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To cite this version:

Sylviane Valdois, Thierry Phénix, Mathilde Fort, Julien Diard. Atypical viewing position effect in developmental dyslexia: A behavioural and modelling investigation. Cognitive Neuropsychology, 2021, pp.1-17. 10.1080/02643294.2021.2004107 . hal-03582350

HAL Id: hal-03582350

https://hal.univ-grenoble-alpes.fr/hal-03582350

Atypical viewing position effect in developmental dyslexia: a behavioral and modeling exploration.

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Abstract

The probability of recognizing a word depends on the position of fixation during processing. In typical readers, the resulting word-recognition curves are asymmetrical, showing a left-of-center optimal viewing position (OVP). First, we report behavioral results from dyslexic participants who show atypical word-recognition curves characterized by the OVP being right of center with recognition probability being higher on the rightmost than on the leftmost letters. Second, we used BRAID, a Bayesian model of word recognition that implements gaze position, an acuity gradient, lateral interference and a visual attention component, to explore how variations in the deployment of visual attention would affect the OVP curves. We show that the atypical dyslexic curves are well simulated assuming a narrow distribution of visual attention and a shifting of visual attention towards the left visual field. These behavioral and modeling findings are discussed in light of current theories of visual attention deficits in developmental dyslexia.

1. Introduction

The efficiency of word recognition varies depending on fixation location within the word letter-string. The optimal viewing position (OVP) paradigm was designed by O'Regan, Levy-Schoen, Pynte, & Brugaillère (1984) to systematically explore the influence of the location of a single fixation on word identification. In this paradigm, briefly presented words are presented on the screen so that letters at different positions are under fixation. For example, the word TABLE can be presented with the T or the A or any other letter aligned with fixation and word recognition performance is measured for each fixation position.

The use of this paradigm revealed that recognition is optimal -- that is, faster and more accurate -- when the eyes fixate near the word center for shorter words or slightly towards the beginning of the word for longer words, a position called the optimal viewing position (OVP; O'Regan & Jacobs, 1992; O'Regan & Lévy-Schoen, 1987; O'Regan, Levy-Schoen, Pynte, & Brugaillère, 1984). The probability of word recognition decreases asymmetrically when fixation location deviates from the OVP (Brysbaert & Nazir, 2005; Nazir, O'Regan & Jacobs, 1991; Nazir et al., 1992; Nazir et al., 1998). For languages that are read left-to-right, words are more accurately identified when the initial fixation is left rather than right of the word center, so that typical viewing position curves that result from plotting accurate word identification against fixation location show an inverted J-shaped function, characterized by a leftward bias.

The OVP effect is quite a robust phenomenon. It has been reported in different tasks (O'Regan & Jacobs, 1992) and in a variety of languages (Farid & Grainger, 1996; Hyönä & Bertram, 2011; Kajii & Osaka, 2000; Liu & Li, 2013). While most studies have been carried out with adult skilled readers, exploration of word recognition using the OVP paradigm revealed a very similar pattern with children. Aghababian & Nazir (2000) reported variations of word recognition with fixation location from the end of the first grade and throughout primary school. The viewing position curves were asymmetrical at all grades, characterized by a leftward bias in children as in adults. Their results suggest that the viewing position curves' shape emerges quite early, after only one year of literacy instruction, and that it is not sensitive to further improvement in reading expertise (see Ducrot, Pynte, Ghio & Lété, 2013, for similar results). This conclusion must be qualified in some way. In the OVP paradigm in general, exposure duration is adjusted for each participant to ensure at least 50% accurate recognition for words presented centered on fixation while keeping exposure duration short enough to avoid multiple fixations. In the study by Aghababian & Nazir (2000), exposure duration did vary with grades, and the same curve shapes were observed for exposure durations that were twice as long in first grade than in fifth grade. The overall performance scores of the viewing position curves also changed with reading expertise and word length. While first graders showed a strong length effect, this effect decreased with grades and tended to disappear in adult readers.

Surprisingly, few studies have used the OVP paradigm to explore word recognition in dyslexic children (Bellocchi & Ducrot, 2021; Dubois, Lafaye de Micheaux, Noël & Valdois, 2007; Ducrot, Lété, Sprenger-Charolles, Pynte & Billard, 2003). The small amount of available data suggests atypical viewing position curves in this population. Dubois, Lafaye de Micheaux, Noël & Valdois (2007) assessed recognition performance depending on fixation location for 5- and 7-letter words in a single case study of surface dyslexia and in chronological age-matched control participants. While the control participants exhibited the classical inverted J-shaped viewing position curves regardless of word length, the dyslexic participant's viewing position curve followed an inverted V-shape for 5-letter words with an OVP located at the word center and more symmetrical slopes on either side (data from 7-letter words could not be used due to a floor effect). Similar alteration of the shape of the OVP curve was reported in poor readers for 6-letter words (Aghababian & Nazir, 2000), suggesting that OVP at the word center and inverted V-shaped curves may characterize word recognition in children with reading difficulties. In the two above-cited studies, word presentation duration was strongly limited to guarantee processing within a single fixation. Other studies, that used less limited exposure duration, reported different viewing position functions characterized by higher likelihood of word recognition when fixating slightly left of fixation in dyslexic individuals like in typical readers, but they lacked the typical left-right asymmetry (Bellocchi & Ducrot, 2021; Ducrot et al., 2003). Moreover, investigating the OVP effect in children with dyslexia was challenging. Even at the optimal viewing position, word recognition performance was usually low in the dyslexic population and sometimes characterized by a floor effect, at least for the processing of longer words (Dubois et al., 2007; Ducrot et al., 2003).

Theoretically, the location of the OVP and the shape of the viewing position curve provide insights on how letter identity information is extracted from printed words in a single fixation. The atypical curve features reported in poor and dyslexic readers were thus interpreted as suggesting a reduction in the number of letters that could be simultaneously processed (Dubois et al., 2007; see also Aghababian & Nazir, 2000). The OVP paradigm thus appears to be potentially relevant for characterizing the word identification deficit in developmental dyslexia. Therefore, the first aim of the present study was to provide new data from the OVP paradigm with a group of dyslexic children. Atypical curve shapes were expected to characterize this population. One important issue was to check whether the pattern of inverted V-shaped function previously reported in one dyslexic individual (and some poor readers) might be replicated in a larger group of dyslexic individuals when exposure duration was short enough to force parallel processing within a single fixation.

A second main purpose of the current study was to contribute to the debate on the mechanisms underlying the OVP effect, with a focus on visual attention. There is strong evidence that the perceptual constraints that affect letter identification within the letter string interact with lexical knowledge to account for the OVP effect. Among visual constraints, the acuity gradient is viewed as a major contributor in making letter identification worse for letters farther away from fixation (Kajii & Osaka, 2000; McConkie et al., 1989; Nazir, Heller & Sussmann, 1992; Nazir, O'Regan & Jacobs, 1991). Interference between adjacent letters, that has been described in studies on the crowding effect (Bouma, 1970; Pelli, Palomares & Majaj, 2004; Whitney & Levi, 2011), is another visual factor that affects letter identification as a function of eccentricity (Pelli et al., 2007; Pelli & Tillman, 2008). Accordingly, visual acuity and crowding should more strongly interfere with the identification of distant letters when fixating an outer letter than when fixating near word center, thus contributing to the OVP effect. Recent evidence that the viewing position curves for object recognition share a number of features with the OVP curves for words, namely optimal identification when fixating near the object center and decline in naming speed when deviating towards the object boundaries, is consistent with the involvement of general visual constraints like acuity drop-off and interference (or crowding) in the OVP effect (van der Linden & Vitu, 2016). However, evidence that the curve decline is symmetric for object recognition suggests that some linguistic factor further affects the OVP curve shape for written words.

All letters within words are not equally informative for identifying the target word and several studies have reported a modulation of the OVP depending on the informativeness of the initial or final letters for word recognition (Clark & O'Regan, 1999; Farid & Grainger, 1996; Stevens & Grainger, 2003; see also Deutsch & Rayner, 1999). Recent mathematical models thus assume that a combination of visual constraints and lexical factors best account for the OVP function (Kajii & Osaka, 2000; see also Bernard & Castet, 2019).

Despite growing evidence that visual attention is a major factor involved in word recognition (Besner et al., 2016; Lachter et al., 2004; Risko et al., 2010; Waechter et al., 2011) and despite the involvement of visual attention in the OVP effect having been theorized and discussed (Bellocchi & Ducrot, 2021; Bellocchi et al., 2013; Brysbaert & Nazir, 2005; Grainger & Ducrot, 2007; Ducrot et al., 2013; Nazir, Ben-Boutayab, Decoppet, Deutsch, & Frost, 2004), very little is known about the specific mechanisms by which visual attention would affect the OVP effect. An attentional bias in favor of the right visual hemifield has been reported for linguistic stimuli in languages read left-to-right. In studies involving divided visual fields, letter and word recognition performance is generally better for stimuli presented in the right visual field (Brysbaert & Nazir, 2005; Ducrot et al., 2013; Ducrot & Grainger, 2007; Lindell & Nichols, 2003; Nazir et al., 2004; Sieroff & Riva, 2011). During text reading, the region from which letter identity can be extracted in a single fixation extends farther into the right than the left visual field (Henderson et al., 1990; Rayner, 1998, 2010). These findings suggest that fixating to the left half of words would optimize word recognition, by boosting identification of the most informative initial letters and by affecting the way attentional resources are distributed over the letter string.

