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Visual attention modulates reading acquisition.

Short title: visual attention and reading acquisition

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1 Abstract

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

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2 Keywords (6)

3 Reading acquisition, Visual attention, longitudinal study, multi-element parallel processing,
4 prereaders, models of reading.

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8 3-5 bullet points (85 characters max including spaces)

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- 10
- Visual attention span reflects visual attention capacity for simultaneous processing
- 11
- Pre-readers' visual attention span predicts reading fluency at the end of Grade 1
- 12
- Visual attention uniquely contributes to word, pseudo-word and text reading
- 13
- A conceptual model of the role of visual attention in learning to read is proposed

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1 **1. Introduction**

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

14

15 In most languages, a written word is defined by the identity and position of its constituent
16 letters. Letters are the building blocks of words, so that single letter identification is a first
17 step towards word processing. Some letters share many of their visual features (R and P for
18 example), thus increasing the probability of misidentification and letter confusion (Pelli,
19 Burns, Farell & Moore-Page, 2006); some differ by visual properties that are not relevant for
20 object identification. The visual system of pre-readers and illiterates is tuned to identify visual
21 objects regardless of their orientation (Kolinsky & Fernandes, 2014). The identity of an
22 animal, a person or an object is not affected by a left-right or up-down reversal. But this does
23 not hold true for letters. Differences in left-right or up-down orientation define letters that
24 differ in identity (e.g., b and d or u and n). Reading acquisition thus requires learning to
25 discriminate letters of similar shapes but different orientations, which implies “unlearning”

1 the general principle of mirror-invariance (Dehaene, Cohen, Morais & Kolinsky, 2015;
2 Pegado et al., 2014). This is not straightforward. Some children show mirror-letter confusions
3 at the beginning of literacy instruction (Dehaene et al., 2010) and dyslexic children tend to
4 process symmetrical letters as identical (Lachman & Van Leeuwen, 2007). Reading
5 acquisition thus relies on functional specialization of the visual system through implicit visual
6 perceptual learning (Gilbert, Sigman & Crist, 2001).

7 Reading involves visual specialization for accurate letter processing, but normal processing of
8 isolated letters is not enough to guarantee efficient reading. Additional visual mechanisms are
9 at play for the processing of letters within strings. The visibility of letters within words is
10 modulated by both the acuity gradient and crowding (Bernard & Castet, 2019; Grainger,
11 Dufau & Ziegler, 2016). Acuity is maximal for the letter under fixation but the drop-off in
12 visual acuity as a function of distance from fixation makes letter identification worse with
13 eccentricity. Letter identification within strings is further limited by crowding, i.e., lateral
14 interference due to nearby letters (Bouma, 1970; Whitney & Levi, 2011). Maximal
15 interference is observed for letters surrounded by a letter on each side, so that the inner letters
16 of a word are more difficult to identify than the outer letters (i.e., the first and last letters;
17 Scaltritti & Balota, 2013; Tydgate & Grainger, 2009). Crowding affects visual feature
18 integration. The features of both the target letter and nearby letters are combined, which may
19 result in letter identity confusions and/or location errors (Pelli, Palomares & Majaj, 2004;
20 Whitney & Levi, 2011). Variations in crowding relates to variations in reading speed.
21 Reading speed is limited by crowding in typical readers (Pelli et al., 2007) and some dyslexic
22 children --but not all (Ziegler, Pech-Georgel, Dufau & Grainger, 2010) -- show greater
23 crowding than their peers, which affects their ability to recognize words faster (Bouma &
24 Legge, 1977; Atkinson, 1993; Spinelli, de Luca, Judica & Zoccolotti, 2002; Martelli, di
25 Filippo, Spinelli & Zoccolotti, 2009; Callens, Whitney, Tops & Brysbaert, 2013).

1 Fortunately, the deleterious effects of crowding on letter processing within strings are
2 attenuated when inter-letter spacing is increased, which results in improved reading speed
3 (Spinelli et al., 2002; Martelli et al., 2009; Zorzi et al., 2012).

