Prince Text also improved post-intervention and positive effects were further observed on regular and irregular words. In contrast, the effect of intervention was fairly modest on pseudo-words. These findings may suggest a selective effect of the intervention on the global reading procedure in French.

Differential effects were expected in French and Spanish. Indeed, improved VA span abilities would allow longer and longer units to be progressively processed. Accordingly a positive effect of intervention would more strongly affect a language like French that is characterized by multi-letter graphemes and long syllables than a one-letter grapheme language like Spanish. Accordingly, higher improvement was expected in French than Spanish following the intervention. As expected, the word reading speed improvement reported in French was not found in Spanish and MP read the French text faster than the Spanish text following the intervention. Overall, VA span intervention primarily resulted in faster and more accurate identification of words in French but no similar improvement in Spanish. This is not to say that a selective VA span intervention would not facilitate reading in Spanish. If processing relies on short orthographic units in most Spanish words, then a VA span improvement would only result in faster reading speed if large enough to cover the whole word letter string. More sensitive tasks comparing reading speed performance on words varying in length before and after intervention should be designed to more directly address this issue.

Reading speed improvement in French was found while the same lists of words and the same text were presented before and after intervention. However, accuracy improvement in French was also found when using different lists of words at each assessment session. It follows that improvement seems independent of word lists and cannot be attributed to just a familiarity or repetition effect. Besides, a repetition effect would have resulted in better performance in Spanish as well, which was not observed. In the same way, if extensive assessment and intensive intervention had stimulated the development of more general learning abilities, similar improvement would have been observed in the two languages, which was not found. Moreover, pre–post training reading improvement cannot easily be attributed to the natural evolution of performance with time and literacy exposure independently of intervention. Indeed, MP's reading level (in French) did not improve during the same time period prior to the intervention (T0–T1 comparison). Moreover, MP's reading level was comparable to that of very beginning readers at the initial assessment suggesting a 3 months gain in reading acquisition for each previous period of 1 year of literacy instruction. This very slow acquisition rate strongly contrasts with the 4 months improvement in reading age that was observed during the 2-months pre–post intervention period. The overall behavioural data thus suggests that specific VA span intervention produced significant transfer to reading (at least or mainly in French).

We cannot exclude the possibility that better VA span abilities resulting in more accurate and faster grapheme processing may have in turn improved phonological processing skills (Vidyasagar & Pammer, 2010). Nevertheless, any direct effect of phonological skills on reading improvement is rather unlikely. First, MP's phonological skills were already very good before the intervention, so that any further improvement resulting indirectly from the intervention should not have been the key agent in improving her reading performance. Second, improved phonological skills would have affected pseudo-word reading more than word reading, contrary to what we observed.

Another potentially important result is the long-term effect of the intervention on reading. Indeed, the use of different reading lists in French suggests that regular word reading only improved immediately after the intervention while improvement on irregular words was more gradual and only significant later on at T3. In the same way, reading performance on the Alouette Test continued to improve after the end of the intervention (T2–T3 comparison). As spontaneous improvement due to practice in reading can be estimated as having been fairly modest prior to the intervention, long-term improvement following the intervention may suggest that basic visual analysis processes were developed through intervention that were later used when exposed to printed texts. When intervention focuses on basic cognitive mechanisms (as the VA span here), then the newly acquired competences have to be used in the context of ecological reading (external practice) for significant reading improvement to occur. A strict control of external practice with text reading during the intervention period (and later on) may be useful to better understand how external practice interacts with the intervention to improve reading performance.

5.4. *Brain modulation following VA span intervention*

Using functional magnetic resonance imaging (fMRI), previous studies have identified the neural underpinnings of VA span in skilled readers (Peyrin et al., 2008) and typically developing children (Lobier, et al., 2012; Peyrin et al., 2011). Enhanced activation of the superior parietal lobes bilaterally was found when multiple visual elements were simultaneously processed. A number of functional brain imaging studies converged to indicate a failure of these same regions to function properly in those dyslexic individuals who showed a VA span disorder at the behavioural level (Peyrin et al., 2011, 2012; Reilhac et al., 2013). In line with these findings, neuroimaging investigation conducted in MP prior to the intervention revealed underactivation of the superior parietal lobes bilaterally. A second fMRI session was administered to MP after training to check whether intervention resulted in specific activation changes in those brain regions involved in VA span. Greater activation of the superior parietal lobes was found after training compared with before training. Thus, MP who was administered a specific VA span intervention not only improved her reading but further showed increased activation of the VA span neural underpinnings (i.e., the superior parietal lobes), bringing brain activation in these regions closer to that seen in non-dyslexic children. These findings suggest that the training exercises administered to MP did target VA span abilities.