An impact of visual attention on the shape of the OVP curve would predict atypical curves when attentional processing is deficient (Aghababian & Nazir, 2000; Bellocchi & Ducrot, 2021). This would in particular apply for dyslexic children who exhibit a visual attention deficit. Two types of visuo-attentional disorders have been described in developmental dyslexia. Using the Posner's cueing paradigm, tasks that required detecting a non-verbal stimulus displayed on either the right or left visual field revealed slower detection speed for targets displayed in the left visual field but faster detection for targets displayed in the right visual field in dyslexic individuals than in typical readers (Facoetti et al., 2000, 2001, 2006; Facoetti & Molteni, 2001; see Sireteanu et al., 2005, for converging evidence from a line bisection task). Actually, this left "mini-neglect" and right-side enhancement in visual processing characterized only a subset of dyslexic individuals with poor pseudo-word reading, suggesting a link between spatial attention orienting and graphemic parsing during sublexical processing (Bellocchi et al., 2013; Facoetti et al., 2006; Ruffino et al., 2014; Vidyasagar & Pammer, 2010). A second type of visual attention deficit, namely a visual attention span deficit, was reported in another subset of dyslexic individuals (Lallier et al., 2012; Valdois et al., 2019). The visual attention span deficit refers to a deficit in multi-element parallel processing that limits the number of letters that can be simultaneously processed within words and reflects limited visual attention capacity (Bogon et al., 2014; Dubois et al., 2010; Frey & Bosse, 2018; Lobier et al., 2013). In affecting parallel letter processing, the deficit impacts fast word recognition (Bosse et al., 2007; Chen et al., 2019; Valdois et al., 2003, 2011, 2020, 2021; Zhao et al., 2018). A reduced VA span would affect the OVP curve. Deployment of visual attention on fewer letters within words would affect longer word more than shorter word processing. In the extreme cases in which a single letter receives enough attention for accurate identification, we would predict relatively accurate recognition of the shorter words when fixating at midpoint since the combined effects of visual attention allocation on the central letter and lesser interference on the outer letters would allow accurate identification of most of the letters within the word. However, departing from this central fixation position would increase the acuity drop-off on the opposite side, which would severely affect the identification of the more eccentric letters. As a result, word recognition would be impaired, all the more than fixation position deviates from the center and all the more for longer words. Overall, reduced VAS might result in the inverted V-shaped curve that was reported in some dyslexic/poor readers.

To better understand how visual attention might affect word recognition and the OVP curve, we used BRAID, a computational model of word recognition that includes mechanisms of visual acuity, lateral interference and visual attention (Phénix et al., submitted; Phénix et al., 2018; Ginestet et al., 2019), as an experimental substitute. In particular, we explored whether and how manipulated differences in the distribution of visual attention affected the simulated OVP curves. We further identified the conditions of visual attention deployment that allowed simulating the OVP curves reported in developmental dyslexia.

To summarize, the originality of the present paper is twofold. We will first report new empirical data on the way dyslexic children with a visual attention span deficit extract visual information depending on the position of fixation within words. For this purpose, we used the same OVP task and the same protocol as described in Aghababian & Nazir (2000). No new control group was included in the present study due to the high stability of the OVP effect. Indeed, an impressive number of studies has established that word recognition in Indo-European languages was best when fixating slightly left of the word center and better for fixations to the left than to the right (e.g., Aghababian & Nazir, 2000; Bellocchi & Ducrot, 2021; Brysbaert & Nazir, 2005; Dubois et al., 2007; Ducrot et al., 2003; 0'Regan et al., 1992; Nazir, O'Regan & Jacobs, 1991; Stevens & Grainger, 2003). The same pattern has been reported in different tasks (naming aloud, lexical decision, perceptual identification). It has been found to generalize over languages and characterizes words that differ in length and/or frequency. More importantly for the present purpose, the same OVP effect and VP curve shapes have been reported from the end of the first grade to the adult age (Aghababian & Nazir, 2000). Furthermore, we will consider the patterns reported in Aghababian and Nazir (2000)'s study as representative of the performance of typical readers to facilitate comparison with the viewing position curves described in our dyslexic participants. A reduction of visual attention span was expected to result in inverted-V-shaped viewing position curves, as reported for poor readers in their experiment, rather than in the inverted J-shaped curves reported in typical readers at all ages. Second, using a model of word recognition that, for the first time, implements both the visual mechanisms of visual acuity and lateral interference and a visual attention component, we will explore through simulations how modulations of visual attention distribution affect the OVP curves. We will then identify the parameters that best account for the viewing position curves behaviorally reported in the dyslexic population.

2. Experimental study

2.1. Material and Method

2.1.1. Participants

Twenty-four French dyslexic children (13 boys) were recruited in speech therapy private offices. All participants attended school regularly and were in 4th, 5th or 6th Grade at the time of testing. They were 10 year, 11 months old on average (mean=131,33 months; SD=9.5; min-max: 113-147). For all children, the diagnosis of dyslexia was based on a comprehensive neuropsychological examination, including evidence for a delay of at least 18 months on the Alouette reading test, a standardized French test of reading level (Lefavrais, 1967). Their reading performance, which was assessed through the text reading task of the BALE battery (Jacquier-Roux, Valdois & Zorman, 2010), was 2.27 standard deviations below the norms (mean number of accurately read words per minute = 66.71; SD=26.44; min-max=19-129 vs. 136.8 (30.87) in chronological-age matched typical readers from the BALE norm), showing a severe deficit in reading fluency. All participants were monolingual native-French speakers. They had a normal non-verbal IQ (exclusion if performance was below the 25th percentile on the PM38 Raven test or if the Verbal Comprehension Index and Perceptual Reasoning Index were below 85 on the WISC IV test), no auditory problems and normal or corrected-to-normal vision, in the absence of clinical or neurological history. Individuals with specific language impairment (SLI) or attention deficit hyperactivity disorder (ADHD) were not retained as participants. Associated arithmetic deficits were reported in three dyslexic participants, and one dyslexic child exhibited a developmental coordination disorder. Twenty-two children were right-handed, the two left-handed participants were not excluded because most left-handers have a dominant left-hemisphere for language and because excluding them from the OVP analysis did not affect the results. The global report task of the EVADYS standardized battery (Valdois et al., 2014) was administered to measure their visual attention span. By reference to the EVADYS software norms (Valdois et al., 2014), the participants exhibited a reduced visual attention span (mean z-score=-2,16, SD=1.03). The study was approved by the ethics committee of the "Université de Poitiers". It was performed according to the guidelines of the Declaration of Helsinki. Written informed consent was obtained from the participants and their legal guardians.

2.1.2. Material

The OVP task was designed as the replication of that described by Aghababian & Nazir (2000). As the list of words was not provided in their paper, we designed a new list based on similar selection criteria.

As in Aghababian and Nazir (2000), our stimuli were French words of 4, 5 or 6 letters. A total of 75 words were selected, 25 per length. In their study, word selection was based on the "Echelle Dubois-Buyse" (Reichenbach & Mayer, 1977), a French database that provides the list of words that were accurately spelled at the different grade levels. We used the more recent EOLE scale (Pothier & Pothier, 2003) to check that the experimental words' spellings were typically acquired by the end of primary school. Since the main challenge for this kind of experiment is to avoid floor effects with the dyslexic participants, we checked that our words were of relatively high frequency for school-age children, using the MANULEX database (Lété et al., 2004). The three lists of words, for each length, were matched for frequency and for age of spelling acquisition (respectively for lengths 4, 5 and 6: mean frequency = 243.68, 243 and 242.90 and correct spelling above 87%, 90% and 89.9% from the third grade). Further, as the asymmetry of VP curves is sensitive to the multimorphemic structure of words (Farid & Grainger, 1996), all words (nouns and adjectives) were selected to be monomorphemic. The selected experimental words are listed in Appendix 1.

Another list of 20 5-letter words was used to determine the exposure duration of the experimental words and adjust it to each child. The words were selected according to the same frequency and age of spelling acquisition criteria as the experimental words. Fifteen additional 5-letter words were further selected to be presented at the beginning of the experimental task for familiarization.

Following the methodology of Aghababian & Nazir (2000), and as typically done in this field of research (O'Regan et al., 1992, 1994; Nazir et al., 1998; Ducrot et al., 2013; Bellochi & Ducrot, 2021), each word was divided into five zones of equal width. The midpoint of each zone was designated as a potential fixation position. Different word groups of five items were identified for each word length, to which a particular fixation zone was attributed (that varied from one participant to the other). Each word was presented with a single fixation position to each participant but fixation position was varied across words for each participant and, considering all participants, each word was seen from all five viewing positions. Words were blocked by length with a set of five letter words presented at the beginning of each block for familiarization. Word order within a block was randomly varied for each participant.

2.1.3. Protocol

The words, displayed in lower case standard in the Courier new font, were presented on the monochrome screen of a PC computer refreshed at 60 Hz. The words were displayed in black on a white background. At a viewing distance of 30 cm, each letter subtended a visual angle of 0.76°. The words were briefly presented with the chosen zone midpoint aligned with fixation. Exposure duration was adjusted for each participant prior to the beginning of the experimental task. For this purpose, 5-letter words were presented systematically aligned with the word center followed by a mask (a series of #s). Their exposure duration was initially varied randomly from 16 ms to 200 ms and then gradually adapted to estimate the minimum exposure duration that allowed at least 60% accurate recognition[1].

