



## Visual attention modulates reading acquisition

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### ABSTRACT

The processing of letters within strings is challenging for beginning readers. Letter identification is affected by visual similarity, loss of information with eccentricity and interference from nearby letters. In contrast, visual attention enhances letter identification. We here explored whether visual attention resources for multi-element processing, as measured through tasks of visual attention span prior to literacy instruction, predicted reading fluency performance one year later. One hundred and twenty-four mainstream children were assessed in kindergarten on their visual attention span abilities, phonological awareness, letter-name knowledge, early literacy knowledge, verbal short-term memory and non-verbal IQ. The participants' reading performance was measured at the end of grade 1 using tasks of irregular word, pseudo-word and text reading. Results from regression analyses showed that kindergarteners' VA span predicted reading fluency for text, irregular words and pseudo-words one year later, after controlling for age, non-verbal IQ, phonological skills, letter name knowledge and early literacy skills. Path analyses carried out to estimate the differential contribution of VA span to the different reading skills revealed a stronger contribution for pseudo-word reading than irregular word or text reading at the end of Grade 1. These results suggest that pre-reading visual attention resources contribute to later reading fluency, whatever the reading subskills and whatever the reading context (words in isolation or in sentences), with higher involvement to pseudo-word reading. We propose a new conceptual model of the role of visual attention in reading acquisition and argue that many aspects of the models are already supported by available findings.

### 1. Introduction

Reading is both a visual and a linguistic task. However, most studies on reading acquisition have focused on the linguistic dimensions of reading, emphasizing the importance of letter-sound mapping and prior phonological processing skills (Castles & Coltheart, 2004; Melby-Lervåg, Lyster & Hulme, 2012). Some studies have even suggested that learning to read is not a visual skill (Goswami, 2015) and that visual processing skills only have moderate impact on reading acquisition, if any (Share, 1999; Ziegler, Perry, & Zorzi, 2014). In the current paper, we will focus on the visual mechanisms that are involved in reading and how they can modulate reading acquisition. Our main hypothesis is that visual attention is critical for learning to read. We will argue that learning to read relies on the capacity to accurately identify the whole letters that form relevant orthographic units in the language under concern and that simultaneous letter identification within these units depends on the amount of visual attention resources available for processing.

In most languages, a written word is defined by the identity and

position of its constituent letters. Letters are the building blocks of words, so that single letter identification is a first step towards word processing. Some letters share many of their visual features (R and P for example), thus increasing the probability of misidentification and letter confusion (Pelli, Burns, Farell, & Moore-Page, 2006); some differ by visual properties that are not relevant for object identification. The visual system of pre-readers and illiterates is tuned to identify visual objects regardless of their orientation (Kolinsky & Fernandes, 2014). The identity of an animal, a person or an object is not affected by a left–right or up–down reversal. But this does not hold true for letters. Differences in left–right or up–down orientation define letters that differ in identity (e.g., b and d or u and n). Reading acquisition thus requires learning to discriminate letters of similar shapes but different orientations, which implies “unlearning” the general principle of mirror-invariance (Dehaene, Cohen, Morais & Kolinsky, 2015; Pegado et al., 2014). This is not straightforward. Some children show mirror-letter confusions at the beginning of literacy instruction (Dehaene et al., 2010) and dyslexic children tend to process symmetrical letters as identical (Lachman & Van Leeuwen, 2007). Reading acquisition thus

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relies on functional specialization of the visual system through implicit visual perceptual learning (Gilbert, Sigman, & Crist, 2001).

Reading involves visual specialization for accurate letter processing, but normal processing of isolated letters is not enough to guarantee efficient reading. Additional visual mechanisms are at play for the processing of letters within strings. The visibility of letters within words is modulated by both the acuity gradient and crowding (Bernard & Castet, 2019; Grainger, Dufau, & Ziegler, 2016). Acuity is maximal for the letter under fixation but the drop-off in visual acuity as a function of distance from fixation makes letter identification worse with eccentricity. Letter identification within strings is further limited by crowding, i.e., lateral interference due to nearby letters (Bouma, 1970; Whitney & Levi, 2011). Maximal interference is observed for letters surrounded by a letter on each side, so that the inner letters of a word are more difficult to identify than the outer letters (i.e., the first and last letters; Scaltritti & Balota, 2013; Tydgat & Grainger, 2009). Crowding affects visual feature integration. The features of both the target letter and nearby letters are combined, which may result in letter identity confusions and/or location errors (Pelli, Palomares, & Majaj, 2004; Whitney & Levi, 2011). Variations in crowding relates to variations in reading speed. Reading speed is limited by crowding in typical readers (Pelli, Tillman, Freeman, Su, Berger, & Majaj, 2007) and some dyslexic children –but not all (Ziegler, Pech-Georgel, Dufau, & Grainger, 2010)– show greater crowding than their peers, which affects their ability to recognize words faster (Bouma & Legein, 1977; Atkinson, 1993; Spinelli, De Luca, Judica, & Zoccolotti, 2002; Martelli, Di Filippo, Spinelli, & Zoccolotti, 2009; Callens, Whitney, Tops, & Brysbaert, 2013). Fortunately, the deleterious effects of crowding on letter processing within strings are attenuated when inter-letter spacing is increased, which results in improved reading speed (Spinelli et al., 2002; Martelli et al., 2009; Zorzi et al., 2012).

Thus, three factors – visual similarity between letters, the acuity gradient and crowding –contribute to degrade letter identification in typically formatted words. How can we accurately identify the letters that make words based on so degraded information on the input string?