The superior parietal lobes are not typically identified as part of the reading neural network and superior parietal activations are not among the most reproducible foci in large metanalyses (Jobard, Crivello, & Tzourio-Mazoyer, 2003; Richlan, Kronbichler, & Wimmer, 2011). However, more and more data suggests that this brain region plays a key role in both expert reading and reading acquisition. In adult skilled readers, the role of the superior parietal lobes is well documented in long pseudo-word reading (Valdois, Carbonnel, Juphard, Baciu, Ans, Peyrin & Segebarth, 2006) and letter string processing (Levy et al., 2008; Lobier, Peyrin, LeBas & Valdois, 2012). These regions are activated in visual matching tasks that require letter identification within strings (Reilhac et al., 2013) and are strongly engaged whenever words are displayed in unusual formats (Cohen, Dehaene, Vinckier, Jobert, & Montavont, 2008). Available data thus suggests a specific role of the parietal lobes in the visual processing of letter strings. These regions may be even more strongly involved in reading acquisition due to the particular role of VA in learning to read (Laberge & Samuels, 1974). Accordingly, developmental increases of brain activity in bilateral superior parietal lobe have been reported, which more strongly relate to visuo-orthographic processing (Cao et al., 2010). The involvement of this region in letter string processing is further documented through the study of dyslexic children with a visual multi-element parallel processing disorder (Peyrin et al., 2011, 2012). In identifying relevant orthographic units through visual multi-letter parallel processing, the superior parietal lobes may play a critical role in perceptual learning and reading acquisition.

5.5. *VA span abilities as one cause of success in learning to read*

A large amount of evidence has now been accumulated to show that the larger the VA span, the better a child tend to be in reading (Bosse et al., 2007; Bosse & Valdois, 2009; Zoubrinetzky et al., submitted for publication). However, most of the studies that reported an association between VA span and reading were based on concurrent correlations between VA span and reading performance after control of phoneme awareness skills. Previous findings thus support the existence of a relationship between VA span and reading acquisition but no evidence was provided for a causal relationship. A causal connection from VA span to reading was assumed based on the multi-trace memory (MTM) model of reading (Ans et al., 1998). The MTM model explains the role of VA span in skilled reading and postulates that VA span and phonological processing are two components of the model that independently contribute to reading performance. Simulations further showed that a selective VA span reduction affected reading performance. The model further provided strong insights on the role of VA span in reading acquisition (Valdois et al., 2004). It was argued that multi-letter parallel processing is a key feature of reading acquisition. Normal establishment of grapheme–phoneme correspondences relies on graphemes perceptual learning, which in turn depends on the ability to process all the letters of grapheme units in parallel. Thus, the impact of VA span abilities is expected to be all the more important in multi-letter grapheme languages, as French. Progressively, parallel processing of larger orthographic units (syllables and words) contributes to their perceptual learning, thus participating to the establishment of a faster global reading procedure for fluent reading. The VA span thus appeared as a strong candidate to explain the cognitive cause of reading difficulties in those dyslexic individuals (as MP) that are not phonological.

Because poor performance on reading related tasks can just be the consequence of the child poor reading abilities, VA span abilities of dyslexic children and younger children of the same reading age were compared. Against the delay hypothesis, Bosse and Valdois (2003) showed that VA span abilities were lower in the VA span impaired dyslexic group than in RA-matched controls. Similar results were reported in the case study of a dyslexic teenager (Valdois et al., 2003). In another case study (Valdois et al., 2011), poor VA span in the dyslexic participant did not differ from that of younger RA-matched controls. In this latter study as in MP, RA-matched controls were very beginning readers who were very poor at single letter identification, so that their poor performance in multiple letter processing primarily reflected their poor letter identification skills rather than a VA span disorder. Note that in this case study as in MP, the dyslexic child had developed single letter identification skills at the expected level for his age. Good VA span abilities in dyslexic children with a single phonological disorder but the same reading age as VA span impaired children is further evidence that poor VA span abilities in dyslexic individuals are not just the consequence of their poor reading level (Peyrin et al., 2012; Valdois et al., 2003).

A causal relationship cannot be easily demonstrated. We explored the effect of a selective VA span intervention programme in MP to provide first evidence that instruction in VA span directly affects reading performance. Training in MP resulted in higher scores on the report tasks and increased activation of the VA span neural underpinnings, thus providing strong evidence that intervention specifically improved VA span abilities. In support of a causal relationship, improved VA span abilities and the amelioration of disrupted functions in the brain regions associated with VA further resulted in enhanced reading performance (mainly in French). The current findings are thus compatible with the causal hypothesis. However, additional studies are required to provide strong support for a causal relationship between VA span abilities and reading acquisition. First, training studies are needed to show not only that instruction in VA span improves reading performance in groups of VA span impaired dyslexic children but also that VA span training facilitates reading acquisition in typically developing beginning readers. Second, a definite demonstration of a direct causal relationship would require longitudinal studies showing that VA span abilities prior to literacy instruction predict subsequent reading performance. MP's case study only represents a first step toward such a demonstration.