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

8
9 Eye movement studies provide important insights on this issue. Eye movements in reading are
10 characterized by a succession of fixations and saccades. Information about letter identity is
11 acquired during fixations and the primary function of a saccade is to move the eyes towards
12 another portion of the word or text for detailed letter processing (for a review, see Rayner,
13 2009). There is now a consensus that visual attention shifting precedes eye movement and
14 that visual attention is required for word identification (Besner et al., 2016; Lachter, Forster &
15 Ruthruff , 2004; Rayner & Reichle, 2010; Risko, Stolz & Besner, 2010). Attention is
16 allocated to one word (or a few short words, or a portion of a word) at a time; it acts as a filter
17 that enhances letter identification under the attentional focus, thus limiting the detrimental
18 effects of acuity and crowding (Carrasco, 2011; Strasburger, 2005; Yeshurun & Rashal,
19 2010). In compensating for acuity limitations and adjacent letter interference, visual attention
20 allows accurate parallel processing of letter identities under the attentional focus (Bundesen,
21 1990; Carrasco, 2011). As a result, the number of letters that can be accurately processed in
22 parallel within a letter string (i.e., a sublexical orthographic unit or a word) should vary
23 depending on the amount of attention resources available for processing. Assuming that
24 reading speed is higher when processing longer orthographic units – thus, more letters in

1 parallel–, the amount of attention available for parallel processing should modulate how fast
2 words (or more generally letter strings) can be processed.

3

4 The amount of visual attention available for the parallel processing of letters within strings
5 can be estimated through the measure of visual attention (VA) span (Bogon, Finke &
6 Stenneken, 2014; Lobier, Dubois & Valdois, 2013). More generally, this span corresponds to
7 the number of distinct visual elements that can be processed simultaneously in a multi-
8 element configuration (Bosse, Tainturier & Valdois, 2007). The VA span differs from the
9 perceptual span. Although the latter was also defined as an attentional span of effective vision
10 (Pollatsek et al., 1981; Rayner, 2009), the two spans differ in their estimated size, symmetry
11 around fixation and foveal/parafoveal limits (for a review, Frey & Bosse, 2018) but, more
12 importantly, the VA span is assumed to be a purer measure of the visual attention mechanisms
13 involved in reading. Indeed, the VA span --which is measured through tasks that require the
14 processing of meaningless material, as consonant strings, digit strings or strings of unknown
15 shapes (Lobier et al., 2012a; Valdois et al., 2003, 2012)-- does not reflect any lexical
16 processing or linguistic skills. In contrast, the perceptual span that is measured in conditions
17 of meaningful text reading is affected by linguistic variables as word frequency or context
18 effects (Rayner, 1998). The VA span mainly reflects the quantity of visual attention available
19 for processing and how attention distributes over the letter-string to modulate letter identity
20 processing (see Ginestet et al., in press, for an implementation of visual attention in a model
21 of word recognition). This specificity of the VA span is supported by neuroimaging data. The
22 superior parietal lobules have been identified as the neural underpinnings of the VA span,
23 showing that VA span specifically relates to the dorsal attentional network (Lobier, Peyrin,
24 LeBas & Valdois, 2012b; Peyrin, Démonet, Baciou, LeBas & Valdois, 2011; Peyrin, Lallier,

1 Démonet, Baciú, LeBas & Valdois, 2012; Reilhac, Peyrin, Démonet, & Valdois, 2013;
2 Valdois, Lassus-Sangosse, Lallier, Moreaud & Pisella, 2019).

3
4 Different tasks of whole and partial report (Dubois et al., 2010; Valdois et al., 2003;
5 Zoubrinetsky et al., 2014, 2016), categorization (Lobier et al., 2012a) or visual 1-back
6 (Lallier, Acha & Carreiras, 2016) are relevant to measure VA span. Appropriate VA span
7 tasks must meet certain standards. To ensure parallel processing, the multielement array has
8 to be displayed for a short-enough time ($\leq 200\text{ms}$) that allows deployment of attention while
9 avoiding useful eye movements. Inter-element spacing is increased to avoid potential
10 crowding effects. Even in partial report conditions, the task must force parallel processing of
11 all the elements of the array, so that no cue indicating the position or identity of the element to
12 be processed is provided prior to the array offset. Because we are interested in the amount of
13 attention deployed in parallel for identity processing, identification tasks are used while
14 avoiding location encoding tasks that more likely rely on serial processing. We must further
15 ensure that poor performance in multi-element processing is not just the consequence of a
16 single element identification problem, so that a control task of single element processing
17 efficiency is further proposed. Furthermore and because parallel processing of unknown items
18 is challenging for the visual system (Shovman & Ahissar, 2006; Ziegler et al., 2010; Collis,
19 Kohnen & Kinoshita, 2013), familiar visual elements are more likely to be used in
20 identification tasks while categorization tasks that do not require precise target identification
21 are more appropriate when using unfamiliar visual items.