The experimental OVP task began with the central presentation of a colon mark (:) for one second, followed by the presentation of the word 50 ms after the colon offset. The word was

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[1] Initially, 30 dyslexic children were administered the 5-letter word recognition task for exposure duration calibration. Only the 24 children who reached at least 60% accurate recognition rate for exposure durations lower than 200ms were included in the present study.

presented for a duration adjusted to the participant, immediately followed by a backward mask (a string of #s corresponding to the word letter length plus one # on each side). Exposure duration was 134.39 ms on average (SD=42.05 ms; min-max=66-200) for our population of dyslexic children, close to the exposure duration reported by Aghababian and Nazir (2000) for first grade children. The adjusted exposure duration was below the latency of a useful saccade for all participants to ensure that words were processed within a single fixation. Eye movements were not recorded but the experimenter reminded the child to fixate the dots of the colon mark and not to move their eyes, every ten trials or more often if required. Although the dyslexic participants may not always follow this instruction, not respecting the distance or gaze position constraint would likely result in more data variability, thus decreasing the probability to obtain statistically significant results. The child was informed about the word length of the forthcoming list and was asked to read aloud the word immediately after its presentation or to orally report the letters she/he had identified when the word was not recognized. The response was registered by the experimenter who provided no feedback to the child. The OVP task lasted around 20 minutes.

2.2. Experimental Results

Figure 1 shows the experimental word identification performance for the three word-lengths as a function of viewing position.

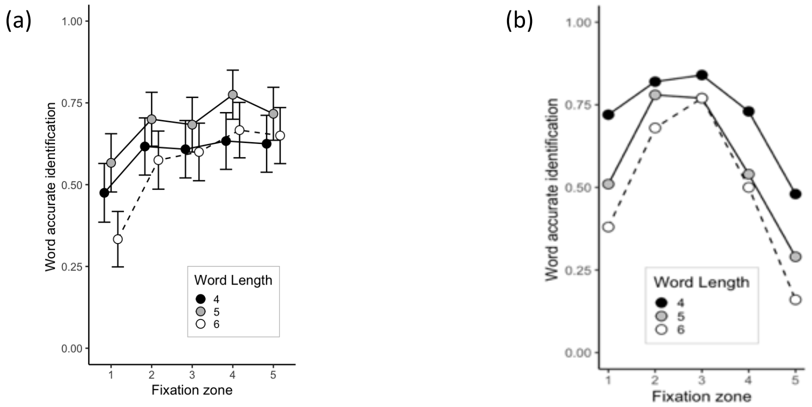

Figure 1. Probability of accurate report for four-, five- and six-letter words (black circles solid line, grey circles solid line and open circles dotted line respectively), as a function of viewing position. (a) the original data plotted with standard error bars for our dyslexic participants; (b) the data replotted from Figure 6 (list 2) of Aghababian & Nazir (2000).

An ANOVA was performed with participants as random factor, word-length (4, 5 and 6 letter words) and viewing position (zones 1 to 5) as within-subject factors. Results showed a significant main effect of length [$F(2, 46) = 9.44$, $p < .001$, $\eta^2 = 0.291$] and viewing position [$F(4,92) = 17.33$ 5, $p < .001$, $\eta^2 = 0.43$] on word identification but no length-by-viewing-position interaction [$F(8, 184) = 1.33$, $p = .23$]. Contrast analyses (adjusted by the Bonferroni method) showed that 5-letter words were better identified, all viewing positions considered, than 4-letter words [$t_{(23)} = -3.44$, $p < .01$] or 6-letter words [$t_{(23)} = 5.03$, $p < .0001$]. Four and six letter words showed similar probability of identification [$t_{(322)} = 0.74$, $p = .46$].

Contrast analyses with a Bonferroni method adjustment further showed that the rate of word recognition was significantly lower with first fixation position than with any of the other positions (P1 vs. P2 [$t_{(23)} = -4.99$, $p < .0001$], P1 vs. P3 [$t_{(23)} = -4.69$, $p < .0001$], P1 vs. P4 [$t_{(23)} = -8.67$, $p < .0001$] and P1 vs. P5 [$t_{(23)} = -5.23$, $p < .0001$]), all the other differences not being significant (all *ps* >.05). These results contrast with those of Aghababian & Nazir (2000) who reported higher word identification when fixating in the middle of the word (in positions P2-P3; see Figure 1b).

Inspection of Figure 1 suggests that the viewing position effect was characterized by a rightward bias whatever word length. In other words, word identification was higher when fixating right rather than left of the word center. To test the hypothesis of a rightward bias, the percent average word identification performance for the rightmost (Zone 4 + Zone 5) and leftmost (Zone 1 + Zone 2) viewing positions were computed for each word length. A significant asymmetry in favor of rightward fixations (i.e., better word recognition in zones 4-5 than 1-2) was observed for length 4 [$t_{(71)} = -2.02$, $p < .05$], length 5 [$t_{(71)} = -3.10$, $p < .01$] and length 6 [$t_{(71)} = -5.47$, $p < .0001$]. Thus, word identification was best when dyslexic participants fixated right of the word center, which contrasts with the left-of-center advantage reported by Aghababian and Nazir (2000) in typical readers.

3. Modeling the OVP curve shapes

3.1. Method

3.1.1. The BRAID model

BRAID is a Bayesian model of word recognition that includes a visual attention component in addition to an acuity gradient and a mechanism of lateral interference between adjacent letters. A schematic illustration of the model is provided in Figure 2; its full mathematical description can be found in Phénix et al. (submitted). The model is composed of four submodels. Information on letter identity is extracted from the input word at the sensory level of processing. The flow of sensory information, modulated by the visual attention submodel, is then transmitted to the perceptual level of processing, in which bottom-up perceptual evidence about letter identity accumulates over time. Letter identity at the perceptual level is further influenced by top-down information from lexical knowledge. As a direct consequence, letters are more efficiently identified when belonging to a real word than a non-word and all the more efficiently when the word is more frequent (Phénix et al., submitted; Saghiran et al., 2020). For the present simulations, the lexical submodel was configured using the lexical database from the French Lexicon Project, featuring the spelling of 38,840 French words and their frequency (Ferrand et al., 2010).

As shown in Figure 2, letter identification in the BRAID model is affected by three main mechanisms. An acuity gradient modulates letter identity processing at the sensory level. Acuity is maximal at fixation and symmetrically drops with eccentricity, so that weaker information on letter identity is extracted as eccentricity from fixation increases. Letter identification is further modulated by lateral interference between adjacent letters. Because they have only one flanking letter, the identification of the first and last letters of a letter-string is improved as compared to inner letters that suffer lateral interference from two flanking letters.

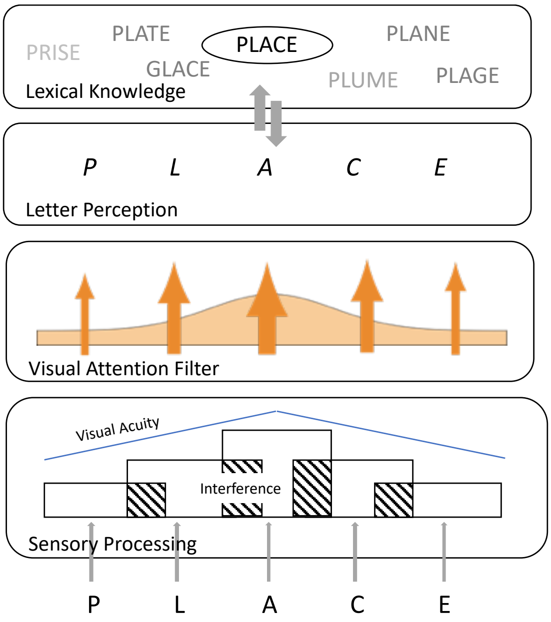

Figure 2: Schematic representation of the BRAID model when processing the French word "PLACE". Gaze position/fixation is on the third letter that aligns with the peak of the acuity gradient and the focus of attention. The arrow thickness in the visual attention layer symbolizes the amount of attention allocated to each letter depending on its distance from fixation.

Implementation of an original visual attention mechanism in BRAID allows studying how visual attention properties affect word recognition. In BRAID, visual attention acts as a filter that modulates the transfer of bottom-up information on letter identity from the sensory to the perception layer. The spatial distribution of visual attention across the input letter-string is defined by a Gaussian probability distribution (for an illustration, see Figure 3, top-left), specified by two parameters: the μ_A parameter that corresponds to the position of the focus of attention (i.e., the peak of the Gaussian distribution) and the σ_A parameter, the standard deviation of the distribution that defines attentional dispersion. Attention modulates letter identification depending on the values of these two parameters. In the experimental tasks that restrict fixation position, the focus of attention is assumed to coincide with gaze/fixation position, so that the letter at fixation (e.g., for 5-letter words) or the letters nearby fixation (for words of even length) receive maximal attention. However, gaze position and the focus of attention in BRAID are independent parameters that can be dissociated from one another, as required in the experimental paradigms that manipulate the orienting of visual attention in the absence of eye movements (Posner, 2016). In previous studies, a σ_A parameter value of 1.75, considered as the default σ_A parameter value, was used to simulate a variety of behavioral effects in word recognition, including length, frequency, neighborhood or priming effects in lexical decision or reading aloud (Ginestet et al., 2019; Phénix et al., 2018, Phénix et al., submitted; Saghiran et al., 2020). Thus, any σ_A parameter value higher than 1.75 can be used to simulate distributions of attention with wider spread over the word letter-string, whereas lower values would allow simulating narrower distributions of attention.