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Appendix A

The little prince text for evaluating reading performance in French and Spanish. The French text was extracted from the 1997 edition published by Gallimard (Paris). The Spanish text was translated by Martha Valdés, in 1976, for Editorial Epoca (Mexico).

Text in French

J'appris bien vite à mieux connaître cette fleur. Il y avait toujours eu, sur la planète du petit prince, des fleurs très simples, ornées d'un seul rang de pétales, et qui ne tenaient point de place, et qui ne dérangeaient personne. Elles apparaissaient un matin dans l'herbe, et puis elles s'éteignaient le soir. Mais celle-là avait germé un jour, d'une graine apportée d'on ne sait où, et le petit prince avait surveillé de très près cette brindille qui ne ressemblait pas aux autres brindilles. Ça pouvait être un nouveau genre de baobab. Mais l'arbuste cessa vite de croître, et commença de préparer une fleur.

Text in Spanish

Pronto aprendí a conocer mejor esa flor. En el planeta del principito siempre había habido flores muy sencillas, adornadas con una sola hilera de pétalos, que casi no ocupaban espacio y que a nadie molestaban ni llamaban la atención. Aparecían una mañana entre la hierba y morían por la tarde. Pero aquélla había germinado un día de una semilla venida de algún lugar desconocido y el principito había cuidado muy de cerca a esa brizna y no tenía ninguna semejanza a las otras briznas. Esta podía ser un nuevo género de baobab. Pero el arbusto, de pronto, dejó de crecer y brotó una flor.

Appendix B

Metaphonological tasks in Spanish.

Phoneme segmentation: baño, faro, dado, jarra, gato, sapo, pala, malo, casa, rata, tapa, fila, bebe, jugo, plaza, pájaro, problema, apellidos, caballo, divertida, claridad, plastilina, hablando, descalzo, funcionar, lágrimas, merienda, practicar.

Phoneme deletion: gota, mesa, pico, arco, jugar, carro, leche, jaque, huevo, cordón, cuerno, plegar, grapa, placer, mariposa, corazón, fábula, parásito, contando, baldoza.

Acronyms: color hechizo, meta iguana, peso abanico, burla olor, gris halcón, camión uva, placer otro, choque azul, calabaza ironía, frase ave.

Appendix C

Assessment timeline, tasks used in French (FR) and Spanish (SP) and MP's variations in CA across sessions.

Tasks	T0 CA = 7; 10	T1 CA = 8; 1	T2 CA = 8; 4	T3 CA = 9; 3
General assessment (in French)	XX			
IQ (WISC IV; Raven matrices)	XX			
Executive functions (London tower)	XX			
Attentional abilities (NEPSY, Conners)	XX			
Oral language abilities (discrimination, comprehension, fluency)	XX			
Reading performance				
Reading level FR (Alouette)	XX	XX	XX	XX
Text reading FR (ODEDYS: petit monsieur)	XX			
Single item reading FR (ODEDYS; RW-IW-PW)	XX	XX	XX	XX
Single item reading SP (PROLEC; RW-PW)	XX	XX	XX	
Single item computer-based assessment FR				
List 1 (RW-IW-PW)		XX		
List 2 (RW-IW-PW)			XX	
List 3 (RW-IW-PW)				XX
Text reading FR (le petit prince)	XX	XX	XX	
Text reading SP (le petit prince)	XX	XX	XX	
Phonological processing				
Phoneme awareness				
(Segmentation, acronyms, deletion) FR	XX		XX	
(Segmentation, acronyms, deletion) SP	XX		XX	
Verbal short term memory	XX		XX	
Digit span FR and SP				
VA span assessment				
Global and partial letter report FR,	XX		XX	XX
Global and partial digit report SP	XX		XX	
Single letter identification Control task FR	XX			

XX indicates that the task was administered to MP during the session; T0 : initial assessment; T1 = pre-intervention assessment; T2 = post-intervention assessment; T3 = long term follow-up. The grey columns identify the pre-post intervention period.

REFERENCES

Abu-Rabia, S., & Siegel, L. S. (2002). Reading, syntactic, orthographic and working memory skills of bilingual Arabic–English speaking Canadian children. *Journal of Psycholinguistic Research, 31*(6), 661–678.

Adelman, J. S., Marquis, S. J., & Sabatos de Vito, S. G. (2010). Letters in words are read simultaneously, not left-to-right. *Psychological Science, 21*(12), 1799.

Aghababian, V., & Nazir, T. A. (2000). Developing normal reading skills: aspects of the visual processes underlying word recognition. *Journal of Experimental Child Psychology, 76*, 123–150.

Ans, B., Carbonnel, S., & Valdois, S. (1998). A connectionist multi-trace memory model of polysyllabic word reading. *Psychological Review, 105*, 678–723.