22
23 Strong relationships have been reported between VA span and reading in typical and dyslexic
24 readers. Typical children with higher VA span make lesser fixations in text reading, thus
25 processing more letters per fixation (Prado, Dubois & Valdois, 2007). They are less prone to

1 show length effects in word reading (van den Boer, de Jong & Haentjens-van Meeteren ,
2 2013), show higher performance in irregular word reading accuracy (Bosse & Valdois, 2009)
3 and read words, pseudo-words and texts more fluently (Lallier et al., 2014; Lobier et al.,
4 2013). Higher VA span capacities associated to faster pseudo-word reading have also been
5 reported in young adults (Antzaka et al., 2018). Evidence from developmental dyslexia
6 further supports the VA span-reading relationship. A VA span deficit characterizes a subset of
7 the dyslexic population (Bosse et al., 2007; Germano, Reilhac, Capellini & Valdois, 2014;
8 Zoubinetzky et al., 2014, 2016). The VA span deficit contributes to poor reading accuracy
9 and slow reading speed in this population, whatever the type of items to be read (words,
10 irregular words and pseudo-words) and regardless of the child's phonological skills. Greater
11 length effects in word reading are also reported in dyslexic children with a VA span deficit
12 (Valdois et al., 2003, 2011; van den Boer et al., 2013). The overall findings offer a quite
13 coherent pattern. Visual attention is deployed over the letter string to enhance letter
14 identification. Higher visual attention capacity allows allocating enough attention to a higher
15 number of letters, thus increasing probability of accurate parallel processing of the whole
16 letters that make longer orthographic units. Parallel processing of longer orthographic units
17 improves reading fluency and reduces length effects with potential additional effects on
18 reading accuracy, at least for the languages with long graphemes and irregular words.
19 Accurate reading of irregular words involves processing the word letter-string as a whole,
20 which requires allocating enough attention to all of the word letters simultaneously. Thus,
21 irregular word reading should be more specifically sensitive to the amount of visual attention
22 available for processing; this is supported by consistent reports of poor irregular word reading
23 accuracy in individuals with poor VA span (Dubois et al., 2010; Valdois et al., 2003, 2011).
24 In a similar way, more attention is recruited for accurate identification of all the letters that

1 make longer graphemic units, yielding grapheme parsing errors in dyslexic children with poor
2 VA span skills (Zoubrinetzky et al., 2014).

3

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

21

22 **2. Material and Methods**

23

24 **2.1. Participants**

1 One hundred and twenty-six children (56 males) were recruited from eight local Grenoble
2 public schools. All children had normal hearing and normal or corrected-to-normal vision.
3 First assessment took place prior to formal literacy instruction (at T1) when the participants
4 were 5 years 10 months (SD=3.3 months) old. The second assessment (at T2) was carried out
5 one year later at the end of Grade 1 (mean CA=6:10 years, SD = 3.4 months). All participants
6 were French native speakers who attended school regularly. Their mean reading age at T2
7 was 7:01 years (SD = 7.9). Their non-verbal IQ corresponded to a mean percentile of 56 (SD
8 = 27). We ensured that all the participants were able to name all the digits in kindergarten,
9 which was required to assess their visual attention span abilities. The parents/legal tutors of
10 the pupils gave informed written consent for participation of their child to the study. Ethics
11 approval for the study was granted by the local Ethic Committee of the Grenoble-Alpes
12 University and by the “Commission Nationale de l’Informatique et des Libertés” (CNIL
13 number: 0820589).

14

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

22

23 2.2. Material and Procedure

24 2.2.1. Assessment in kindergarten

25

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

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

9 *Procedure:* At the start of each trial, a central fixation point was presented for 1000ms
10 followed by a blank screen for 50ms. The digit string was then presented centred on fixation
11 for 200ms. In the whole report condition, a white screen was displayed at the offset of the
12 digit string, and participants were asked to report verbally all the digits they had identified
13 (max = 64). The number of accurately identified digits was scored independently of their
14 position. For example, the target string 4 9 2 1 scored four points either reported as 4 9 2 1 or
15 9 1 4 2, while reporting 4 9 1 only scored 3 points. In partial report, a vertical bar indicating
16 the digit to be reported was presented for 50ms, 1.1° below the target digit, at the offset of the
17 digit string. Each digit was used as target once in each position. Participants had to report the
18 cued digit only (1 point per target digit, max = 32). The experimental trials were preceded by
19 five training trials for which participants received feedback. No feedback was given during
20 the test trials. The participant's responses were recorded by the experimenter on the numerical
21 keyboard.

22 It is worth noting that the partial report condition as the global report condition requires
23 parallel processing of the entire digit string since the position of the target to be reported is
24 unknown and cannot be guessed at the time the string is displayed. Furthermore, as in global
25 report, the partial report condition mainly taps identity processing skills. Indeed, due to the

1 appearance of the vertical bar immediately at the offset of the digit string, the digit to be
2 reported is perceived as being physically present above the vertical bar. Partial report
3 performance thus reflects how well the target is identified without requiring any encoding of
4 its relative position within the string.