Eye movement studies provide important insights on this issue. Eye movements in reading are characterized by a succession of fixations and saccades. Information about letter identity is acquired during fixations and the primary function of a saccade is to move the eyes towards another portion of the word or text for detailed letter processing (for a review, see Rayner, 2009). There is now a consensus that visual attention shifting precedes eye movement and that visual attention is required for word identification (Besner et al., 2016; Lachter, Forster & Ruthruff, 2004; Rayner & Reichle, 2010; Risko, Stolz, & Besner, 2010). Attention is allocated to one word (or a few short words, or a portion of a word) at a time; it acts as a filter that enhances letter identification under the attentional focus, thus limiting the detrimental effects of acuity and crowding (Carrasco, 2011; Strasburger, 2005; Yeshurun & Rashal, 2010). In compensating for acuity limitations and adjacent letter interference, visual attention allows accurate parallel processing of letter identities under the attentional focus (Bundesen, 1990; Carrasco, 2011). As a result, the number of letters that can be accurately processed in parallel within a letter string (i.e., a sublexical orthographic unit or a word) should vary depending on the amount of attention resources available for processing. Assuming that reading speed is higher when processing longer orthographic units – thus, more letters in parallel–, the amount of attention available for parallel processing should modulate how fast words (or more generally letter strings) can be processed.

The amount of visual attention available for the parallel processing of letters within strings can be estimated through the measure of visual attention (VA) span (Bogon, Finke & Stenken, 2014; Lobier, Dubois, & Valdois, 2013). More generally, this span corresponds to the number of distinct visual elements that can be processed simultaneously in a multi-element configuration (Bosse, Tainturier, & Valdois, 2007). The VA span differs from the perceptual span. Although the latter was also

defined as an attentional span of effective vision (Pollatsek, Bolozky, Well, & Rayner, 1981; Rayner, 2009), the two spans differ in their estimated size, symmetry around fixation and foveal/parafoveal limits (for a review, Frey & Bosse, 2018) but, more importantly, the VA span is assumed to be a purer measure of the visual attention mechanisms involved in reading. Indeed, the VA span –which is measured through tasks that require the processing of meaningless material, as consonant strings, digit strings or strings of unknown shapes (Lobier, Zoubrinetzky & Valdois, 2012; Valdois et al., 2003, Valdois, Lassus-Sangosse & Lobier, 2012)– does not reflect any lexical processing or linguistic skills. In contrast, the perceptual span that is measured in conditions of meaningful text reading is affected by linguistic variables as word frequency or context effects (Rayner, 1998). The VA span mainly reflects the quantity of visual attention available for processing and how attention distributes over the letter-string to modulate letter identity processing (see Ginestet, Phénix, Diard, & Valdois, 2019, for an implementation of visual attention in a model of word recognition). This specificity of the VA span is supported by neuroimaging data. The superior parietal lobules have been identified as the neural underpinnings of the VA span, showing that VA span specifically relates to the dorsal attentional network (Lobier, Peyrin, LeBas & Valdois, 2012b; Peyrin, Démonet, Baci, LeBas & Valdois, 2011; Peyrin et al., 2012; Reilhac, Peyrin, Démonet, & Valdois, 2013; Valdois, Lassus-Sangosse, Lallier, Moreaud, & Pisella, 2019).

Different tasks of whole and partial report (Dubois et al., 2010; Valdois et al., 2003; Zoubrinetzky, Bielle, & Valdois, 2014, Zoubrinetzky, Collet, Serniclaes, Nguyen-Morel & Valdois, 2016), categorization (Lobier, Zoubrinetzky et al., 2012) or visual 1-back (Lallier, Acha, & Carreiras, 2016) are relevant to measure VA span. Appropriate VA span tasks must meet certain standards. To ensure parallel processing, the multielement array has to be displayed for a short-enough time ( $\leq 200$  ms) that allows deployment of attention while avoiding useful eye movements. Inter-element spacing is increased to avoid potential crowding effects. Even in partial report conditions, the task must force parallel processing of all the elements of the array, so that no cue indicating the position or identity of the element to be processed is provided prior to the array offset. Because we are interested in the amount of attention deployed in parallel for identity processing, identification tasks are used while avoiding location encoding tasks that more likely rely on serial processing. We must further ensure that poor performance in multi-element processing is not just the consequence of a single element identification problem, so that a control task of single element processing efficiency is further proposed. Furthermore and because parallel processing of unknown items is challenging for the visual system (Shovman & Ahissar, 2006; Ziegler et al., 2010; Collis, Kohnen, & Kinoshita, 2013), familiar visual elements are more likely to be used in identification tasks while categorization tasks that do not require precise target identification are more appropriate when using unfamiliar visual items.

Strong relationships have been reported between VA span and reading in typical and dyslexic readers. Typical children with higher VA span make lesser fixations in text reading, thus processing more letters per fixation (Prado, Dubois, & Valdois, 2007). They are less prone to show length effects in word reading (van den Boer, de Jong, & Haentjens-van Meeteren, 2013), show higher performance in irregular word reading accuracy (Bosse & Valdois, 2009) and read words, pseudo-words and texts more fluently (Lallier, Valdois, Lassus-Sangosse, Prado, & Kandel, 2014; Lobier et al., 2013). Higher VA span capacities associated to faster pseudo-word reading have also been reported in young adults (Antzaka et al., 2017). Evidence from developmental dyslexia further supports the VA span-reading relationship. A VA span deficit characterizes a subset of the dyslexic population (Bosse et al., 2007; Germano, Reilhac, Capellini, & Valdois, 2014; Zoubrinetzky et al., 2014, 2016). The VA span deficit contributes to poor reading accuracy and slow reading speed in this population, whatever the type of items to be read (words, irregular words and

pseudo-words) and regardless of the child's phonological skills. Greater length effects in word reading are also reported in dyslexic children with a VA span deficit (Valdois et al., 2003, 2011; van den Boer et al., 2013). The overall findings offer a quite coherent pattern. Visual attention is deployed over the letter string to enhance letter identification. Higher visual attention capacity allows allocating enough attention to a higher number of letters, thus increasing probability of accurate parallel processing of the whole letters that make longer orthographic units. Parallel processing of longer orthographic units improves reading fluency and reduces length effects with potential additional effects on reading accuracy, at least for the languages with long graphemes and irregular words. Accurate reading of irregular words involves processing the word letter-string as a whole, which requires allocating enough attention to all of the word letters simultaneously. Thus, irregular word reading should be more specifically sensitive to the amount of visual attention available for processing; this is supported by consistent reports of poor irregular word reading accuracy in individuals with poor VA span (Dubois et al., 2010; Valdois et al., 2003, 2011). In a similar way, more attention is recruited for accurate identification of all the letters that make longer graphemic units, yielding grapheme parsing errors in dyslexic children with poor VA span skills (Zoubinetsky et al., 2014).