It was previously demonstrated that several behavioral effects, like the crowding effect or the word length effect in reading and lexical decision, were sensitive to variations in the distribution of attention over the word letter string (Ginestet et al., 2019; Phénix et al., submitted; Saghiran et al., 2020). More importantly for the present purpose, we showed in a previous study that the model, using default parameter values, successfully simulated the OVP curves reported in proficient readers (Phénix et al., submitted). Actually, the model provided a very good fit of the predicted OVP curves to the experimental data when simulated on the same set of stimuli as in the targeted experiment (Montant et al., 1998).

3.1.2. Variations of the visual attention parameters

In the present study, a series of simulations was carried out to check the impact of visual attention on the OVP curve shapes generated from the same set of words as used in the behavioral study in order to provide insight regarding the mechanisms that could account for the atypical curves reported in our dyslexic participants. In Simulation 1, the viewing position curves were generated using the model default parameters. Although typical leftward biased curves have been replicated quite widely in behavioral studies while using different sets of words, our purpose was to check that the rightward bias observed in our dyslexic participants was not just induced by the particular set of words we used. We thus expected the simulations to result in classical inverted J-shaped curves, as reported for typical readers in Aghababian & Nazir (2000, see Figure 1b), and in many other studies using different word sets (e.g., Ducrot et al., 2013; Nazir et al., 1991; O'Regan & Jacobs, 1992; O'Regan & Lévy-Schoen, 1987; O'Regan et al., 1984). We then explored the effect of a wide diffuse attention distribution on the OVP effect (Simulation 2). For this purpose, the OVP curves were generated using a large σ_A value ($\sigma_A = 100.0$), so that each letter received the same amount of attention irrespective of its location (as if attention was uniformly distributed on the stimulus). Simulation 3 explored the effect of a narrow distribution of attention ($\sigma_A = 0.75$) on word recognition depending on fixation position. In BRAID, visual attention narrowing limits the number of letters that receive attention during processing, which was expected to simulate the visual attention span reduction highlighted in the dyslexic population. Simulation 4 was carried out to identify the visual attention parameters that allowed generating the OVP curves that best fitted the dyslexic participants' curve shapes. Two series of simulations were performed. In the first, the μ_A and σ_A parameters were both modified to simulate the combined effects of narrow distribution of attention and attention shifting with respect to gaze position; in the second, the focus of attention (the μ_A parameter) alone was shifted to disentangle the specific effects of each one of the parameters on the viewing position curves. Figure 3 illustrates the different conditions of visual attention distributions that were used in the simulations.

To illustrate the results of the simulations and allow comparison with the behavioral data, we stopped simulations at the iteration for which the optimal viewing position of at least one curve reached a rate of word identification as close as possible to the maximal accurate identification rate observed in dyslexic children (i.e., around 75%, see Figure 1a). In the simulations, we systematically report the number of iterations required to reach the identification threshold in each condition of visual attention distribution. The time unit of the model has been calibrated so that one iteration corresponds to one millisecond. A higher number of iterations shows that more time was required for the model to reach the same level of accuracy in word recognition. For each condition of visual attention distribution, contrast analyses were computed to test the left-right asymmetry of the VP curves (i.e., comparison of word recognition in P1-P2 as compared to P4-P5). Pairwise comparisons were used to determine whether word recognition was significantly higher in some viewing positions as compared to the others, in support of an OVP effect. The data were analyzed with Python version 3.9.7 by means of linear mixed effect models (Pingouin version 0.4.0; Vallat, 2018) with word-length and fixation location as fixed factors, and items as random factor. Post-hoc comparisons were performed using Bonferroni contrast. Files describing the statistical analyses are available as Supplementary Material.

3.2. Simulation Results

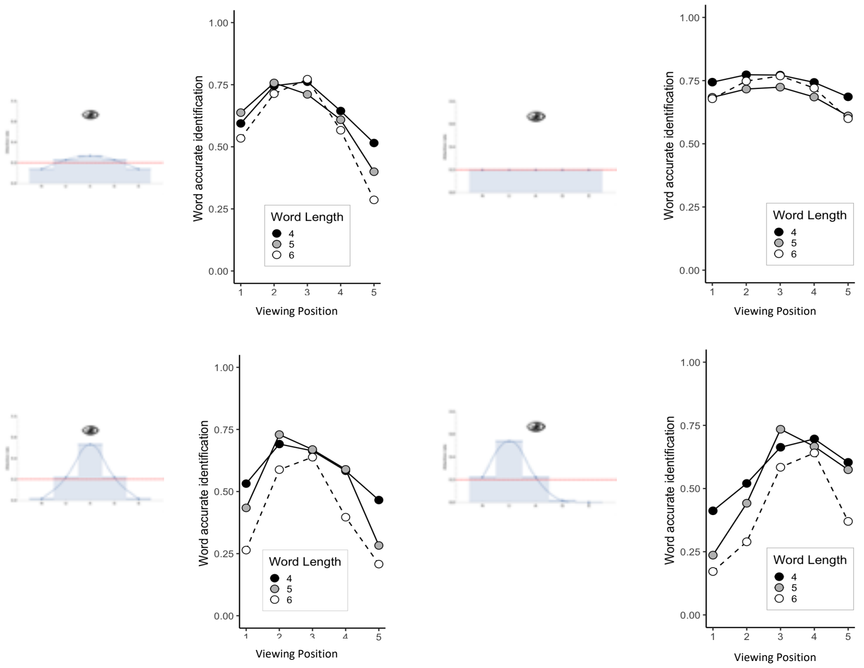

Figure 3: Simulated OVP curves for 4-, 5- and 6-letter words depending on variations of attention distribution and for the two positions of the focus of attention, centered or leftward shifted with respect to gaze position. Top, left (Simulation 1): default Gaussian distribution ($\sigma_A = 1.75$); focus of attention (μ_A) and gaze position (g) are aligned (i.e., $\mu_A = g$). Top-right (Simulation 2): diffused attention distribution ($\sigma_A = 100.00$). Bottom, left (Simulation 3): narrow distribution of attention ($\sigma_A = 0.75$), $\mu_A = g$. Bottom, right (Simulation 4): narrow distribution of attention ($\sigma_A = 0.75$), $\mu_A = g-1$ so that the focus of attention is shifted one position to the left of gaze position.

3.2.1. Simulation 1: Typical visual attention distribution

Results, presented on Figure 3 (Top, left), show the curves generated by the model using the default Gaussian distribution of visual attention ($\sigma_A = 1.75$). The curves were obtained after 340 iterations, corresponding to a maximal word identification rate of 77.2%. Results showed no significant main effect of word length [$F(2, 72) < 1$, *ns*] but a significant viewing position effect [$F(4, 288) = 58.41$, $p < .001$, $\eta^2 = 0.448$] and a significant length-by-viewing-position interaction [$F(8,288) = 2{,}73$, $p < .01$, $\eta^2 = 0.07$] on word identification. The VP curves (see Figure 3; top-left graph) were characterized by an OVP located near the word center or slightly left, as typically reported in normal readers. More precisely, word recognition rate was similar in position 2 as in position 3 [$t_{(74)} = -0.535$, ns], and the words were better recognized in these positions than in Position 1 (for P1 vs. P2: [$t_{(74)} = -9.95$, $p < .001$, $\eta^2 = 0.08$]; for P1 vs. P3 : [$t_{(74)} = -6.05$, $p<.001$, $\eta^2 = 0.09$]) or Position 4 (for P2 vs. P4 : [$t_{(74)} = 5.54$, $p<.001$, $\eta^2 = 0.06$]; for P3 vs. P4: [$t_{(74)} = 7.70$, $p < .001$, $\eta^2 = 0.075$]) or Position 5 (for P2 vs. P5 : [$t_{(74)} = 10.21$, $p<.001$, $\eta^2 = 0.31$]; for P3 vs. P5: [$t_{(74)} = 10.99$, $p < .001$, $\eta^2 = 0.33$]). The curves were further characterized by a left-right asymmetry, with better word recognition when fixation was located on the initial (P1-P2) than final (P4-P5) viewing positions [$t_{(74)} = 5.76$, $p < .0001$, $d = 0.65$]. Thus, results of Simulation 1 provide clear evidence that the OVP curves that were generated by the model on the set of words we used in the current study are similar to those reported by Aghababian & Nazir (2000) for typical readers on a comparable set of words. This finding suggests that the atypical performance observed in our dyslexic participants would unlikely result from particularities of the experimental words' lexical properties.