Aylward, E. H., Richards, T. L., Berninger, V. W., Nagy, W. E., Field, K. M., Grimme, A. C., et al. (2003). Instructional treatment associated with changes in brain activation in children with dyslexia. *Neurology, 61*(2), 212–215.

Bergmann, J., & Wimmer, H. (2008). A dual route perspective on poor reading in a regular orthography: evidence from phonological and orthographic lexical decision. *Cognitive Neuropsychology, 25*(5), 653–676.

Bosse, M. L., Tainturier, M. J., & Valdois, S. (2007). Developmental dyslexia: the visual attention span deficit hypothesis. *Cognition, 104*, 198–230.

Bosse, M. L., & Valdois, S. (2003). Patterns of developmental dyslexia according to a multi-trace memory model of reading. *Current Psychology Letters, 1*, 10. Electronic article http://cpl.revues.org/document.

Bosse, M. L., & Valdois, S. (2009). Influence of the visual attention span on child reading performance: a cross-sectional study. *Journal of Research in Reading, 32*(2), 230–253.

Bouvier-Chaverot, M., Peiffer, E., N'Guyen Morel, M. A., & Valdois, S. (2012). Un cas de dyslexie développementale avec trouble isolé de l'empan visuo-attentionnel [A case of developmental dyslexia with a single visual attention span disorder]. *Revue de Neuropsychologie, 4*(1), 24–35.

Broom, Y. M., & Doctor, E. A. (1995). Developmental surface dyslexia: a case study of the efficacy of a remediation programme. *Cognitive Neuropsychology, 12*, 69–110.

Brunsdon, R., Coltheart, M., & Nickels, L. (2005). Treatment of irregular word spelling in developmental surface dysgraphia. *Cognitive Neuropsychology, 22*, 213–251.

Brunsdon, R., Coltheart, M., & Nickels, L. (2006). Severe developmental letter-processing impairment: a treatment case study. *Cognitive Neuropsychology, 23*(6), 795–821.

Bundesen, C. (1990). A theory of visual attention. *Psychological Review, 97*, 523–547.

Cao, F., Lee, R., Shu, H., Yang, Y., Xu, G., Li, K., et al. (2010). Cultural constraints on brain development: evidence from a developmental study of visual word processing in Mandarin Chinese. *Cerebral Cortex, 20*, 1223–1233.

Castles, A., & Coltheart, M. (1996). Cognitive correlates of developmental surface dyslexia: a single case study. *Cognitive Neuropsychology, 13*(1), 25–50.

Castles, A., & Coltheart, M. (2004). Is there a causal link from phonological awareness to success in learning to read? *Cognition, 91*, 77–111.

Catach, N. (1995). *Dictionnaire historique de l'orthographe française*. Larousse.

Chung, K. K. H., & Ho, C. S. H. (2010). Second language learning difficulties in Chinese children with dyslexia: what are the reading-related cognitive skills that contribute to English and Chinese word reading. *Journal of Learning Disabilities, 43*(3), 195–211.

Cline, T. (2000). Multilingualism and dyslexia. *Dyslexia, 6*(1), 3–12.

Cohen, L., Dehaene, S., Vinckier, F., Jobert, A., & Montavont, A. (2008). Reading normal and degraded words: contribution of the dorsal and ventral visual pathways. *NeuroImage, 40*(1), 353–366.

Coltheart, M., Rastle, K., Perry, C., Langdon, R., & Ziegler, J. (2001). DRC: a dual route cascaded model of visual word recognition and reading aloud. *Psychological Review, 108*, 204–256.

Crawford, J. R., & Garthwaite, P. H. (2002). Investigation of the single case in neuropsychology: confidence limits on the abnormality of test scores and test score differences. *Neuropsychologia, 40*, 1196–1208.

Crawford, J. R., & Garthwaite, P. H. (2005). Testing for suspected impairments and dissociations in single-case studies in neuropsychology: evaluation of alternatives using Monte Carlo simulations and revised tests for dissociations. *Neuropsychology, 19*, 318–331.

Crawford, J. R., & Garthwaite, P. H. (2006). Methods of testing for a deficit in single case studies: evaluation of statistical power by Monte Carlo simulation. *Cognitive Neuropsychology, 23*(6), 877–904.

Crawford, J. R., Garthwaite, P. H., & Porter, S. (2010). Point and interval estimates of effect sizes for the case-controls design in neuropsychology: rational, methods, implementations and proposed reporting standards. *Cognitive Neuropsychology, 27*(3), 245–260.

Crawford, J. R., & Howell, D. C. (1998). Comparing an individual's test score against norms derived from small samples. *The Clinical Neuropsychologist, 12*(4), 482–486.

Cuetos, F., Rodríguez, B., & Ruano, E. (2000). *PROLEC: Batería de evaluación de los procesos lectores de los niños de Educación Primaria*. Madrid: TEA Ediciones.