Although a relationship between VA span and reading performance has been reported from the end of first grade (Bosse & Valdois, 2009), whether VA span develops with printed word exposure as a consequence of reading acquisition (Goswami, 2015; see however Lobier & Valdois, 2015) or reflects visual attention capacity prior to formal literacy instruction remains an open issue. We here address this issue through the longitudinal follow-up of a cohort of typical children from kindergarten to first grade. Four digit-strings were used to assess pre-readers' VA span through tasks of global and partial report. A variety of cognitive skills known to relate with reading acquisition were further assessed in kindergarten, namely phonological skills (Bradley & Bryant, 1983), verbal short-term memory (de Jong and van der Leij, 2002), letter-name (Foulin, 2005; Georgiou, Torppa, Manolitsis, Lyytinen, & Parilla, 2012) and letter-sound knowledge (Caravolas et al., 2012; Hulme, Bowyer-Crane, Carroll, Duff, & Snowling, 2012). Following Castles and Coltheart (2004)'s recommendation, we further controlled for early literacy knowledge to exclude any potential influence of early reading skills on VA span performance in kindergarten. Their reading skills were assessed one year later at the end of first grade through tasks of irregular word, pseudo-word and text reading fluency. Regression and path analyses were used to explore whether VA span in kindergarten contributed significantly and independently to reading speed one year later.

## 2. Material and methods

### 2.1. Participants

One hundred and twenty-six children (56 males) were recruited from eight local Grenoble public schools. All children had normal hearing and normal or corrected-to-normal vision. First assessment took place prior to formal literacy instruction (at T1) when the participants were 5 years 10 months (SD = 3.3 months) old. The second assessment (at T2) was carried out one year later at the end of Grade 1 (mean CA = 6:10 years, SD = 3.4 months). All participants were French native speakers who attended school regularly. Their mean reading age at T2 was 7:01 years (SD = 7.9). Their non-verbal IQ corresponded to a mean percentile of 56 (SD = 27). We ensured that all the participants were able to name all the digits in kindergarten, which was required to assess their visual attention span abilities. The parents/legal tutors of the pupils gave informed written consent for participation of their child to the study. Ethics approval for the study was granted by the local Ethic Committee of the Grenoble-Alpes University and by the "Commission Nationale de l'Informatique et des Libertés" (CNIL

number: 0820589).

Note that in France, formal literacy instruction only starts from Grade 1. In kindergarten, teachers mainly focus on oral language skills to develop oral vocabulary and communication abilities. Letter-name is systematically taught including letter recognition and discriminability. Letter-sound knowledge is often taught in Grade 1 only. With respect to phonological skills, teachers try to improve both the ability of pupils to manipulate syllables and rhymes and their sensitivity to alliterations but they do not systematically train phoneme awareness, which is the focus of Grade 1 (Ziegler & Goswami, 2005).

### 2.2. Material and procedure

#### 2.2.1. Assessment in kindergarten

**Visual Attention Span. Stimuli:** Random 4-digit strings (e.g., 4 2 6 1) were built up from 8 digits (1, 2, 3, 4, 5, 6, 7 and 8). Digits were presented in black on a white background (Arial, 7 mm high). The strings contained no repeated digits. To avoid crowding effects, the inter-digit distance was increased (1 cm center-to-center). The array subtended an angle of approximately 4.2° at a viewing distance of 50 cms.

Sixteen digit-strings were displayed in the whole report condition. Each digit appeared twice in each position. Thirty-two random 4-digit strings were presented in the partial report condition. Each digit occurred four times in each position.

**Procedure:** At the start of each trial, a central fixation point was presented for 1000 ms followed by a blank screen for 50 ms. The digit string was then presented centred on fixation for 200 ms. In the whole report condition, a white screen was displayed at the offset of the digit string, and participants were asked to report verbally all the digits they had identified (max = 64). The number of accurately identified digits was scored independently of their position. For example, the target string 4 9 2 1 scored four points either reported as 4 9 2 1 or 9 1 4 2, while reporting 4 9 1 only scored 3 points. In partial report, a vertical bar indicating the digit to be reported was presented for 50 ms, 1.1° below the target digit, at the offset of the digit string. Each digit was used as target once in each position. Participants had to report the cued digit only (1 point per target digit, max = 32). The experimental trials were preceded by five training trials for which participants received feedback. No feedback was given during the test trials. The participant's responses were recorded by the experimenter on the numerical keyboard.

It is worth noting that the partial report condition as the global report condition requires parallel processing of the entire digit string since the position of the target to be reported is unknown and cannot be guessed at the time the string is displayed. Furthermore, as in global report, the partial report condition mainly taps identity processing skills. Indeed, due to the appearance of the vertical bar immediately at the offset of the digit string, the digit to be reported is perceived as being physically present above the vertical bar. Partial report performance thus reflects how well the target is identified without requiring any encoding of its relative position within the string.

**Phonological awareness.** Three tasks of rhyme judgement, syllable deletion and syllable reversal were administered to pre-readers. In the *rhyme judgement task*, 10 pairs of spoken words were presented and the child had to decide whether the words in each pair rhymed or not. The *syllable deletion task* was taken from the ODEDYS battery (Jacquier-Roux, Valdois, & Zorman, 2002). Children had to delete the first, median or final syllable of bi- and tri-syllabic spoken words (N = 12) and pronounce the resulting pseudo-word. The *syllable reversal task* of the BELEC battery (Mousty, Leybaert, Alegria, Content, & Morais, 1994) required switching the syllables of 10 spoken bi-syllabic words or pseudo-words (e.g., /doka/ → /kado/).