3.2.2. Simulation 2: Diffuse distribution of attention

The graph, on Figure 3 (top, right), shows the curves generated by the model using a diffuse distribution of visual attention ($\sigma_A = 100.00$). The curves were obtained after 320 iterations, corresponding to a maximal word identification rate of 77.3%. Results showed no significant main effect of word length [$F(2, 72) < 1$, *ns*] but a significant viewing position effect [$F(4, 288) = 70.25$, $p < .001$, $\eta^2 = 0.49$] and a significant length-by-viewing-position interaction [$F(8,288) = 3.14$, $p < .005$, $\eta^2 = 0.08$] on word identification. The OVP remained centered on the word letter-string or slightly left. Word recognition was similar in Position 2 as in Position 3 [$t_{(74)} = -2.03$, p>.05], but higher in these positions than in Position 1 (for P1 vs. P2: [$t_{(74)} = -8.73$, $p < .001$, $\eta^2 = 0.01$]; for P1 vs. P3 : [$t_{(74)} = -6.11$, $p<.001$, $\eta^2 = 0.01$]) or Position 4 (for P2 vs. P4 : [$t_{(74)} = 3.96$, $p<.001$, $\eta^2 = 0.004$]; for P3 vs. P4: [$t_{(74)} = 8.35$, $p < .001$, $\eta^2 = 0.007$]) or Position 5 (for P2 vs. P5 : [$t_{(74)} = 10.15$, $p<.001$, $\eta^2 = 0.05$]; for P3 vs. P5: [$t_{(74)} = 12.11$, $p < .001$, $\eta^2 = 0.06$]). The expected left-right asymmetry was found [$t_{(74)} = 5.28$, $p<.0001$, $d=0.20$] but the viewing position curves were characterized by a lesser left-right asymmetry in the diffuse than in the normal attention distribution condition [mean left-right difference = 0.07 vs. 0.19 respectively; t(74) =3.72, p<.001, d=0.5].

3.2.3. Simulation 3: Narrow visual attention distribution

The OVP curves generated in conditions of visual attention narrowing ($\sigma_A = 0.75$) are presented on Figure 3 (bottom, left graph). The OVP curves were obtained after 1,000 iterations for a maximal word recognition rate of 72.9%. Narrowing the attention distribution slowed down letter and word recognition, so that many more iterations were required to reach a maximal word identification rate similar to that of the default control condition, or to that of the participants. There were significant main effects of word length [$F(4, 72) = 13.44$, $p < .001$, $\eta^2 = 0.27$] and viewing position [$F(4, 288) = 46.97$, $p < .001$, $\eta^2 = 0.39$], together with a significant interaction between the two factors [$F(8, 288) = 2.64$, $p < .01$, $\eta^2 = 0.07$]. Visual attention narrowing affected the curve shapes, despite an OVP located on the word center or slightly left, as in the previous conditions. The expected left-right asymmetry was obtained, with higher word recognition when fixating the beginning of words [$t_{(74)} = 4.05$, $p < .001$, $d = 0.644$]. All lengths combined, asymmetry was weaker than in the default (normal) condition [mean left-right difference = 0.09 vs. 0.19 for narrow and normal attention distribution respectively; t(74) =2.53, p<.05, d=0.33]. Word recognition was drastically impaired when fixating on the first letter as compared to the central letters [mean P2-P1 difference = 0.26 vs 0.15 for narrow and normal attention distribution respectively, t(74) =-3.39, p<.005, d=0.54] but remained equivalent when fixating on the last position compared to the central letter [mean P3-P5 difference = 0.35 vs 0.34 for narrow and normal attention distribution respectively, t(74)<1, ns] . While the curve shapes for 4-and 5-letter words remained similar in the conditions with narrow as with normal attention distribution, the narrow condition alone generated an inverted V-shaped function for the longer 6-letter words [for 6-letter words: mean P1 = 0.26, mean P5 = 0.21, t(24)=-1.57, p=0.13].

3.2.4. Simulation 4: Narrow visual attention distribution plus attention shifting

None of the previous variations in attention distribution allowed replicating the rightward-biased OVP effect behaviorally reported in the dyslexic participants. Our purpose in Simulation 4 was to identify the visual attention parameters that better fitted the reported OVP curves. The rationale was to keep the distribution of attention narrowed since a reduction in the number of letters that could be simultaneously processed was highlighted in the dyslexic population, but this narrow distribution was further combined with a shift of the focus of attention toward the left visual field. The OVP curves, reported for Simulation 4 in Figure 3 (bottom, right graph), were obtained following both visual attention narrowing ($\sigma_A = 0.75$), as in Simulation 3, and visual attention shifting to the left of fixation (one letter left). A maximal word recognition rate of 73.4% was obtained at the OVP after 1000 iterations. Results showed significant effects of word length [$F(4, 72) = 11.97$, $p < .001$, $\eta^2 = 0.25$] and viewing position [$F(4, 288) = 58.83$, $p < .001$, $\eta^2 = 0.45$] together with a significant interaction [$F(8, 288) = 2.54$, $p < .05$, $\eta^2 = 0.07$]. Reverted J-shaped viewing position curves were generated, showing an OVP located near the word center or slightly right. Maximal recognition was obtained in Positions 3 and 4, with a similar level of performance in the two locations [$t_{(74)} = -0.28$, p>.05] and higher performance than in all the other viewing positions (all $ps < .01$). Although the left-right asymmetry (P1-P2 vs. P4-P5) was not significant [$t_{(74)} = -1.15$, $p > .05$, d=.135], the computed curves were characterized by a lower word recognition rate in Position 1 than in the other positions (P1 vs. P2 [$t_{(23)} = -8.142$, $p < .001$, $\eta^2 = 0.11$], P1 vs. P3 [$t_{(23)} = -12.89$, $p < .0001$, $\eta^2 = 0.47$], P1 vs. P4 [$t_{(23)} = -11.96$, $p < .0001$, $\eta^2 = 0.447$] and P1 vs. P5 [$t_{(23)} = -7.00$, $p < .0001$, $\eta^2 = 0.26$]), thus mimicking the rightward asymmetry reported for the behavioral data.

An additional control simulation was performed in condition of leftward shifting of attention but typical attention distribution ($\sigma_A = 1.75$). The resulting curves showed an OVP at the word center or slightly right [mean P2= 0.63, mean P3= 0.75, mean P4= 0.72, mean P5= 0.54; P2-P3 comparison: t(74)= -8.38, p < .0001, η^2= 0.056 ; P3-P4 comparison: t(74)= 1.92, p= 0.59; P4-P5 comparison: t(74)= 9.24, p < .0001, η^2= 0.12]. However, in contrast to the experimental data, the decline of word recognition when deviating from the OVP was symmetrical [mean P1= 0.49, mean P5= 0.54, t(74)= -1.38, p=1.0] (Figure available in Supplementary Materials). This suggests that the combination of narrow visual attention distribution and leftward attention shifting is required to fit the behavioral data.

4. Discussion

While the OVP effect is well-documented in expert readers, relatively few results have been reported for dyslexic children (Bellocchi & Ducrot, 2021; Ducrot et al., 2003, 2013; Dubois et al., 2007). A first main contribution of the present paper was to report new behavioral data on the OVP effect in developmental dyslexia. Dyslexic children showed atypical viewing position curves, characterized by an OVP slightly right of the word center with better recognition when words were fixated on the right half. The viewing position curves of our dyslexic participants are thus the left-right mirror image of the inverted J-shaped curves typically reported in both proficient and beginning readers (Clarck & O'Regan, 1999; Ducrot et al., 2013; Nazir, 1991; Nazir et al., 1992; Stevens & Grainger, 2003). They also differ from the curve shapes reported for typical readers on the same experimental task by Aghababian & Nazir (2000). In normally developing children, inverted J-shaped curves have consistently been reported from the first grade (Aghababian & Nazir, 2000; Bellochi & Ducrot, 2021; Ducrot et al., 2003), suggesting that word recognition was deviant in our dyslexic population and that the observed atypical VP curves would unlikely result from their poor reading level. The observed pattern is further unlike that previously reported by Dubois et al. (2007) in their dyslexic participant or by Aghababian & Nazir (2000) in poor readers. An inverted V-shaped curve characterized the performance of their participants instead of the inverted J-shaped curves reported in the present study.

To our knowledge, there is no report of a similar pattern in children with reading impairment but evidence from the OVP task in dyslexic children was scarce, in particular when limiting comparison to the studies that used highly restricted exposure duration to prevent eye movements (Aghababian & Nazir, 2000; Dubois et al., 2007). However, a similar rightward atypical asymmetry of the viewing position curves was previously reported in a brain-damaged patient with pure alexia (Montant, Nazir and Poncet, 1998; see also Stevens & Grainger, 2003, for better within-string letter visibility in adult poor readers when fixating the right of center). Interestingly, this patient was further described as exhibiting a deficit in decoding arrays of letters in a parallel manner, which mirrors the multi-element simultaneous processing deficit (i.e., the visual attention span deficit) highlighted in our population of dyslexic children. The current findings, together with this brain-damaged case report, suggest that viewing position curves defined by an atypical rightward fixation advantage would characterize the performance of dyslexic individuals with a visual attention deficit when engaged in the OVP paradigm. Note that although there is a consensus for atypical VP curves in dyslexic individuals, the shape of these curves has been shown to vary, since different inverted V-shaped curves (Dubois et al., 2007) or inverted J-shaped curves (Montant et al., 1998; and the present findings) have been reported while using similar paradigms that forced parallel processing.

Our second main contribution was to use the computational BRAID model of word recognition as an experimental substitute to investigate the relationship between visual attention and word recognition performance, as a function of the location of fixation within the letter string. A main prediction of the model is that variations in the distribution of visual attention would modulate the viewing position curve shapes. Simulations showed that a Gaussian distribution of attention, assumed to simulate typical visual attentional processing, yields the inverted J-shaped VP curves reported in typical readers across age. A more diffuse distribution, allocating a similar amount of visual attention to each letter within the word, yields relatively flat and symmetrical curves that do not correspond to the curve shapes behaviorally reported in our dyslexic participants. It is worth noting that flatter and more symmetrical curve shapes than typically found in normal readers have sometimes been reported in dyslexic individuals. This pattern was observed when exposure duration in OVP tasks was not restricted enough to prevent eye movements (Bellocchi & Ducrot, 2021; Ducrot et al., 2003). In these lax conditions of exposure duration, the positions of the focus of attention might be shifted and located on different word letters across trials and across participants. Such shifting would on average amount to spreading attention more uniformly over letter positions, thus resulting in a pattern close to the one simulated under condition of diffuse visual attention distribution. Last, a peaked distribution allocating attention to only a few letters yields inverted V-shaped curves for the longer words without significantly affecting curve shapes for the shorter ones, as previously reported in dyslexic and poor readers in strict conditions of exposure duration (Aghababian & Nazir, 2000; Dubois et al., 2007).