Da Fontoura, H. A., & Siegel, L. S. (1995). Reading, syntactic and working memory skills of bilingual Portuguese–English Canadian children. *Reading and Writing, 7*(1), 139–153.

Davies, R., Barbon, A., & Cuetos, F. (2013). Lexical and semantic age-of-acquisition effects on word naming in Spanish. *Journal of Memory and Language, 41*(2), 297–311.

Davies, K., Cuetos, F., & Glez-Seijas, R. M. (2007). Reading development and dyslexia in a transparent orthography: a survey of Spanish children. *Annals of Dyslexia, 57*(2), 179–198.

Davies, R., Cuetos, F., & Rodriguez-Ferrero, J. (2010). Recovery in reading: a treatment study of acquired deep dyslexia in Spanish. *Aphasiology, 24*(10), 1115–1131.

Davies, R., Rodriguez-Ferreiro, J., Suarez, P., & Cuetos, F. (2013). Lexical and sublexical effects on accuracy, reaction time and response duration: impaired and typical word and pseudoword reading in a transparent orthography. *Reading and Writing: An Interdisciplinary Journal, 26*, 721–738.

Dubois, M., Kyllingsbaek, S., Prado, C., Peiffer, E., Lassus-Sangosse, D., & Valdois, S. (2010). Fractionating the multi-element processing deficit in developmental dyslexia: evidence from two case studies. *Cortex, 46*(6), 717–738.

Dubois, M., Lafaye de Micheaux, P., Noël, M. P., & Valdois, S. (2007). Pre-orthographical constraints on visual word recognition: evidence from a case study of developmental surface dyslexia. *Cognitive Neuropsychology, 24*(6), 623–660.

Eden, G. F., Jones, K. M., Cappell, K., Gareau, L., Wood, F. B., Zeffiro, T. A., et al. (2004). Neural changes following remediation in adult developmental dyslexia. *Neuron, 44*, 411–422.

Ehri, L. C., Nunes, S. R., Willows, D. M., Schuster, B. V., Yaghoub Zadeh, Z., & Shanahan, T. (2001). Phonemic awareness instruction helps children learn to read: evidence from the National Reading Panel's meta-analysis. *Reading Research Quarterly, 36*, 250–287.

Forster, K. I., & Forster, J. C. (2003). DMDX: a Windows display program with multisecond accuracy. *Behavior Research Methods, Instruments and Computers, 35*(1), 116–124.

Friston, K. J., Holmes, A. P., Worsley, K. J., Poline, J. P., Frith, C. D., & Frackowiack, R. S. J. (1995). Statistical parametric maps in functional imaging: a general linear approach. *Human Brain Mapping, 2*, 189–210.

Friston, K. J., Zarahn, E., Josephs, O., Henson, R. N., & Dale, A. M. (1999). Stochastic designs in event-related fMRI. *NeuroImage, 10*, 607–619.

Frith, U. (1997). Brain, mind and behaviour in dyslexia. In C. Hulme, & M. Snowling (Eds.), *Dyslexia: Biology, cognition and intervention* (pp. 1–19). London: Whurr Publishers.

Gaab, N., Gabrielli, J. D. E., Deutsch, G. K., Tallal, P., & Temple, E. (2007). Neural correlates of rapid auditory processing are disrupted in children with developmental dyslexia and ameliorated with training: an fMRI study. *Restorative Neurology and Neuroscience, 25*(3), 295–310.

Gak, V. G. (1976). *L'orthographe du français: Essai de description théorique et pratique*. Paris: Selaf.

Goswami, U., Wang, H. L. S., Cruz, A., Fosker, T., Mead, N., & Huss, M. (2011). Language-universal sensory deficits in developmental dyslexia: English, Spanish and Chinese. *Journal of Cognitive Neuroscience, 23*(2), 325–337.

Griffiths, Y., & Stuart, M. (2013). Reviewing evidence-based practice for pupils with dyslexia and literacy difficulties. *Journal of Research in Reading, 36*(1), 96–116.

Hadzibeganovic, T., Van den Noort, M. W. M. L., Bosch, M. P. C., Prec, M., Van Kralingen, R., Mondt, K., et al. (2010). Cross-linguistic neuroimaging and dyslexia: a critical view. *Cortex, 46*, 1312–1316.

Hanley, J. R., & Gard, F. (1995). A dissociation between developmental surface and phonological dyslexia in two undergraduate students. *Neuropsychologia, 33*, 909–914.

Hawelka, S., & Wimmer, H. (2005). Impaired visual processing of multi-element arrays is associated with increased number of eye movements in reading. *Vision Research, 45*, 855–863.

Jacquier-Roux, M., Valdois, S., & Zorman, M. (2002). *ODEDYS: un outil de dépistage des dyslexies*. Grenoble: Laboratoire cogni-sciences, IUFM de Grenoble.