**Letter-name and letter-sound knowledge.** Sixteen upper-case letters (A, F, R, S, M, D, L, B, J, I, N, V, O, P, T, E) were presented in a 4X4 table (Arial, 48). In two separate sessions, the experimenter asked the child to report the name or the sound of each letter in turn. Accurate responses

**Table 1**

Mean, standard deviation (SD) and range (min–max) of the children’s skills and chronological age in kindergarten (T1) and at the end of Grade 1 (T2).

Assessment in Kindergarten (T1; N = 126)	Mean (SD)	Range (min–max)
Chronological age (in months)	70.65 (3.34)	65–76
Visual Attention Span		
Whole report performance (raw score, max = 64)	38.17 (8.11)	19–58
Partial report performance (raw score, max = 32)	18.17 (6.90)	2–30
Composite Visual attention span (%)	58.20 (15.09)	25–89
Phonological skills		
Rhyme judgement (raw score, max = 10)	8.21 (1.76)	2–10
Syllable deletion (raw score, max = 12)	7.40 (3.35)	0–12
Syllable reversal (raw score, max = 10)	5.97 (3.47)	0–10
Composite phonological skills (%)	67.82 (22.36)	20–100
Letter name knowledge (raw score, max = 16)	12.78 (4.15)	1–16
Letter sound knowledge (raw score, max = 16)	7.33 (5.65)	0–16
Early word identification (raw score, max = 12)	3.87 (3.09)	0–12
Verbal short-term memory (raw score, max = 10)	6.95 (1.24)	4–10
Assessment in Grade 1 (T2; N = 126)		
Chronological age (in months)	82.58 (3.40)	77–88
Raven Matrices (raw score, max = 36)	26.36 (5.49)	13–36
Text reading fluency (wpm)	40.79 (25.57)	2.5–113
Pseudo-word reading fluency (wpm)	14.97 (12.63)	0–63.5
Irregular word reading fluency (wpm)	12.11 (14.15)	0–76

were summed to derive scores of letter-name and letter-sound knowledge. Letter name was proposed first to half participants.

**Early word identification.** Children were asked to read aloud 12 French words: le, la, une, ou, ri, lu, son, ami, école, papa, maman, Noël (respectively: the (male), the (female), a (female), or, laughed, read, his, friend, school, daddy, mummy, Christmas). All were short frequent words that usually occurred on posters in classrooms or in children’s picture books (mean frequency in first grade books = 8006 per one million, from MANULEX: Lété, Sprenger-Charolles, & Colé, 2004). Words were written (black upper case, Arial 28) in two columns on a white sheet. Performance on the task was the number of words accurately named.

**Verbal short-term memory.** The participants were administered the digit span task (forward and backward recall) of the WISC IV. A composite short-term memory score was calculated as the sum of the forward and backward spans.

### 2.2.2. Grade 1 assessment

**Fluid Intelligence.** We administered the Raven’s colour matrices, PM47 (Raven, Raven, & Court, 1998), to assess fluid intelligence. The raw score (max = 36) was used as a control variable in the analyses.

**Text reading fluency.** Children were asked to read a text aloud for 2 min. The text from a child book for beginning readers consisted of 278 words (18 lines) printed (upper and lower case, times 14) in black on a white sheet. An illustration of the story appeared below the text. Text reading performance was the number of words accurately read per minute.

**Pseudo-word and irregular word reading.** Two lists of 20 pseudo-words (PWs) and 20 high frequency irregular words (mean frequency = 126 per million) from the ODEDYS battery (Jacquier-Roux et al., 2002) were administered. The PWs were legal and pronounceable 1-to-3 syllable PWs. Words and PWs were matched in length (mean letter length: 5.75). They were presented by blocks printed (lower case, times 14) in column in black on a white sheet. Children were asked to read aloud each item as quickly and accurately as possible. Reading fluency was measured as the number of words or PWs accurately read per minute.

### 2.3. Design and analysis

We first provide descriptive information for each of the administered tasks as well as correlations between all the variables in kindergarten and Grade 1 and across years. Partial correlations were then

computed after control for age and IQ, with the main purpose to identify the T1 cognitive skills that related with reading knowledge at T2.

Regressions and path analyses were then performed, focussing on the direct links between early skills at T1 (predictive factors) and reading performance at T2, considering text reading, pseudo-word reading and irregular word reading fluency as the outcome variables. All of the relevant variables were residualized for Age and IQ to examine Age- and IQ-independent relationships between the variables. The residual values were then used in all subsequent analyses (i.e., partial correlations, regressions and path analyses). All the models were tested using the R package Lavaan (Rosseel, 2012) and MPLUS (Version 7.2). Mahalanobis distance (D2) was used to detect multivariate outliers. Two participants with probability lower than 0.001 for D2 were not included in the path analyses. Maximum likelihood parameter estimates with robust standard errors and a mean-adjusted chi-square test statistic were used to account for the fact that some measures were not normally distributed.

## 3. Results

### 3.1. Descriptive statistics

Performance of the 126 participants in kindergarten (T1) and at Grade 1 (T2) is reported in Table 1. Theoretically-driven composite scores of VA span and phonological skills were computed as the mean percentage of performance on the two tasks of global and partial report for the former and from the three tasks of rhyme judgement, syllable deletion and syllable reversal for the latter. Table 1 shows the absence of either ceiling or floor effects on any of the measures. However as expected, the two tasks of letter-sound knowledge (median = 7) and early word identification (median = 3) were rather difficult for kindergarteners. Twenty percent children were unable to sound out any letter, 13% did not read any word.