The impact of visual attention on word recognition in the model is due to the fact that the identification of letters is facilitated when they receive more attention. When the distribution is Gaussian, identification of the left-most letters, that are also the most informative, is facilitated in the condition of initial letter fixation where these letters benefit from more attention (and more acuity). In contrast, identification is degraded when fixation is at the end of words where the enhanced letters are less critical for word recognition. This yields the left-right asymmetry typically reported in OVP paradigms. In condition of diffuse attention distribution, the more eccentric letters receive more attention than in the condition with default parameters, which counterbalances the acuity drop-off with eccentricity, thus reducing the left-right asymmetry without affecting word recognition speed. In the condition of narrow distribution of attention, virtually a single letter (under the focus of attention, see Figure 3, bottom left) receives enough attention to enhance its identification. Word identification is then drastically slowed – three times as many iterations are then required to achieve the same level of performance –, even for shorter words. For longer words, fixating on the initial or final letter yields poor identification of most of the word letters that suffer from severe attention and acuity drop-offs. Then, only fixation at the center of the letter-string allows extracting enough information on letter identity to enable word recognition, leading to inverted-V-shaped viewing position curves.

Besides, the model predicts that a deficit in multi-letter simultaneous processing due to reduced visual attention capacity would affect processing time and result in a word length effect. This prediction is consistent with the reported privileged link between visual attention span and reading fluency (Bosse & Valdois, 2009; Chan & Yeung, 2020; Huang, Lorusso, Luo & Zhao, 2019; Lobier et al., 2013; Valdois et al., 2019, 2021) or the word length effect (van den Boer et al., 2013; see Ginestet et al., 2019 for word length effect modeling within the BRAID framework) in typical readers. It further matches with behavioral evidence for impaired reading speed and/or stronger word length effects in dyslexic individuals with a visual attention span deficit (Bosse et al. 2007; Chen, Zheng & Ho, 2019; Valdois et al., 2003, 2011, 2020; Zoubrinetzky et al., 2014).

Overall, the model predicts that a narrow attention distribution would result in atypical inverted V-shaped curves in dyslexic individuals with a visual attention span reduction. On the one hand, this prediction matches with the inverted V-shaped curve reported by Dubois et al. (2007) in their dyslexic participant. On the other hand, our dyslexic participants and the case of pure alexia reported by Montant et al. (1998) did not show inverted V-shaped viewing position curves despite exhibiting a multi-letter parallel processing deficit. Results of the last simulation in which both attention distribution and the focus of attention were manipulated may help understand these apparently discrepant results. This last simulation revealed that reverted J-shaped curves and a rightward OVP were obtained when combining both a narrow visual attention distribution and a shifting of attention toward the left visual field. This leads to reformulating the previous prediction. A narrow visual attention distribution should yield atypical viewing position curves but the shape of the curves might vary depending on whether the focus of attention is aligned with, or decorrelated from, gaze position.

Most surprising however is the prediction of a leftward shifting of attention since previous studies have mainly reported an excessive spatial attentional bias towards the right (not the left) visual field in developmental dyslexia (Facoetti et al., 2010; Facoetti & Molteni, 2001; Geiger et al., 1992; Hari et al., 2001; Ruffino et al., 2014; Sireteanu et al., 2005). It is worth noting that this atypical rightward bias of attention was reported in experimental conditions that differed from the present one, as they mainly required the processing of a non-verbal stimulus that was randomly displayed in either the left or right visual field. Actually, it is well admitted that the deployment of attention varies depending on task constraints and task instructions (Mozer & Behrmann, 1990; Nazir et al., 2004; Stenneken, van Eimeren, Keller, Jacobs & Kerkhoff, 2008; Stevens & Grainger, 2003). The case study of a dyslexic child with a visual attention span deficit revealed better report of letters at the right of fixation when the task did not constrain the order of naming but better report of the leftmost letters in more reading-like conditions (Valdois et al., 2011). Furthermore, the leftmost advantage in the latter condition was reversed when instruction explicitly required reporting first the best identified letters, suggesting that more reading-like conditions may implicitly favor leftward attention shifting, at least in languages characterized by a left-right scanning. It thus appears that the left-right asymmetry depends on the way attention is deployed across the visual fields which itself is tuned to the task (and language) demand. A severe reduction of attention distribution in our dyslexic participants might well induce the predicted leftward shifting of attention in the OVP paradigm. Assuming that the initial word letters are more informative for word recognition and that reduced attention distribution allows only one or a very few letters at, or around fixation to be identified, most fixation conditions in the OVP paradigm would prevent normal processing of the word initial letters. Under conditions of limited visual attention span, shifting attention toward the left of fixation prior to word onset might be a reasonable strategy to try to compensate the deficit and optimize word recognition. Not only would identification of the letter at (or around) fixation improve due to maximal acuity but identification of the letter left-of-fixation would further be enhanced due to maximal attention. Thus, dissociating the attentional focus from gaze position might lead to superior word recognition performance than pooling visual and attentional resources in the same position, at least as far as fixation position is located rightward enough to place a higher number of letters in the left visual field. The hypothesis of a left-side attentional bias is consistent with evidence that typical readers orient their attention toward the left of fixation when processing unfamiliar strings and that reduced attentional windows, when used for pseudo-word processing, induce a left-side over right-side advantage (Leclercq & Siéroff, 2016).

A last, but nonetheless significant, contribution of the current paper is to show how computational models of word recognition can provide new insights regarding the underlying mechanisms involved in the OVP task and how different VP curves can be obtained depending on visual attention distribution. The simulated findings suggest that attentional factors contribute to the location of the OVP and the shape of the viewing position curves. The narrowing of visual attention distribution is predicted to result in the atypical inverted V-shaped VP curves sometimes reported for dyslexic individuals in the OVP paradigm. However, different curve shapes are expected when participants adopt task-specific visuo-spatial attentional strategies that aim to optimize processing under conditions of reduced visual attention span. Many studies have manipulated the distribution of attention during visual processing and reading, showing an impact of attention distribution on performance (Auclair & Siéroff, 2002; Leclercq & Siéroff, 2016) while others have shown adjustment of visual attention distribution to the task constraints (Danna, Massendari, Furnari & Ducrot, 2018; Stenneken et al., 2008). More systematic exploration of the effect of spatial attention distribution manipulation on word recognition in the OVP paradigm might help achieve a better understanding of these complex interactions and contribute to a more systematic evaluation of the BRAID model predictions.

5. Acknowledgements

This work was supported by the "Fondation de France" (Ph.D. grant to T.P.) and the "Caisse des Dépôts et Consignations" (e-Fran FLUENCE project Grant to S.V.). We thank all the speech therapists who helped us for the recruitment of the dyslexic participants. Many thanks to the children and their parents for their participation. We also thank two experts during the review process for their helpful comments and Brenda Rapp for her suggestion of the interpretation of the leftward dissociation of attention focus as a strategy to cope with the limitation of a narrow attention distribution.

6. References

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. https://doi.org/10.1006/jecp.1999.2540

Auclair, L., & Siéroff, E. (2002). Attentional cueing effect in the identification of words and pseudowords of different length. *The Quarterly Journal of Experimental Psychology*, 55, 445–463. doi:10.1080/02724980143000415

Bellochi, S. & Ducrot, S. (2021). « Same, same but different: The optimal viewing position effect in developmental dyslexia, developmental coordination disorders and comorbid disorders. *Dyslexia*. doi: 10.1002/dys.1688

Bellochi, S., Muneaux, M., Bastien-Toniazzo, M. & Ducrot, S. (2013). I can read it in your eyes: What eye movements tell us about visuo-attentional processes in developmental dyslexia. *Research in developmental disabilities*, 34, 1, 452-460. https://doi.org/10.1016/j.ridd.2012.09.002

Bernard, J. B., & Castet, E. (2019). The optimal use of non-optimal letter information in foveal and parafoveal word recognition. *Vision Research*, *155*(5241), 44–61. https://doi.org/10.1016/j.visres.2018.12.006

Besner, D., Risko, E. F., Stolz, J. A., White, D., Reynolds, M., O'Malley, S., & Robidoux, S. (2016). Varieties of attention: Their roles in visual word identification. *Current Directions in Psychological Science*, 25(3), 162–168. https://doi.org/10.1177/0963721416639351

Bogon, J., Finke, K., & Stenneken, P. (2014). TVA-based assessment of visual attentional functions in developmental dyslexia. *Frontiers in Psychology*, *5*, 1172. https://doi.org/10.3389/fpsyg.2014.01172

Bosse, M.-L., Tainturier, M. J., & Valdois, S. (2007). Developmental dyslexia: The visual attention span deficit hypothesis. *Cognition*, *104*(2), 198–230. https://doi.org/10.1016/j.cognition.2006.05.009

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. https://doi.org/10.1111/j.1467-9817.2008.01387.x

Bouma, H. (1970). Interaction effects in parafoveal letter recognition. *Nature*, *226*(5241), 177–178. https://doi.org/10.1038/226177a0