Jiménez, J. E. (1997). A reading level match study of phonemic processes underlying reading disabilities in a transparent orthography. *Reading and Writing, 9*, 23–40.

Jiménez, J. E., & Hernandez-Valle, I. (2000). Word identification and reading disorders in the Spanish language. *Journal of Learning Disabilities, 33*, 44–60.

Jiménez, J. E., & Ramirez, G. (2002). Identifying subtypes of reading disability in the Spanish language. *Spanish Journal of Psychology, 3*, 37–46.

Jiménez, J. E., Rodriguez, C., & Ramirez, G. (2009). Spanish developmental dyslexia: prevalence, cognitive profiles and home literacy experiences. *Journal of Experimental Child Psychology, 103*(2), 167–185.

Jobard, G., Crivello, F., & Tzourio-Mazoyer, N. (2003). Evaluation of the dual route theory of reading: a metanalysis of 35 neuroimaging studies. *NeuroImage, 20*(2), 693–712.

Kipp, K. H., & Mohr, G. (2008). Remediation of developmental dyslexia: tackling a basic memory deficit. *Cognitive Neuropsychology, 25*(1), 38–55.

Korkman, M., Kiri, U., & Kemp, S. (1998). *NEPSY: A developmental neuropsychological assessment*. San Antonio, TX: The Psychological Corporation.

Laberge, D., & Samuels, S. J. (1974). Toward a theory of automatic information processing in reading. *Cognitive Psychology, 6*(2), 293–323.

Lallier, M. (2011). Orthographic transparency shapes visual attention underlying orthographic encoding: the case of Welsh–English bilingualism. *Annales de la foundation Fyssen, 26*, 44–52.

Lallier, M., Carreiras, M., Tainturier, M. J., Savill, N., & Thierry, G. (2013). Orthographic transparency modulates the grain size of orthographic processing: behavioral and ERP evidence from bilingualism. *Brain Research, 1505*, 47–60.

Lallier, M., Donnadieu, S., Berger, C., & Valdois, S. (2010). A case study of developmental phonological dyslexia: is the attentional deficit in rapid stimuli sequences processing amodal? *Cortex, 46*, 231–241.

Lallier, M., Donnadieu, S., & Valdois, S. (2013). Investigating the role of visual and auditory search in developmental dyslexia. *Frontiers in Human Neuroscience, 7*, 597–609. http://dx.doi.org/10.3389/fnhum.2013.00597.

Landerl, K., Ramus, F., Moll, K., Lyytinen, H., Leppänen, P. H. T., Lohvansuu, K., et al. (2013). Predictors of developmental dyslexia in European orthographies with varying complexity. *Journal of Child Psychology and Psychiatry, 54*(6), 686–694.

Landerl, K., Wimmer, H., & Frith, U. (1997). The impact of orthographies consistency in dyslexia: a German–English comparison. *Cognition, 63*(3), 315–334.

Lassus-Sangosse, D., N'Guyen-Morel, M. A., & Valdois, S. (2008). Sequential or simultaneous visual processing deficit in developmental dyslexia. *Vision Research, 48*, 979–988.

Lefavrais, P. (1965). *Test de l'Alouette*. Paris: Editions du centre de psychologie appliquée.

Levy, J., Pernet, C., Treserras, S., Boulanouar, K., Berry, I., Aubry, F., et al. (2008). Piecemeal recruitment of left-lateralized brain areas during reading: a spatio-functional account. *NeuroImage, 43*, 581–591.

Lobier, M., Dubois, M., & Valdois, S. (2013). Processing reading speed and reading speed development. *PLoS One, 8*(4), e58097.

Lobier, M., Peyrin, C., Pichat, C., LeBas, J. F., & Valdois, S. (2012). Neural correlates of pre-orthographic character string processing. *Neuropsychologia, 50*(9), 2195–2204.

Lobier, M., Zoubrinetzky, R., & Valdois, S. (2012). The visual attention span deficit in developmental dyslexia is visual and not verbal. *Cortex, 48*(6), 768–773.

Loney, T., & Milich, A. (1985). *The Conners questionnaire*.

Lorusso, M. L., Facoetti, A., Paganoni, P., Pezzani, M., & Molteni, M. (2006). Visual hemisphere specific stimulation vs. reading-focused training in dyslexic children. *Neuropsychological Rehabilitation, 16*(2), 194–212.

Lussier, F., Guerin, F., Dufresne, A., & Lassonde, M. (1998). Normative study of executive functions in children: Tower of London. *Approche Neuropsychologique des Apprentissages chez l'Enfant, 10*(2), 42–52.

Mousty, P., Leybaert, J., Alegria, J., Content, A., & Morais, J. (1994). BELEC: Batterie d'évaluation de la lecture. In P. Grégoire, & B. Piérart (Eds.), *Evaluer les troubles de la lecture: les nouveaux modèles théoriques et leurs implications diagnostiques* (pp. 127–145). Bruxelles: De Boeck.