5

6 *Phonological awareness*

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

15

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

21

22 *Early word identification.* Children were asked to read aloud 12 French words: le, la, une, ou,
23 ri, lu, son, ami, école, papa, maman, Noël (respectively: the (male), the (female), a (female),
24 or, laughed, read, his, friend, school, daddy, mummy, Christmas). All were short frequent
25 words that usually occurred on posters in classrooms or in children's picture books (mean

1 frequency in first grade books = 8006 per one million, from MANULEX: Lété, Sprenger-
2 Charolles & Colé, 2004). Words were written (black upper case, Arial 28) in two columns on
3 a white sheet. Performance on the task was the number of words accurately named.

4

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

8

9 2.2.2. Grade 1 Assessment

10

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

14

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

19

20 *Pseudo-word and irregular word reading.* Two lists of 20 pseudo-words (PWs) and 20 high
21 frequency irregular words (mean frequency=126 per million) from the ODEDYS battery
22 (Jacquier-Roux et al., 2002) were administered. The PWs were legal and pronounceable 1-to-
23 3 syllable PWs. Words and PWs were matched in length (mean letter length: 5.75). They were
24 presented by blocks printed (lower case, times 14) in column in black on a white sheet.

1 Children were asked to read aloud each item as quickly and accurately as possible. Reading
2 fluency was measured as the number of words or PWs accurately read per minute.

3

4 2.3. Design and analysis

5 We first provide descriptive information for each of the administered tasks as well as
6 correlations between all the variables in kindergarten and Grade 1 and across years. Partial
7 correlations were then computed after control for age and IQ, with the main purpose to
8 identify the T1 cognitive skills that related with reading knowledge at T2.

9 Regressions and path analyses were then performed, focussing on the direct links between
10 early skills at T1 (predictive factors) and reading performance at T2, considering text reading,
11 pseudo-word reading and irregular word reading fluency as the outcome variables. All of the
12 relevant variables were residualized for Age and IQ to examine Age- and IQ-independent
13 relationships between the variables. The residual values were then used in all subsequent
14 analyses (i.e., partial correlations, regressions and path analyses). All the models were tested
15 using the R package Lavaan (Rosseel, 2012) and MPLUS (Version 7.2; Muthén & Muthén,
16 2015). Mahalanobis distance (D2) was used to detect multivariate outliers. Two participants
17 with probability lower than 0.001 for D2 were not included in the path analyses. Maximum
18 likelihood parameter estimates with robust standard errors and a mean-adjusted chi-square
19 test statistic were used to account for the fact that some measures were not normally
20 distributed.

21

22 **3. Results**

23 3.1. Descriptive statistics

24 Performance of the 126 participants in kindergarten (T1) and at Grade 1 (T2) is reported in
25 Table 1. Theoretically-driven composite scores of VA span and phonological skills were

1 computed as the mean percentage of performance on the two tasks of global and partial report
 2 for the former and from the three tasks of rhyme judgement, syllable deletion and syllable
 3 reversal for the latter. Table 1 shows the absence of either ceiling or floor effects on any of
 4 the measures. However as expected, the two tasks of letter-sound knowledge (median = 7)
 5 and early word identification (median = 3) were rather difficult for kindergarteners. Twenty
 6 percent children were unable to sound out any letter, 13% did not read any word.

7

8 Table 1: Mean, standard deviation (SD) and range (min-max) of the children's skills and
 9 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

1

2

3 3.2. Correlation analyses

4 Table 2 provides correlations between performance on the tasks measured in kindergarten

5 (VA span, phonological awareness, letter-name and letter-sound knowledge, early word

6 identification and verbal short-term memory) and correlations between the tasks administered

7 in kindergarten and at Grade 1. Age correlated with performance in phonological awareness

8 and visual attention span in kindergarten. Non-verbal IQ significantly related to the same two

9 cognitive subskills but further to early word identification and verbal short-term memory.