Brysbaert, M., & Nazir, T. (2005). Visual constraints in written word recognition: Evidence from the optimal viewing position. *Journal of Research in Reading*, *28*(3), 216–228. https://doi.org/10.1111/j.1467-9817.2005.00266.x

Chan, K.S.C. & Yeung, P.S. (2020). Prediction of Chinese reading fluency by verbal and non-verbal visual attention span measures. *Frontiers, in Psychology*, 10:3049. doi: 10.3389/fpsyg.2019.03049

Chen, N.T., Zheng, M & Ho, C. S-H. (2019). Examining the visual attention span deficit hypothesis in Chinese developmental dyslexia. *Reading and Writing*, 32, 639-662. https://doi.org/10.1007/s11145-018-9882-1

Clark, J. J., & O'Regan, J. K. (1999). Word ambiguity and the optimal viewing position in reading. *Vision Research*, *39*(4), 843– 857. https://doi.org/10.1016/S0042-6989(98)00203-X

Danna, J., Massendari, D., Furnari, B. & Ducrot, S. (2018). The optimal viewing position effect in printed versus cursive words: Evidence of a reading cost for cursive font. *Acta Psychologica*, 188, 110-121. https://doi.org/10.1016/j.actpsy.2018.06.003

Deutsch, A., & Rayner, K. (1999). Initial fixation location effects in reading Hebrew words. *Language & Cognitive Processes*, *14*, 393–421. https://doi.org/10.1080/016909699386284

Dubois, M., Kyllingsbaek, S., Prado, C., Musca, S.C., Peiffer, E., et al. (2010). Fractionating the multi-character processing deficit in developmental dyslexia: Evidence from two case studies. *Cortex*, 46, 717–738. doi:10.1016/j.cor- tex.2009.11.002.

Dubois, M., Lafaye de Micheaux, P., Noël, M.-P., & Valdois, S. (2007). Preorthographical constraints on visual word recognition: Evidence from a case study of developmental surface dyslexia. *Cognitive Neuropsychology*, *24*(6), 623–660. https://doi.org/10.1080/02643290701617330

Ducrot, S. & Grainger, J. (2007). Deployment of spatial attention to words in central and peripheral vision. *Perception and Psychophy*sics, 69, 4, 578-590. https://doi.org/10.3758/BF03193915

Ducrot, S., Lété, B., Sprenger-Charolles, L., Pynte, J., & Billard, C. (2003). The optimal viewing position effect in beginning and dyslexic readers. *Current Psychology Letters*, *1*(10). https://doi.org/10.4000/cpl.99

Ducrot, S., Pynte, J., Ghio, A., & Lété, B. (2013). Visual and linguistic determinants of the Eyes' initial fixation position in reading development. Acta Psychologica, 142, 287–298. http://dx.doi.org/10.1016/j.actpsy.2013.01.013

Facoetti, A., Paganoni, P., Turatto, M. Marzola, V. & Mascetti, G.G. (2000). Visual-spatial attention in developmental dyslexia. *Cortex*, 36, 109-123. https://doi.org/10.1016/S0010-9452(08)70840-2

Facoetti, A., & Molteni, M. (2001). The gradient of visual attention in developmental dyslexia. *Neuropsychologia*, *39*, 352–357. https://doi.org/10.1016/S0028-3932(00)00138-X

Facoetti, A., Trussardi, A. N., Ruffino, M. & Lorusso, M.-L. (2010). Multisensory spatial attention deficits are predictive of phonological decoding skills in developmental dyslexia. *Journal of Cognitive Neuroscience*, *22*(5), 1011–1025. https://doi.org/10.1162/jocn.2009.21232

Facoetti, A., Zorzi, M., Cestnick, L., Lorusso, M.-L., Molteni, M., Paganoni, P., Umilta, C. & Mascetti, G. G. (2006). The relationship between visuo-spatial attention and nonword reading in developmental dyslexia. *Cognitive Neuropsychology*, *23*(6), 841–855. https://doi.org/10.1080/02643290500483090

Farid, M., & Grainger, J. (1996). How initial fixation position influences visual word recognition: A comparison of French and Arabic. *Brain and Language*, *53*, 351–368. https://doi.org/10.1006/brln.1996.0053

Ferrand, L., New, B., Brysbaert, M., Keuleers, E., Bonin, P., Méot, A., Augustinova, M. & Pallier, C. (2010). The French Lexicon Project: Lexical decision data for 38,840 French words and 38,840 pseudowords. *Behavior Research Methods*, 42(2), 488–496. doi:10.3758/BRM.42.2.488

Frey, A., & Bosse, M.-L. (2018). Perceptual span, visual span, and visual attention span: Three potential ways to quantify limits on visual processing during reading. *Visual Cognition*. https://doi.org/10.1080/13506285.2018.1472163.

Geiger, G., Jerome, Y., & Zegarra-Moran, O. (1992). Task-determined strategies of visual process. *Cognitive Brain Research*, *1*(1), 39–52. https://doi.org/10.1016/0926-6410(92)90004-B

Ginestet, E., Phénix, T., Diard, J., & Valdois, S. (2019). Modelling length effect for words in lexical decision: The role of visual attention. *Vision Research*, 159, 10-20. https://doi.org/10.1016/j.visres.2019.03.003

Hari, R., Renvall, H. & Tanskanen, T. (2001). Left Mini-neglect in dyslexic adults. *Brain*, 124, 7, 1373-1380. https://doi.org/10.1093/brain/124.7.1373

Henderson, J.M. & Ferreira, F. (1990). Effects of foveal processing difficulty on the perceptual span in reading: Implications for attention and eye movement control. *Journal of Experimental Psychology: Learning, Memory and Cognition*, 16, 3, 417-429. https://doi.org/10.1037/0278-7393.16.3.417

Huang, C., Lorusso, M.L., Luo, Z. & Zhao, J. (2019). Developmental differences in the relationship between visual attention span and Chinese reading fluency, Frontiers in Psychology, 10:2450. doi: 10.3389/fpsyg.2019.02450

Hyönä, J., & Bertram, R. (2011). Optimal viewing position effects in reading Finnish. *Vision Research*, *51*(11), 1279–1287. https://doi.org/10.1016/j.visres.2011.04.004

Jacquier-Roux, J., Valdois, S., & Zorman, M. (2010). *BALE: Batterie Analytique du Langage Ecrit.* Laboratoire Cogni-Sciences, Grenoble. Retrieved from http://www.cognisciences.com/ accueil/outils/article/bale

Kajii, N., & Osaka, N. (2000). Optimal viewing position in vertically and horizontally presented Japanese words. *Perception* & *Psychophysics*, *62*, 1634–1644. https://doi.org/10.3758/BF03212161

Leclercq, V. & Siéroff, E. (2016). Attentional processing of letter strings by children. *Child Neuropsychology*, 22, 1, 110-132. http://dx.doi.org/10.1080/09297049.2014.977242

Lefavrais, P. (1967). Test de l'alouette. Paris, France : Éditions du centre de psychologie appliquée.

Lachter, J., Forster, K. I., & Ruthruff, E. (2004). Forty-five years after Broadbent (1958): Still no identification without attention*. Psychological Review*, 111, 880–913. https://doi.org/10.1037/0033-295X.111.4.880

Lallier, M. & Valdois, S. (2012). Sequential versus simultaneous processing deficits in developmental dyslexia. In T.N. Wydell & Fern-Pollack, L. (Eds.), *Dyslexia: A comprehensive and International approach* (pp. 73-108). INTECH open Science.

Lété, B., Sprenger-Charolles, L., & Colé, P. (2004). Manulex: A grade-level lexical database from French elementary-school readers. *Behavior Research Methods, Instruments, and Computers*, *36*, 156–166. https://doi.org/10.3758/BF03195560

Lindell, A.K. & Nicholls, M.E.R. (2003). Attentional deployment in visual half field tasks: The effect of cue position on word naming latency. *Brain & Cognition*, 53, 273-277. https://doi.org/10.1016/S0278-2626(03)00125-8

Liu, P., & Li, X. (2013). Optimal viewing position effects in the processing of isolated Chinese words. *Vision Research*, *81*, 47– 57. http://dx.doi.org/10.1016/j.visres.2013.02.004

Lobier, M., Dubois, M., & Valdois, S. (2013). The role of visual processing speed in reading speed development. *PLoS ONE*, *8*(4), e58097. https://doi.org/10.1371/ journal.pone.0058097

McConkie, G. W., Kerr, P. W., Reddix, M. D., Zola, D., & Jacobs, A. M. (1989). Eye movement control during reading: II. Frequency of refixating a word. *Perception & Psychophysics*, *46*(3), 245–253. https://doi.org/10.3758/BF03208086

Montant, M., Nazir, T. A., & Poncet, M. (1998). Pure alexia and the viewing position effect in printed words. *Cognitive neuropsychology*, *15*(1-2), 93–140. https://doi.org/10.1080/026432998381230

Mozer, M.C. & Behrmann, M. (1990). On the interaction of selective attention and lexical knowledge: A connectionist account of neglect dyslexia. *Journal of Cognitive Neuroscience*, 2, 2, 96-123. https://doi.org/10.1162/jocn.1990.2.2.96

Nazir, T. A. (1991). On the role of refixations in letter strings: The influence of oculomotor factors. *Perception & Psychophysics*, *49*(4), 373–389. https://doi.org/10.3758/BF03205995