New, B., Ferrand, L., Pallier, C., & Brysbaert, M. (2006). Re-examining word length effects in visual word recognition: new evidence from the English Lexicon Project. *Psychonomic Bulletin and Review, 13*(1), 45–52.

Pammer, K., Lavis, R., Cooper, C., Hansen, P. C., & Cornelissen, P. L. (2005). Symbol-string sensitivity and adult performance in lexical decision. *Brain and Language, 94*(3), 278–296.

Pammer, K., Lavis, R., Hansen, P., & Cornelissen, P. L. (2004). Symbol-string sensitivity and children's reading. *Brain and Language, 89*(3), 601–610.

Paulesu, E., Démonet, J. F., Fazio, E., McCrory, E., Chanoine, V., Brunswick, N., et al. (2001). Dyslexia: cultural diversity and biological unity. *Science, 291*, 2165–2167.

Pernet, C., Valdois, S., Celsis, P., & Démonet, J. F. (2006). Lateral masking, levels of processing and stimulus category: a comparative study between normal and dyslexic readers. *Neuropsychologia, 44*, 2374–2385.

Perry, C., Ziegler, J. C., & Zorzi, M. (2007). Nested incremental modelling in the development of computational theories: the CDP+ model of reading aloud. *Psychological Review, 114*(2), 273–315.

Peyrin, C., Démonet, J. F., N'guyen-Morel, M. A., Le Bas, J. F., & Valdois, S. (2011). Superior parietal lobes dysfunction in a homogeneous group of dyslexic children with a visual attention span disorder. *Brain and Language, 118*, 128–138.

Peyrin, C., Lallier, M., Démonet, J. F., Baciu, M., Pernet, C., Le Bas, J. F., et al. (2012). Neural dissociation of phonological and visual attention span disorders in developmental dyslexia: FMRI evidence from two case reports and normal readers. *Brain and Language, 120*(3), 381–394.

Peyrin, C., Lallier, M., & Valdois, S. (2008). The visual attention span brain mechanisms in normal and dyslexic readers. In M. Baciu (Ed.), *Behavioural, neuropsychological and neuroimaging studies of spoken and written language*. Signpost Edition.

Plaut, D. C. (1999). A connectionist approach to word reading and acquired dyslexia: extension to sequential processing. *Cognitive Science, 23*(4), 543–568.

Prado, C., Dubois, M., & Valdois, S. (2007). Eye movements in reading aloud and visual search in developmental dyslexia: impact of the VA span. *Vision Research, 47*, 2521–2530.

Ramus, F., Rosen, S., Dakin, S. C., Day, B. L., Castellote, J. M., White, S., et al. (2003). Theories of developmental dyslexia: insights from a multiple case study of dyslexic adults. *Brain, 126*, 841–865.

Reilhac, C., Peyrin, C., Démonet, J. F., & Valdois, S. (2013). Role of the superior parietal lobes in letter-identity processing within strings: fMRI evidence from skilled and dyslexic readers. *Neuropsychologia, 51*(4), 601–612.

Richlan, F., Kronbichler, M., & Wimmer, H. (2011). Meta-analyzing brain dysfunctions in dyslexic children and adults. *NeuroImage, 56*, 1735–1742.

Romani, C., Ward, J., & Olson, A. (1999). Developmental surface dysgraphia: what is the underlying cognitive impairment? *The Quarterly Journal of Experimental Psychology, 52A*, 97–128.

Seidenberg, M. S., & McClelland, J. L. (1989). A distributed developmental model of word recognition and naming. *Psychological Review, 96*, 523–568.

Serrano, F., & Defior, S. (2008). Dyslexia speed problems in a transparent orthography. *Annals of Dyslexia, 58*(1), 81–95.

Seymour, P. H., Aro, E. R., & Skine, J. M. (2003). Foundation literacy acquisition in European orthographies. *British Journal of Psychology, 94*(2), 143–174.

Shaywitz, B. A., Shaywitz, S. E., Blachman, B. A., Pugh, K. R., Fulbright, R. K., Skudlarski, P., et al. (2004). Development of left occipitotemporal systems for skilled reading in children after a phonologically-based intervention. *Biological Psychiatry, 55*, 926–933.

Silani, G., Frith, U., Démonet, J. F., Fazio, F., Perani, D., Price, C., et al. (2005). Brain abnormalities underlying altered activation in dyslexia: a voxel-based morphometry study. *Brain, 128*(10), 2453–2461.