### 3.2. Correlation analyses

Table 2 provides correlations between performance on the tasks measured in kindergarten (VA span, phonological awareness, letter-name and letter-sound knowledge, early word identification and verbal short-term memory) and correlations between the tasks administered in kindergarten and at Grade 1. Age correlated with performance in

**Table 2**

Correlations (above the diagonal) and partial correlations (after control of age and IQ effects; below the diagonal) between predictive variables in kindergarten (T1) and, text, pseudo-word (PW) and irregular word (IW) reading performance at Grade 1 (T2).

	2	3	4	5	6	7	8	9	10	11
1. Age	0.14	<b>0.35</b>	<b>0.40</b>	0.09	0.25	0.19	0.20	0.19	0.14	0.11
2. Raven Matrices	–	<b>0.37</b>	<b>0.52</b>	0.14	0.29	<b>0.30</b>	<b>0.37</b>	0.25	0.29	0.23
3. T1 VA span	–	–	<b>0.57</b>	0.13	0.28	<b>0.37</b>	0.29	<b>0.38</b>	<b>0.41</b>	<b>0.39</b>
4. T1 Phonological awareness	–	<b>0.41</b>	–	0.21	<b>0.43</b>	<b>0.45</b>	<b>0.51</b>	<b>0.32</b>	<b>0.33</b>	<b>0.30</b>
5. T1 Letter name knowledge	–	0.07	0.15	–	<b>0.56</b>	<b>0.50</b>	0.10	<b>0.34</b>	0.28	<b>0.30</b>
6. T1 Letter sound knowledge	–	0.13	0.29	<b>0.55</b>	–	<b>0.70</b>	0.27	0.29	<b>0.33</b>	<b>0.35</b>
7. T1 Early word identification	–	0.25	<b>0.33</b>	<b>0.48</b>	<b>0.66</b>	–	0.25	<b>0.50</b>	<b>0.53</b>	<b>0.58</b>
8. T1 Verbal STM	–	0.13	<b>0.37</b>	0.04	0.15	0.14	–	0.26	0.29	0.28
9. T2 Text reading fluency	–	0.29	0.18	<b>0.31</b>	0.21	<b>0.44</b>	0.17	–	<b>0.89</b>	<b>0.84</b>
10. T2 PW reading fluency	–	<b>0.33</b>	0.20	0.25	0.25	<b>0.48</b>	0.19	<b>0.88</b>	–	<b>0.87</b>
11. T2 IW reading fluency	–	<b>0.32</b>	0.20	0.27	0.29	<b>0.55</b>	0.21	<b>0.83</b>	<b>0.86</b>	–

In bold, significant correlations after a bonferroni correction ( $p < .0009$ )

phonological awareness and visual attention span in kindergarten. Non-verbal IQ significantly related to the same two cognitive subskills but further to early word identification and verbal short-term memory.

Partial correlations controlling for age and IQ were thus computed. Results are presented on [Table 2](#), below the diagonal.

Phonological awareness, letter-name and letter-sound knowledge correlated with early word identification in kindergarten. The correlation between letter-sound knowledge and early word identification was very high (close to 0.70) suggesting that letter-sound knowledge, as a particular case of grapheme-phoneme mapping, mainly reflected early literacy skills (Hulme et al., 2012). A composite variable was thus computed as mean performance of the two tasks, which resulted in a normally distributed variable. This score was used as an indicator of the pre-readers' literacy knowledge ("Early literacy knowledge" variable hereafter) in subsequent analyses. As expected, early verbal short-term memory correlated with phonological awareness in kindergarten but with none of the reading variables. More unexpectedly, phonological awareness was found to correlate with VA span in kindergarten.

At Grade 1, all the reading variables were highly correlated. Further, significant correlations were seen between performance in Kindergarten and Grade 1. Early word identification significantly correlated with all the reading measures at T2 but none of the correlations between phonological awareness or letter knowledge in kindergarten and reading performance at Grade 1 were significant, except for letter name knowledge that significantly correlated with text reading fluency. Critically, VA span abilities in kindergarten correlated with irregular word and pseudo-word reading fluency at the end of Grade 1. The relationship was close to significance ( $r = 0.29$ ,  $p = .0011$ ; threshold of significance at 0.0009 after Bonferroni correction) for text reading.

### 3.3. Regression and path analyses

We used regression analyses to explore the contribution of basic cognitive skills in kindergarten to reading performance one year later. Verbal short-term memory was not included in the models as it correlated with neither early literacy knowledge nor with any of the reading subskills at the end of Grade 1. Three regression analyses were computed, one for each of the reading subskills, namely text reading, irregular word reading and pseudo-word reading fluency. The measures of letter name knowledge, phonological awareness, VA span and the autoregressive effect of early literacy skill were implemented as potential predictors of reading performance at T2. Results are presented in [Table 3](#) for the three reading measures (regression analyses computed on raw scores while further including Age and IQ as regressors, are presented in [Table S1](#), [supplementary material](#)).

The total model  $R^2$  values ranged from 0.182 for text reading fluency to 0.216 for irregular word reading fluency (all  $ps < 0.001$ ). Early literacy skill was a significant predictor of pseudo-word and irregular word reading fluency, accounting for 5.4% and 6.9% of unique

variance respectively. The contribution of early literacy knowledge was near significance for text reading fluency (1.7% of explained variance,  $p = .09$ ). Letter name knowledge was a significant predictor of text reading fluency only, with a unique contribution of 2.8% of explained variance. Phonological awareness accounted for no additional amount of unique variance whatever the reading subskills. On the contrary, VA span was a significant predictor of all the measures of reading fluency at the end of Grade 1, with a unique contribution of 4.7, 6.3 and 4.6 percent of explained variance, respectively for text, pseudo-word and irregular word reading.

A path diagram was created in which all three reading fluency measures at grade 1 were included as separate endogenous variables with separate paths from all kindergarten predictors (see [supplementary materials S1 and S2](#) for models including global report and partial report performance as separate predictors). After first fitting the saturated model, non-significant paths were removed step-by-step, until a simplified model was obtained in which all remaining paths and covariances were statistically significant. The resulting simplified model, illustrated in [Fig. 1](#), fits the data very well [ $\chi^2(5, N = 124) = 1.013$ ,  $p = .961$ , comparative fit index (CFI) = 1, root mean square error of approximation (RMSEA) = 0 (90% confidence interval CI = 0–0, probability RMSEA < 0.05 = 0.98), Standardized Root Mean Square Residual (SRMR) = 0.015].