10 Partial correlations controlling for age and IQ were thus computed. Results are presented on

11 Table 2, below the diagonal.

12 Phonological awareness, letter-name and letter-sound knowledge correlated with early word

13 identification in kindergarten. The correlation between letter-sound knowledge and early

14 word identification was very high (close to .70) suggesting that letter-sound knowledge, as a

15 particular case of grapheme-phoneme mapping, mainly reflected early literacy skills (Hulme

16 et al., 2012). A composite variable was thus computed as mean performance of the two tasks,

17 which resulted in a normally distributed variable. This score was used as an indicator of the

18 pre-readers' literacy knowledge ("Early literacy knowledge" variable hereafter) in subsequent

19 analyses. As expected, early verbal short-term memory correlated with phonological

1 awareness in kindergarten but with none of the reading variables. More unexpectedly,
2 phonological awareness was found to correlate with VA span in kindergarten.
3 At Grade 1, all the reading variables were highly correlated. Further, significant correlations
4 were seen between performance in Kindergarten and Grade 1. Early word identification
5 significantly correlated with all the reading measures at T2 but none of the correlations
6 between phonological awareness or letter knowledge in kindergarten and reading performance
7 at Grade 1 were significant, except for letter name knowledge that significantly correlated
8 with text reading fluency. Critically, VA span abilities in kindergarten correlated with
9 irregular word and pseudo-word reading fluency at the end of Grade 1. The relationship was
10 close to significance ($r=.29$, $p=.0011$; threshold of significance at $.0009$ after Bonferroni
11 correction) for text reading.

12

13

----- Insert Table 2 about here-----

1 Table 2: Correlations (above the diagonal) and partial correlations (after control of age and IQ
 2 effects; below the diagonal) between predictive variables in kindergarten (T1) and, text,
 3 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	.14	.35	.40	.09	.25	.19	.20	.19	.14	.11
2.Raven Matrices	—	.37	.52	.14	.29	.30	.37	.25	.29	.23
3. T1 VA span	—	—	.57	.13	.28	.37	.29	.38	.41	.39
4. T1 Phonological awareness	—	.41	—	.21	.43	.45	.51	.32	.33	.30
5. T1 Letter name knowledge	—	.07	.15	—	.56	.50	.10	.34	.28	.30
6. T1 Letter sound knowledge	—	.13	.29	.55	—	.70	.27	.29	.33	.35
7. T1 Early word identification	—	.25	.33	.48	.66	—	.25	.50	.53	.58
8. T1 Verbal STM	—	.13	.37	.04	.15	.14	—	.26	.29	.28
9. T2 Text reading fluency	—	.29	.18	.31	.21	.44	.17	—	.89	.84
10. T2 PW reading fluency	—	.33	.20	.25	.25	.48	.19	.88	—	.87
11. T2 IW reading fluency	—	.32	.20	.27	.29	.55	.21	.83	.86	—

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

5

6 3.3. Regression and path analyses

7 We used regression analyses to explore the contribution of basic cognitive skills in
 8 kindergarten to reading performance one year later. Verbal short-term memory was not
 9 included in the models as it correlated with neither early literacy knowledge nor with any of
 10 the reading subskills at the end of Grade 1. Three regression analyses were computed, one for
 11 each of the reading subskills, namely text reading, irregular word reading and pseudo-word
 12 reading fluency. The measures of letter name knowledge, phonological awareness, VA span
 13 and the autoregressive effect of early literacy skill were implemented as potential predictors

1 of reading performance at T2. Results are presented in Table 3 for the three reading measures
 2 (regression analyses computed on raw scores while further including Age and IQ as
 3 regressors, are presented in Table S1, supplementary material).

4

5 Table 3: Hierarchical regression results (standardized coefficients and z values, after control
 6 of age and IQ) of early literacy knowledge, letter-name knowledge, phonological awareness
 7 and VA span in kindergarten as predictors of text reading fluency, pseudo-word and irregular
 8 word fluency at the end of Grade 1; the ΔR^2 columns present the incremental R^2 for each
 9 significant factor when entered after all the others in the analysis, representing the
 10 unique contribution of that factor to the dependent variable.

Dependent variables	Text reading fluency			Pseudo-word reading fluency			Irregular word reading fluency		
Equation results:	R = .39; Adj.R ² = .182; F(4,119) = 6.606 ***			R = .46; Adj.R ² = .214; F(4,119) = 8.083 ***			R = .46; Adj.R ² = .216; F(4,119) = 8.201 ***		
Factors	β	z	ΔR^2	β	z	ΔR^2	β	z	ΔR^2
Early literacy knowledge	.169	1.66~	.017~	.297	2.78**	.054**	.337	2.81**	.069**
Letter name	.207	2.45*	.028*	.071	.91		.072	.99	
Phonological awareness	-.009	-.09		-.021	-.26		-.040	-.41	
Visual attention span	.236	2.72**	.047**	.273	2.95**	.063**	.235	2.67**	.046**