Simos, P. G., Fletcher, J. M., Bergman, E., Breier, J. I., Foorman, B. R., Castillo, E. M., et al. (2002). Dyslexia-specific

brain activation profile becomes normal following successful remediation training. *Neurology, 58*, 1203–1213.
Snowling, M. (2001). From language to reading and dyslexia. *Dyslexia, 7*(1), 37–46.
Sprenger-Charolles, L., Colé, P., Lacert, L., & Serniclaes, W. (2000). On subtypes of developmental dyslexia: evidence from processing time and accuracy scores. *Canadian Journal of Experimental Psychology, 54*, 87–103.
Sprenger-Charolles, L., Siegel, L. S., Jiménez, J. E., & Ziegler, J. C. (2011). Prevalence and reliability of phonological, surface and mixed profiles in dyslexia: a review of studies conducted in languages varying in orthographic depth. *Scientific Studies of Reading*.
Suarez-Coalla, P., & Cuetos, F. (2012). Reading strategies in Spanish developmental dyslexics. *Annals of Dyslexia, 62*, 71–81.
Talairach, J., & Tournoux, P. (1988). *Co-planar stereotaxic atlas of the human brain. 3-dimensional proportional system: An approach to cerebral imaging*. New York: Thieme.
Temple, E., Deutsch, G. K., Poldrack, R. A., Miller, S. L., Tallal, P., Merzenich, M. M., et al. (2003). Neural deficits in children with dyslexia ameliorated by behavioral remediation: evidence from functional MRI. *Proceedings of the National Academy of Sciences of the United States of America, 100*, 2860–2865.
Thorstad, G. (1991). The effect of orthography on the acquisition of literacy skills. *British Journal of Psychology, 82*, 527–537.
Torgesen, J. K., Alexander, A. W., Wagner, R. K., & Rashotte, C. A. (2001). Intensive remedial instruction for children with severe learning disabilities. *Journal of Learning Disabilities, 34*(1), 33–58.
Valdois, S., Bidet-Ildei, C., Lassus-Sangosse, D., Reilhac, C., N'Guyen-Morel, M. A., Guinet, E., et al. (2011). A visual processing but no phonological disorder in a child with mixed dyslexia. *Cortex, 47*, 1197–1218.
Valdois, S., Bosse, M. L., Ans, B., Zorman, M., Carbonnel, S., David, D., et al. (2003). Phonological and visual processing deficits are dissociated in developmental dyslexia: evidence from two case studies. *Reading and Writing, 16*, 543–572.
Valdois, S., Bosse, M. L., & Peyrin, C. in press. *COREVA: un programme d'entraı̂nement de l'empan visuo-attentionnel (COREVA: A VA span intervention programme)*. France: Ortho-Editions, Isbergues.
Valdois, S., Bosse, M. L., & Tainturier, M. J. (2004). The cognitive deficits responsible for developmental dyslexia: review of evidence for a selective visual attentional disorder. *Dyslexia, 10*, 1–25.
Valdois, S., Guinet, E., & Embs, J. L. in press. *EVADYS: outil diagnostic des troubles de l'empan VA [EVADYS: A diagnostic tool for VA span assessment]*. France: Ortho-Editions, Isbergues.
Valdois, S., Juphard, A., Baciu, M., Ans, B., Peyrin, C., Segebarth, C., et al. (2006). Differential length effect in reading and lexical decision: convergent evidence from behavioural data, connectionist simulations and functional MRI. *Brain Research, 1085*(1), 149–162.
Valdois, S., Lassus-Sangosse, D., & Lobier, M. (2012). Impaired letter string processing in developmental dyslexia: what visual-to-phonological code mapping disorder? *Dyslexia, 18*(2), 77–93.
Van der Boer, M., de Jong, P., & Haentjens van Meeteren, M. M. (2013). Modeling the length effect: specifying the relation with visual and phonological correlates of reading. *Scientific Studies of Reading, 17*(4), 243–256.
Vellutino, F. R., Fletcher, J. M., Snowling, M. J., & Scanlon, D. M. (2004). Specific reading disability (dyslexia): what have we learned in the past four decades? *Journal of Child Psychology and Psychiatry, 45*, 2–40.
Vidyasagar, T. R., & Pammer, K. (2010). Dyslexia: a deficit in visuo-spatial attention, not in phonological processing. *Trends in Cognitive Science, 14*(2), 57–63.
Wydell, T. N., & Butterworth, B. (1999). A case study of an English–Japanese bilingual with monolingual dyslexia. *Cognition, 70*, 273–305.
You, H., Gaab, N., Wei, N., Cheng-Lai, A., Wang, Z., Jian, J., et al. (2011). Neural deficit in second language reading: fMRI evidence from Chinese children with English reading impairment. *NeuroImage, 57*, 760–770.
Ziegler, J. C., Pech-Georgel, C., Dufau, S., & Grainger, J. (2010). Rapid processing of letters, digits and symbols: what purely visual attentional deficit in developmental dyslexia? *Developmental Science, 13*(4), F8–F14.
Zoubrinetzky R., Bielle, F., & Valdois S. submitted for publication. New insights on developmental dyslexia subtypes: heterogeneity of mixed reading profiles.