Next, we examined whether the predictive power of VA span differed for the different reading subskills. For this purpose, we computed a new model in which the three path weights originating from VA span were constrained to be the same. Then, the two models were compared with a  $\chi^2$  difference test adjusted with a Satorra-Bentler scaling correction. The Satorra-Bentler scaled  $\chi^2$  difference test was significant ( $\Delta \chi^2 [6] = 32.12p < .001$ ), suggesting that the VA span predictive power differed for the three reading subskills. Results showed that VA span was a stronger predictor of pseudo-word reading fluency than of text or irregular word reading fluency.

## 4. Discussion

The follow-up of a cohort of pupils from kindergarten to first grade shows that children who identified more digits in parallel in kindergarten showed higher reading fluency one year later, regardless of their phonological skills, early literacy knowledge or letter-name knowledge and after control for potential effects of age or IQ. As previously reported (Caravolas et al., 2012; Castles & Coltheart, 2004; Shapiro, Carroll, & Solity, 2013), phonological awareness and letter name knowledge appear as early predictors of later reading skills but their relationship to reading performance at the end of grade 1 was found indirect, via shared variance with other predictors. Several methodological differences with previous studies may explain this finding. Phonological skills in kindergarten were assessed through tasks requiring the manipulation of larger phonological units than phonemes.

**Table 3**

Hierarchical regression results (standardized coefficients and z values, after control of age and IQ) of early literacy knowledge, letter-name knowledge, phonological awareness and VA span in kindergarten as predictors of text reading fluency, pseudo-word and irregular word fluency at the end of Grade 1; the  $\Delta R^2$  columns present the incremental  $R^2$  for each significant factor when entered after all the others in the analysis, representing the unique contribution of that factor to the dependent variable.

Dependent variables Equation results:	Text reading fluency R = 0.39; Adj.R <sup>2</sup> = 0.182; F(4,119) = 6.606 ***			Pseudo-word reading fluency R = 0.46; Adj.R <sup>2</sup> = 0.214; F(4,119) = 8.083 ***			Irregular word reading fluency R = 0.46; Adj.R <sup>2</sup> = 0.216; F(4,119) = 8.201***		
	Factors	$\beta$	z	$\Delta R^2$	$\beta$	z	$\Delta R^2$	$\beta$	z
Early literacy knowledge	0.169	1.66~	0.017~	0.297	2.78**	0.054**	0.337	2.81**	0.069**
Letter name	0.207	2.45*	0.028*	0.071	0.91		0.072	0.99	
Phonological awareness	-0.009	-0.09		-0.021	-0.26		-0.040	-0.41	
Visual attention span	0.236	2.72**	0.047**	0.273	2.95**	0.063**	0.235	2.67**	0.046**

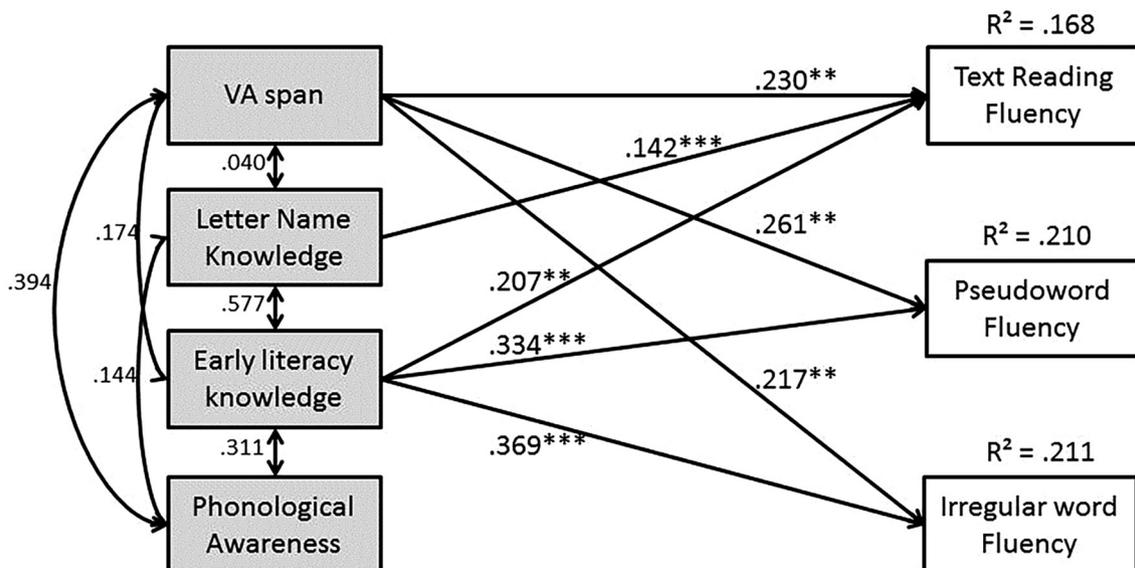
The use of more challenging phoneme awareness tasks in pre-readers might reveal stronger and more direct relationships with later reading skills (Melby-Lervåg et al., 2012). However, for the first time in the current study, the contribution of phonological skills to later reading performance was explored while controlling for both early literacy knowledge and VA span. Future studies are required to clarify whether performance on more challenging phoneme awareness tasks in kindergarten would significantly and more directly contribute to later reading skills, beyond the influence of early literacy knowledge and visual-attention simultaneous processing skills.

The main contribution of the current study is to provide first evidence that VA span prior to formal literacy instruction predicts later reading speed performance, which would support a causal relationship. Our results indeed suggest that higher visual attention capacity in kindergarten allows children to identify more letters simultaneously, thus processing longer orthographic units and reading words and pseudo-words more fluently.