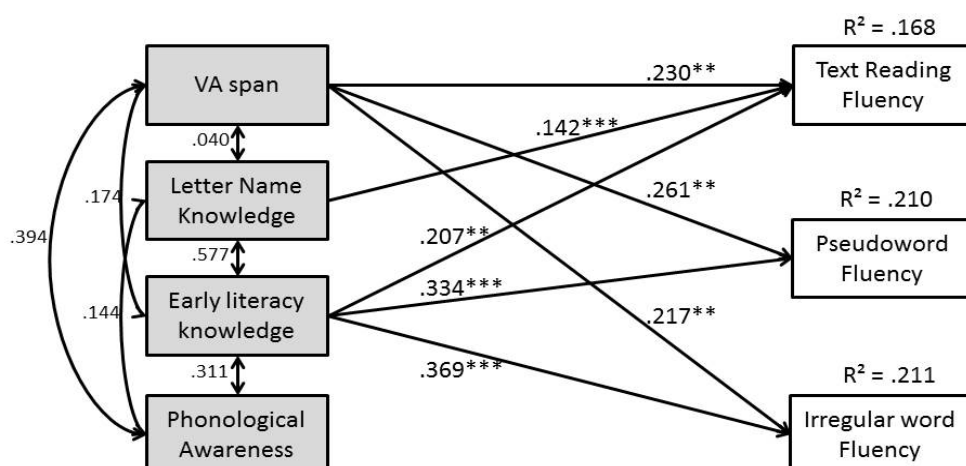
11

12 The total model R^2 values ranged from .182 for text reading fluency to .216 for irregular word
 13 reading fluency (all ps < .001). Early literacy skill was a significant predictor of pseudo-word
 14 and irregular word reading fluency, accounting for 5.4% and 6.9% of unique variance
 15 respectively. The contribution of early literacy knowledge was near significance for text
 16 reading fluency (1.7% of explained variance, p = .09). Letter name knowledge was a
 17 significant predictor of text reading fluency only, with a unique contribution of 2.8% of

1 explained variance. Phonological awareness accounted for no additional amount of unique
2 variance whatever the reading subskills. On the contrary, VA span was a significant predictor
3 of all the measures of reading fluency at the end of Grade 1, with a unique contribution of 4.7,
4 6.3 and 4.6 percent of explained variance, respectively for text, pseudo-word and irregular
5 word reading.

6 A path diagram was created in which all three reading fluency measures at grade 1 were
7 included as separate endogenous variables with separate paths from all kindergarten
8 predictors (see supplementary materials S1 and S2 for models including global report and
9 partial report performance as separate predictors). After first fitting the saturated model, non-
10 significant paths were removed step-by-step, until a simplified model was obtained in which
11 all remaining paths and covariances were statistically significant. The resulting simplified
12 model, illustrated in Figure 1, fits the data very well [$\chi^2(5, N = 124) = 1.013, p = .961,$
13 comparative fit index (CFI) = 1, root mean square error of approximation (RMSEA) = 0 (90%
14 confidence interval CI = 0—0, probability RMSEA < .05 = .98), Standardized Root Mean
15 Square Residual (SRMR) = .015].

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



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

5
 6 4. Discussion

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

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

8
9 The main contribution of the current study is to provide first evidence that VA span prior to
10 formal literacy instruction predicts later reading speed performance, which would support a
11 causal relationship. Our results indeed suggest that higher visual attention capacity in
12 kindergarten allows children to identify more letters simultaneously, thus processing longer
13 orthographic units and reading words and pseudo-words more fluently.

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

21 Are unfamiliar visual characters more relevant than familiar characters to estimate visual
22 attention capacity? Previous studies have shown that single unfamiliar visual characters can
23 be quite efficiently identified after only a few thousand exposures (Pelli et al., 2006).
24 However and despite efficient single character identification, the participants were unable to
25 process more than one or two of these unfamiliar characters at a time (Pelli et al., 2006).

1 Similar findings have been reported by Shovman & Ahissar (2006). They observed that expert
2 readers of Hebrew who could successfully identify the central target of a Georgian (unknown
3 alphabet) three-letter string were unable to accurately identify all three letters simultaneously.
4 These results are quite in line with reports of poor symbol string identity processing in expert
5 readers, showing close-to-chance-level identification of the symbols outside fixation (Ziegler
6 et al., 2010), poor signal to noise ratio (Yeari et al., 2017) and high error rate (Collis et al.,
7 2013). The overall findings are consistent with a balance between object-based and space-
8 based attention, so that increased difficulty for feature integration of unfamiliar and complex
9 visual shapes would proportionally reduce the deployment of visual attention capacity over
10 multiple shapes (Elahipanah, Christensen & Reingold, 2011; Khan et al., 2016).