Nazir, T. A., Ben-Boutayab, N., Decoppet, N., Deutsch, A., & Frost, R. (2004). Reading habits, perceptual learning, and recognition of printed words. *Brain and Language*, *88*(3), 294–311. https://doi.org/10.1016/S0093-934X(03)00168-8

Nazir, T. A., Heller, D., & Sussmann, C. (1992). Letter visibility and word recognition: The optimal viewing position in printed words. *Attention, Perception, & Psychophysics*, *52*(3), 315–328. https://doi.org/10.3758/BF03209148

Nazir, T. A., Jacobs, A. M., & O'Regan, J. K. (1998). Letter legibility and visual word recognition. *Memory and Cognition*, *26*(4), 810–821. https://doi.org/10.3758/BF03211400

Nazir, T. A., O'Regan, J. K., & Jacobs, A. M. (1991). On words and their letters. *Bulletin of the Psychonomic Society*, 29, 2, 171-174. https://doi.org/10.3758/BF03335227

O'Regan, J. K., & Jacobs, A. M. (1992). Optimal viewing position effect in word recognition: A challenge to current theories. *Journal of Experimental Psychology: Human Perception and Performance*, *18*(1), 185–197. https://doi.org/10.1037/0096-1523.18.1.185

O'Regan, J. K., & Lévy-Schoen, A. (1987). Eye-movement strategy and tactics in word recognition and reading. In M. Coltheart (Ed.), *Attention and performance xii: The psychology of reading* (pp. 363–383). L. Erlbaum Associates.

O'Regan, J. K., Lévy-Schoen, A., Pynte, J., & Brugaillère, B. (1984). Convenient fixation location within isolated words of different length and structure. *Journal of Experimental Psychology: Human Perception and Performance*, *10*(2), 250–257. https://doi.org/10.1037/0096-1523.10.2.250

Pelli, D. G., Palomares, M., & Majaj, N. J. (2004). Crowding is unlike ordinary masking: Distinguishing feature integration from detection. *Journal of Vision*, *4*, 1136–1169. https://doi.org/10.1167/4.12.12

Pelli, D. G., & Tillman, K. A. (2008). The uncrowded window of object recognition. *Nature Neuroscience*, *11*(10), 1129–1135. https://doi.org/10.1038/nn.2187

Pelli, D. G., Tillman, K. A., Freeman, J., Su, M., Berger, T. D., & Majaj, N. J. (2007). Crowding and eccentricity determine reading rate. *Journal of Vision*, *7*(2), 20, 1–36. https://doi.org/10.1167/0.0.1

Phénix, T., Ginestet, E., Valdois, S. & Diard, J. (submitted). Visual attention matters during word recognition: A Bayesian modeling approach.

Posner, M.I. (2016). Orienting of attention: Then and now. *The Quarterly Journal of Experimental Psychology*, 69, 10, 1864-1875. http://dx.doi.org/10.1080/17470218.2014.937446

Pothier, B., & Pothier, P. (2003). EOLE: Échelle d'acquisition en orthographe lexicale. Paris, France: Éditions RETZ.

Rayner, K. (1998). Eye movements in reading and information processing: 20 years of research. *Psychological Bulletin*, 124, 3, 372-422. https://doi.org/10.1037/0033-2909.124.3.372

Rayner, K., Slattery, T.J. & Bélanger, N.N. (2010). Eye movements, the perceptual span and reading speed. *Psychonomic Bulletin & Review*, 17, 6, 834-839. https://doi.org/10.3758/PBR.17.6.834

Risko, E. F., Stolz, J. A., & Besner, D. (2010). Spatial attention modulates feature crosstalk in visual word processing. *Attention, Perception and Psychophysics*, 72(4), 989–998. https://doi.org/10.3758/APP.72.4.989.

Ruffino, M., Gori, S., Boccardi, D., Molteni, M. & Facoetti, A. (2014). Spatial and temporal attention in developmental dyslexia. *Frontiers in Human Neuroscience*, 8, 331. https://doi.org/10.3389/fnhum.2014.00331

Saghiran, A., Valdois, S. & Diard, J. (2020). Simulating length and frequency effects across multiple tasks with the Bayesian BRAID-Phon model. In S. Denison, M. Mack., Y. Xu, and B.C. Armstrong (Eds.), *Proceedings of the 42nd Annual Conference of the Cognitive Science Society*. Cognitive Science Society.

Siéroff, E. & Riva, M. (2011). Attention and the identification of parafoveal words in school-age children and adults. *Journal of Neurolinguistics*, 24, 420-434. doi:10.1016/j.jneuroling.2011.01.003

Sireteanu, R., Goertz, R., Bachert, I., & Wandert, T. (2005). Children with developmental dyslexia show a left visual "minineglect". *Vision Research*, *45*(25-26), 3075–3082. https://doi.org/10.1016/j.visres.2005.07.030

Stenneken, P., van Eimeren, L., Keller, I., Jacobs, A.M. & Kerkhoff, G. (2008). Task-dependent modulation of neglect dyslexia? Novel evidence from the viewing position effect. *Brain Research*, 1189, 166-178. doi:10.1016/j.brainres.2007.10.069

Stevens, M., & Grainger, J. (2003). Letter visibility and the viewing position effect in visual word recognition. *Perception & Psychophysics*, *65*(1), 133–151. https://doi.org/10.3758/BF03194790

Valdois, S., Bidet-Ildei, C., Lassus-Sangosse, D., Reilhac, C., N'Guyen, M. A., Guinet, E., & Orliaguet, J.-P. (2011). A visual processing but no phonological disorder in a child with mixed dyslexia. Cortex, 47, 1197–1218. https://doi.org/10.1016/j.cortex.2011. 05.011.

Valdois, S., Bosse, M.-L., Ans, B., Carbonnel, S., Zorman, M., David, D., & Pellat, J. (2003). Phonological and visual processing deficits can dissociate in developmental dyslexia: Evidence from two case studies. *Reading and Writing: An Interdisciplinary Journal*, *16*, 541–572. https://doi.org/10.1023/A:1025501406971

Valdois, S., Guinet, E. & Embs, J.-L. (2014). EVADYS : logiciel d'évaluation de l'empan visuo-attentionnel. https://www.happyneuronpro.com/orthophonie/espace-evaluation/evadys/

Valdois, S., Lassus-Sangosse, D., Lallier, M. Moreaud, O. & Pisella, L. (2019). What bilateral damage of the superior parietal lobes tells us about visual attention disorders in developmental dyslexia? *Neuropsychologia*,130, 78-91. https://doi.org/10.1016/j.neuropsychologia.2018.08.001

Valdois, S., Reilhac, C., Ginestet, E. & Bosse, M.-L. (2021). Varieties of cognitive profiles in poor readers: Evidence for a visual-attention-span-impaired subtype. *Journal of Learning Disabilities*, 54, 3, 221-233. https://doi.org/10.1177/0022219420961332

Valdois, S., Roulin, J.-L. & Bosse, M.-L. (2019). Visual attention modulates reading acquisition. *Vision Research, 165*, 152-161. https://doi.org/10.1016/j.visres.2019.10.011

Vallat, R. (2018). Pingouin: statistics in Python. *The Journal of Open Source Software*, 3, 31, 1026. doi: 10.21105/joss.01026

Van den Boer, M., de Jong, P.F., 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. https://doi.org/10.1080/10888438.2012.683222

van der Linden, L., & Vitu, F. (2016). On the optimal viewing position for object processing. *Attention, Perception and Psychophysics*, *78*, 602–617. https://doi.org/10.3758/s13414-015-1025-z

Vidyasagar, T. R. et Pammer, K. (2010). Dyslexia: A deficit in visuo-spatial attention, not in phonological processing. *Trends in Cognitive Science, 14*(2), 57-63. https://doi.org/10.1016/j.tics.2009.12.003

Waechter, S., Besner, D. & Stolz, J.A. (2011). Basic processes in reading: Spatial attention as a necessary preliminary to orthographic and semantic processing. *Visual cognition*, 19, 2, 171-202. https://doi.org/10.1080/13506285.2010.517228

Whitney, D., & Levi, D. M. (2011). Visual crowding: A fundamental limit on conscious perception and object recognition. *Trends in Cognitive Sciences*, *15*(4), 160–168. https://doi.org/10.1016/j.tics.2011.02.005

Zhao, J., Liu, M., Liu, H. & Wang, C. (2018). Increased deficit of visual attention span with development in Chinese children with developmental dyslexia. *Scientific Reports*, 8:3153. doi:10.1038/s41598-018-21578-5

Zoubrinetzky, R., Bielle, F., & Valdois, S. (2014). New insights on developmental dyslexia subtypes: Heterogeneity of mixed reading profiles. *PLoS ONE*, *9*(6), e99337. https://doi.org/10.1371/journal.pone.0099337

7. Appendix

The experimental word list

Four-letter words: fois, yeux, pied, soir, gens, mois, dent, ours, pain, film, peau, dame, joie, lune, lait, prix, aile, dieu, note, face, robe, mort, port, bain, pont. *Five-letter words*: chien, monde, place, porte, train, table, sujet, conte, carte, image, oncle, repas, fruit, grand, glace, sable, bande, lapin, poule, corde, voile, boule, sport, froid, foule. *Six-letter words*: enfant, maison, cheval, parent, minute, nombre, voyage, course, argent, prince, diable, parole, droite, bouche, renard, marche, plante, gauche, navire, voleur, cahier, cirque, danger, nature, police.