However, the relevance of VA span tasks to measure visual attention capacity when using alphanumeric material and/or verbal paradigms has raised doubts (Banfi et al., 2017; Collis et al., 2013; Yeari, Isser, & Schiff, 2017; Ziegler et al., 2010). Performance on these tasks was interpreted as potentially reflecting verbal/phonological encoding skills instead of visual attention capacity, so that some researchers have privileged the use of unfamiliar visual characters (like symbols, pseudo-letters or letters of unknown alphabets) in the hope of more specifically tap visual attention resources.

Are unfamiliar visual characters more relevant than familiar characters to estimate visual attention capacity? Previous studies have shown that single unfamiliar visual characters can be quite efficiently identified after only a few thousand exposures (Pelli et al., 2006). However and despite efficient single character identification, the participants were unable to process more than one or two of these unfamiliar characters at a time (Pelli et al., 2006). Similar findings have been reported by Shovman and Ahissar (2006). They observed that expert readers of Hebrew who could successfully identify the central target of a Georgian (unknown alphabet) three-letter string were unable to accurately identify all three letters simultaneously. These results are quite in line with reports of poor symbol string identity processing in expert readers, showing close-to-chance-level identification of the symbols outside fixation (Ziegler et al., 2010), poor signal to noise ratio (Yeari et al., 2017) and high error rate (Collis et al., 2013). The overall findings are consistent with a balance between object-based and space-based attention, so that increased difficulty for feature integration of unfamiliar and complex visual shapes would proportionally reduce the deployment of visual attention capacity over multiple shapes (Elahipanah, Christensen, & Reingold, 2011; Khan et al., 2016).

The use of multiple familiar visual shapes (like letters or digits) in VA span tasks was privileged to reduce the amount of visual attention to be allocated to the processing of each single character within the array and rather focus on the amount of attention distributed over multiple elements for parallel processing. It is further noteworthy that the use of letters and digits is quite common in research on visual processing and



**Fig. 1.** Path diagram showing the longitudinal predictors of text reading, pseudo-word reading and irregular word reading fluency. Solid lines represent the statistically significant predictive relationships (standardized results). \*  $p < .05$ ; \*\*  $p < .01$ ; \*\*\* $p < .001$ .

visual attention skills. Letters were used to measure the very early steps of visual processing (Sperling, 1960, 1967) and develop theories of visual attention (Bundesen, 1990; Laberge & Brown, 1989). Furthermore, tasks of whole and partial report are quite classical paradigms to explore simultaneous perception of multiple visual elements (Allport, 1968; Averbach & Sperling, 1968; Duncan et al., 1999; Habekost, 2015; Kyllingsbæk & Bundesen, 2006). Research has clearly established that letters within words and even within consonant strings are identified in parallel (Adelman, Marquis, & Sabatos de Vito, 2010; Marzouki & Grainger, 2014). Parallel information on letter identity is available after presentation durations of only a few tens of milliseconds, before any verbal recoding can take place. For all positions within string, letter identification improves when presentation duration increases but response accuracy curve shapes remain quite similar across presentation durations, suggesting that visual encoding was not abandoned for verbal encoding at longer (yet short enough to force parallel processing) presentation durations (Marzouki & Grainger, 2014). With respect to VA span tasks, Lobier, Zoubrinetzky et al. (2012) explicitly addressed the verbal encoding issue, exploring whether VA span estimation would differ depending on using letters, digits or unfamiliar visual characters. A categorization task procedure was used to avoid floor effects in the condition requiring parallel processing of unfamiliar characters. Results showed that children with higher performance in the conventional VA span whole letter report paradigm also showed higher performance in the categorization tasks regardless of character familiarity. In the same way, dyslexic children with a VA span deficit showed poor performance in the non-verbal categorization task and the deficit was of similar amplitude for the verbal (familiar) and non-verbal (unfamiliar) categories. The available behavioural findings thus suggest that VA span performance is visually-driven whether using familiar letters or digits or unfamiliar character strings.

To definitely establish that VA span tasks tap visual attention processing skills and discard any involvement of phonological/language skills, neuroimaging studies were carried out. The superior parietal lobules bilaterally were consistently identified as the neural underpinnings of VA span, thus brain regions that are neither linguistic nor phonological but belong to the dorsal attention network (Peyrin et al., 2011, 2012; Reilhac et al., 2013; Lobier, Peyrin et al. (2012); Lobier, Peyrin, Pichat, Le Bas, & Valdois, 2014; Valdois et al., 2014; Valdois, Lassus-Sangosse, Lallier, Moreaud, & Pisella, 2019). Typical readers who show higher performance on the whole report task, thus showing higher VA span, further show stronger activation of the superior parietal lobules (SPLs) bilaterally. Dyslexic children with reduced VA span behaviourally – as measured through tasks of whole and partial letter report – show reduced activation of the SPLs (Peyrin, Démonet, Baciú, Le Bas, & Valdois, 2011; Reilhac et al., 2013) while these same brain regions are normally activated during multi-element parallel processing in dyslexic individuals with a selective phonological deficit (Peyrin et al., 2012). Moreover, as a mirror of the experimental findings showing similar VA span estimation regardless of character type, neuroimaging findings have shown similar involvement of the SPLs when using either familiar or unfamiliar character strings in categorization tasks (Lobier, Peyrin et al., 2012, 2014). Converging evidence from behavioural and neuroimaging research thus supports a visual attention interpretation of the results on VA span tasks, which leads to conclude from the present results that children with higher visual attention capacity in kindergarten read more fluently one year later.