11

12 The use of multiple familiar visual shapes (like letters or digits) in VA span tasks was
13 privileged to reduce the amount of visual attention to be allocated to the processing of each
14 single character within the array and rather focus on the amount of attention distributed over
15 multiple elements for parallel processing. It is further noteworthy that the use of letters and
16 digits is quite common in research on visual processing and visual attention skills. Letters
17 were used to measure the very early steps of visual processing (Sperling, 1960, 1967) and
18 develop theories of visual attention (Bundesen, 1990; Laberge & Brown, 1989). Furthermore,
19 tasks of whole and partial report are quite classical paradigms to explore simultaneous
20 perception of multiple visual elements (Allport, 1968; Averbach & Sperling, 1968; Duncan et
21 al., 1999; Habekost, 2015; Kyllingsbaek et al., 2006). Research has clearly established that
22 letters within words and even within consonant strings are identified in parallel (Adelman,
23 Marquis & Sabatos de Vito, 2010; Marzouki & Grainger, 2014). Parallel information on letter
24 identity is available after presentation durations of only a few tens of milliseconds, before any
25 verbal recoding can take place. For all positions within string, letter identification improves

1 when presentation duration increases but response accuracy curve shapes remain quite similar
2 across presentation durations, suggesting that visual encoding was not abandoned for verbal
3 encoding at longer (yet short enough to force parallel processing) presentation durations
4 (Marzouki & Grainger, 2014). With respect to VA span tasks, Lobier et al. (2012a) explicitly
5 addressed the verbal encoding issue, exploring whether VA span estimation would differ
6 depending on using letters, digits or unfamiliar visual characters. A categorization task
7 procedure was used to avoid floor effects in the condition requiring parallel processing of
8 unfamiliar characters. Results showed that children with higher performance in the
9 conventional VA span whole letter report paradigm also showed higher performance in the
10 categorization tasks regardless of character familiarity. In the same way, dyslexic children
11 with a VA span deficit showed poor performance in the non-verbal categorization task and the
12 deficit was of similar amplitude for the verbal (familiar) and non-verbal (unfamiliar)
13 categories. The available behavioural findings thus suggest that VA span performance is
14 visually-driven whether using familiar letters or digits or unfamiliar character strings.

15 To definitely establish that VA span tasks tap visual attention processing skills and discard
16 any involvement of phonological/language skills, neuroimaging studies were carried out. The
17 superior parietal lobules bilaterally were consistently identified as the neural underpinnings of
18 VA span, thus brain regions that are neither linguistic nor phonological but belong to the
19 dorsal attention network (Peyrin et al., 2011, 2012; Reilhac, Peyrin, Démonet & Valdois,
20 2013; Lobier, Peyrin, LeBas & Valdois, 2012b; Lobier et al., 2014; Valdois et al., 2014,
21 2018). Typical readers who show higher performance on the whole report task, thus showing
22 higher VA span, further show stronger activation of the superior parietal lobules (SPLs)
23 bilaterally. Dyslexic children with reduced VA span behaviourally – as measured through
24 tasks of whole and partial letter report – show reduced activation of the SPLs (Peyrin et al.,
25 2011, Reillac et al., 2013) while these same brain regions are normally activated during multi-

1 element parallel processing in dyslexic individuals with a selective phonological deficit
2 (Peyrin et al., 2012). Moreover, as a mirror of the experimental findings showing similar VA
3 span estimation regardless of character type, neuroimaging findings have shown similar
4 involvement of the SPLs when using either familiar or unfamiliar character strings in
5 categorization tasks (Lobier et al., 2012b, 2014). Converging evidence from behavioural and
6 neuroimaging research thus supports a visual attention interpretation of the results on VA
7 span tasks, which leads to conclude from the present results that children with higher visual
8 attention capacity in kindergarten read more fluently one year later.

9
10 How does visual attention capacity affect reading acquisition? We here propose a sketch of
11 the role of visual attention in reading acquisition that is largely inspired by the model initially
12 proposed by Laberge and Samuels (1974). For beginning readers, all printed words are
13 unfamiliar letter strings. Attempting to deploy visual attention over the entire word letter-
14 string would result in diffuse attention deployment, thus allocating not enough attention to
15 each letter for their accurate identification. At the beginning of literacy instruction, children
16 have been familiarized with letter shapes and letter names but the processing of individual
17 letters is not fully automatized. Letters are mainly analysed as combinations of visual features
18 and attention is required to bind these features together into a single letter percept (Treisman
19 & Gelade, 1980; Wolfe & Cave, 1999). The identification of letters within strings is further
20 degraded depending on distance to fixation (the acuity gradient) and due to interference from
21 adjacent letters (crowding effect). Additional visual attention capacity is thus required to
22 compensate for these acuity and crowding effects in order to enhance accurate letter
23 identification (Carrasco, 2011; Risko, Stolz & Besner, 2010). Overall, beginning readers have
24 to allocate a large amount of their visual attention resources to each individual letter
25 processing within strings, allowing to solve the binding problem in integrating relevant visual