How does visual attention capacity affect reading acquisition? We here propose a sketch of the role of visual attention in reading acquisition that is largely inspired by the model initially proposed by Laberge and Samuels (1974). For beginning readers, all printed words are unfamiliar letter strings. Attempting to deploy visual attention over the entire word letter-string would result in diffuse attention deployment, thus allocating not enough attention to each letter for their accurate identification. At the beginning of literacy instruction, children have been familiarized with letter shapes and letter names but the processing

of individual letters is not fully automatized. Letters are mainly analysed as combinations of visual features and attention is required to bind these features together into a single letter percept (Treisman & Gelade, 1980; Wolfe & Cave, 1999). The identification of letters within strings is further degraded depending on distance to fixation (the acuity gradient) and due to interference from adjacent letters (crowding effect). Additional visual attention capacity is thus required to compensate for these acuity and crowding effects in order to enhance accurate letter identification (Carrasco, 2011; Risko et al., 2010). Overall, beginning readers have to allocate a large amount of their visual attention resources to each individual letter processing within strings, allowing to solve the binding problem in integrating relevant visual features to form the letter percept while excluding features from adjacent letters to avoid misidentifications. Visual attention thus concentrates on each letter in turn which improves discriminability and letter identification but results in letter-by-letter reading. With time and exposure to printed letters and words, visual expertise improves. Children more efficiently discriminate the letters of the alphabet that are perceived as wholes, thus requiring minimal attention (Pelli et al., 2006; Wiley, Wilson, & Rapp, 2016). More automatized individual letter identification makes an amount of visual attention resources available for further processing. Visual attention then deploys over adjacent letters, which allows learning statistical letter cooccurrences (Egley, Driver, & Rafal, 1994; Zhao, Cosman, Vatterott, Gupta, & Vecera, 2014). Attention acts as a glue to encode multi-letter units, like bigrams and trigrams (Dehaene, Cohen, Sigman, & Vinckier, 2005), or multi-letter graphemes. Attention thus contributes to the precise and timely encoding of longer and longer orthographic units from bigrams and graphemes to syllables, morphemes and words. The multi-letter units successfully encoded as perceptual units are stored in long-term memory (Lachter, Forster, & Ruthruff, 2004). The model thus predicts that children would initially show an exaggerated length effect due to letter-by-letter reading but that this effect would gradually decrease due to the processing of longer and longer units as wholes. More specifically, variations in the length effect are expected to depend on the child visual attention capacity. Although further research is needed to address this issue more in depth, some available findings already support this prediction. van den Boer et al. (2013) showed that VA span is a unique predictor of individual differences in length effect in second grade children. Dyslexic children and young adults with a VA span deficit show an exaggerated length effect in reading and/or lexical decision (Juphard, Carbonnel, & Valdois, 2004; Valdois et al., 2003, 2011). Evidence from acquired dyslexia also supports a relationship between visual attention capacity and the length effect in reading (Habekost, 2015). Another source of evidence comes from computational modelling showing how variations in the distribution of visual attention affect word length effect in lexical decision (Ginestet et al., 2019). As reading is speeded-up when processing longer units as wholes, a relationship between VA span and reading speed is further expected. Such a relationship is supported by data from typical readers (Bosse & Valdois, 2009; Lobier et al., 2013) and dyslexic children (Bosse et al., 2007; Zoubrinetzky et al., 2014).

Another main result of the current study is that VA span measured in kindergarten predicts future performance in different reading sub-skills (irregular word and pseudo-word reading) and in text reading. This result is quite compatible with the conceptual model proposed above, since the model postulates involvement of visual attention resources whatever the letter-string to be processed. If we assume that a larger amount of visual attention resources allows processing longer units as wholes earlier, then the processing of longer multi-letter graphemes and longer syllables would improve pseudo-word reading speed and more generally sublexical processing. If we assume that words are the largest units that can be processed as wholes then the same logic applies and greater VA span should allow to process words by sight earlier, with a positive effect on irregular word reading speed. Our results further suggest a relationship between VA span and text reading, which is quite compatible with the findings discussed above, assuming

that more speeded reading of individual words would result in more speeded text reading. However, text reading differs from individual word reading in requiring serial shifting of attention and eye movements, and in relying on parafoveal preview (Franceschini, Gori, Ruffino, Pedrolli, & Facchetti, 2012; Ghahghaei, Linnell, Fischer, Dubey & Davis, 2013; Ghahghaei & Linnell, 2018; Schotter, Angele, & Rayner, 2012). The present findings suggest that VA resources that improve the ability to process several adjacent letters as wholes remain as a significant contributor of reading speed independently of the reading context (words in isolation or in sentences).

Although contributing to reading fluency in general, the current findings suggest that VA span when measured in kindergarten more strongly contributes to pseudo-word than to irregular word reading fluency. Interpretation of this finding is not straightforward. Previous studies carried out on older participants rather suggested a privileged relationship between VA span and irregular word reading (Bosse & Valdois, 2009). Available findings might suggest a stronger influence of VA span to pseudo-word reading at the beginning of reading acquisition but higher contribution to irregular word reading later on. If we assume that the size of VA span, that is the amount of visual attention resources, increases during primary school (Bosse & Valdois, 2009) and that only a few letters can be processed simultaneously at the end of kindergarten (2.33 letters on average in the current study), it follows that beginning readers would mainly process relatively short orthographic units simultaneously. This VA span limitation would favour simultaneous processing of sublexical units as compared to whole words. Later on, improvement of VA span abilities would allow the processing of larger and larger units which will enhance simultaneous processing of larger sublexical units and whole words, with potential more sustained effect on irregular words.

## 5. Conclusion

Previous research has widely documented the existence of a relationship between VA span and reading performance in typical readers and dyslexic individuals. The current study for the first time establishes through a longitudinal study that VA span prior to literacy instruction predicts reading fluency one year later, at the end of Grade 1. These findings bring support for a theory that reading acquisition depends critically on the amount of visual attention capacity available for multi-element simultaneous processing. We propose a new conceptual model of the role of visual attention span in learning to read. The model opens new perspectives on reading acquisition and word-specific orthographic learning that would trigger a number of new studies to validate or invalidate all or part of its predictions.

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## Appendix A. Supplementary data

Supplementary data to this article can be found online at <https://doi.org/10.1016/j.visres.2019.10.011>.

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