1 features to form the letter percept while excluding features from adjacent letters to avoid
2 misidentifications. Visual attention thus concentrates on each letter in turn which improves
3 discriminability and letter identification but results in letter-by-letter reading. With time and
4 exposure to printed letters and words, visual expertise improves. Children more efficiently
5 discriminate the letters of the alphabet that are perceived as wholes, thus requiring minimal
6 attention (Pelli et al., 2006; Wiley, Wilson & Rapp, 2016). More automatized individual letter
7 identification makes an amount of visual attention resources available for further processing.
8 Visual attention then deploys over adjacent letters, which allows learning statistical letter
9 cooccurrences (Egley, Driver & Rafal, 1994; Zhao et al., 2014). Attention acts as a glue to
10 encode multi-letter units, like bigrams and trigrams (Dehaene, Cohen, Sigman & Vinckier,
11 2005), or multi-letter graphemes. Attention thus contributes to the precise and timely
12 encoding of longer and longer orthographic units from bigrams and graphemes to syllables,
13 morphemes and words. The multi-letter units successfully encoded as perceptual units are
14 stored in long-term memory (Lachter et al., 2004). The model thus predicts that children
15 would initially show an exaggerated length effect due to letter-by-letter reading but that this
16 effect would gradually decrease due to the processing of longer and longer units as wholes.
17 More specifically, variations in the length effect are expected to depend on the child visual
18 attention capacity. Although further research is needed to address this issue more in depth,
19 some available findings already support this prediction. Van den Boer et al. (2013) showed
20 that VA span is a unique predictor of individual differences in length effect in second grade
21 children. Dyslexic children and young adults with a VA span deficit show an exaggerated
22 length effect in reading and/or lexical decision (Juphard, Carbonnel & Valdois, 2004; Valdois
23 et al., 2003, 2011). Evidence from acquired dyslexia also supports a relationship between
24 visual attention capacity and the length effect in reading (Habekost, 2015). Another source of
25 evidence comes from computational modelling showing how variations in the distribution of

1 visual attention affect word length effect in lexical decision (Ginestet et al., in press). As
2 reading is speeded-up when processing longer units as wholes, a relationship between VA
3 span and reading speed is further expected. Such a relationship is supported by data from
4 typical readers (Bosse & Valdois, 2009; Lobier et al., 2013) and dyslexic children (Bosse et
5 al., 2007; Zoubrinetzky et al., 2014).

6
7 Another main result of the current study is that VA span measured in kindergarten predicts
8 future performance in different reading subskills (irregular word and pseudo-word reading)
9 and in text reading. This result is quite compatible with the conceptual model proposed above,
10 since the model postulates involvement of visual attention resources whatever the letter-string
11 to be processed. If we assume that a larger amount of visual attention resources allows
12 processing longer units as wholes earlier, then the processing of longer multi-letter graphemes
13 and longer syllables would improve pseudo-word reading speed and more generally
14 sublexical processing. If we assume that words are the largest units that can be processed as
15 wholes then the same logic applies and greater VA span should allow to process words by
16 sight earlier, with a positive effect on irregular word reading speed. Our results further
17 suggest a relationship between VA span and text reading, which is quite compatible with the
18 findings discussed above, assuming that more speeded reading of individual words would
19 result in more speeded text reading. However, text reading differs from individual word
20 reading in requiring serial shifting of attention and eye movements, and in relying on
21 parafoveal preview (Franceschini, Gori, Ruffino, Pedrolli & Facoetti, 2012; Ghahghaei,
22 Linnell, Doby & Davis, 2013; Ghahghaei & Linnell, 2018; Schotter, Angele & Rayner, 2012).
23 The present findings suggest that VA resources that improve the ability to process several
24 adjacent letters as wholes remain as a significant contributor of reading speed independently
25 of the reading context (words in isolation or in sentences).

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

16

17 **5. Conclusion**

18 Previous research has widely documented the existence of a relationship between VA span
19 and reading performance in typical readers and dyslexic individuals. The current study for
20 the first time establishes through a longitudinal study that VA span prior to literacy instruction
21 predicts reading fluency one year later, at the end of Grade 1. These findings bring support for
22 a theory that reading acquisition depends critically on the amount of visual attention capacity
23 available for multi-element simultaneous processing. We propose a new conceptual model of
24 the role of visual attention span in learning to read. The model opens new perspectives on

1 reading acquisition and word-specific orthographic learning that would trigger a number of
2 new studies to validate or invalidate all or part of its predictions.

3

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