The visual-attention span deficit in developmental dyslexia: Review of evidence for a visual-attention-based deficit

Sylviane Valdois

Research Article

The Visual-Attention Span Deficit in Developmental Dyslexia: Review of evidence for a visual-attention-based deficit

Sylviane VALDOIS

e-mail address: sylviane.valdois@univ-grenoble-alpes.fr

First published : 28 july 2022 - **https://doi.org/10.1002/dys.1724**

ABSTRACT

The visual attention span (VAS) deficit hypothesis in developmental dyslexia posits that a subset of dyslexic individuals shows a multielement parallel processing deficit due to reduced visual attention capacity. However, the attention-based interpretation of poor performance on visual attention span tasks is hotly debated. After presentation of the different paradigms that have been used for VAS assessment, we assess evidence in support or against a visual interpretation of the VAS deficit. We first review evidence from oral report tasks and verbal material to discuss alternative phonologically-based interpretations of the deficit. We then focus on results from symbol string processing tasks to question generalization of the VAS deficit to non-linguistic material. To provide further insights on the verbal versus visual attention interpretation of the VAS deficit, we explore how VAS relates to other reading-related cognitive skills and then turn to neuroimaging studies that explored the neural underpinnings of VAS. Last, we identify the visual and visual attention mechanisms involved in string processing and question potential effects of visual short-term memory on VAS performance. The overview clarifies the debate on what is being measured through visual attention span tasks and how to interpret the visual attention span deficit in developmental dyslexia.

1. Introduction

Developmental dyslexia is a specific reading acquisition disorder that affects children of normal intelligence, who show no neurological or psychiatric disorder, have no basic sensory deficits and benefited from adequate educational opportunities. Decades of research have led to emphasize the role of phonological deficits, mainly characterized by poor phoneme awareness --an inability to identify and manipulate phonemes-- and poor letter-sound mapping, in developmental dyslexia [1, 2, 3, 4, 5, 6]. However, it has become increasingly clear that a single phonological deficit could hardly account for the heterogeneity of the dyslexic population [7, 8, 9, 10].

Beyond its phonological features, reading is a visual task that relies on accurate identification of letters and parallel letter processing for efficient word recognition. The visual attention span (VAS) deficit hypothesis posits that a subset of dyslexic individuals suffers from poor visual attention capacity, which limits the number of distinct visual elements they can process simultaneously in a multi-element array, yielding reduced VAS [11,12]. The VAS deficit hypothesis has attracted growing interest in recent years. While some research did report evidence in support of the theory, others have questioned its significance [13, 14, 15]. Indeed, the predominant use of alphanumeric characters (letters or digits) and oral report tasks to estimate VAS ability raised doubts on the purely visual interpretation of the deficit. Obviously, oral report tasks require verbal processing, so that poor performance might just as well reflect a problem with verbal coding, rapid naming or verbal short-term memory, thus supporting interpretations more in line with the phonological theory of developmental dyslexia [16, 17, 18, 19]. The use of non-verbal tasks and non-verbal material was viewed as a critical issue to disentangle the visual *versus* phonological interpretation of the deficit. However, inconsistent results emerged. Some studies showed atypical performance in dyslexic individuals but for the verbal strings only, while other studies reported deficits of similar amplitude regardless of the verbal or non-verbal nature of the stimuli.

The purpose of the present paper is to provide an overview of available evidence in support, or against, phonological or visual interpretations of the VAS deficit in developmental dyslexia. We first focus on behavioral evidence from the oral report tasks of VAS to question whether poor performance on these tasks provides strong evidence for a phonological, verbal short-term memory or visual-to-verbal mapping deficit. We then review inconsistent evidence from symbol string processing and question to what extent the report of impaired alphanumeric string processing but unimpaired symbol string processing provides strong evidence against the visual attentional account. Studies on the relationship between VAS and other reading-related cognitive skills provides further insights on the nature of VAS. Then, we extend the review to studies on the cerebral correlates of VAS to explore whether VAS relates to phonological or attentional brain networks. Last, we identify the types of visual or visual attention deficits that might impact performance on VAS tasks and argue that VAS primarily reflects the amount of visual attention capacity that is deployed over the letter string during processing.

2. How is the visual attention span measured?

In their princeps paper, Bosse, Tainturier & Valdois [11] defined VAS as the number of distinct visual elements that can be processed simultaneously in a multi-element array. In this paper, as in many subsequent studies (see supplementary material for an overview), VAS was estimated through tasks of whole and partial letter report [11, 20, 21, 22, 23, 24]. In these tasks, consonant strings (e.g., R V S N T) are displayed for a short duration at the center of the computer screen and the participant is asked to orally report either all of the letters, regardless of their position (whole report paradigm), or a single post-cued letter (partial report paradigm). Standard VAS assessment includes the two whole and partial letter report paradigms, together with a control task of single letter identification threshold. The use of these tasks revealed that, despite accurate and fast single letter processing, a subset of dyslexic individuals exhibited impaired performance on the letter report paradigms, which was interpreted as reflecting a VAS deficit [10, 11, 25, 26, 27].

The whole and partial report tasks share two common features that are the hallmarks of VAS. The array is displayed for a short enough time (≤200ms) to prevent useful eye movements and ensure parallel processing within a single fixation [28]. The two tasks require the processing of multiple elements at once. This even holds for partial report since the location of the target is unpredictable and the location cue is only displayed at the offset of the multielement string. An array of paradigms was subsequently designed to assess VAS (for details see supplementary material), including tasks of non-oral partial report [17, 29, 30, 31], visual-1 back [16, 32, 33, 34, 35, 36, 37, 38, 39], two-alternative forced choice [18, 19, 40, 41,42] and categorization [43, 44, 45, 46,47]. If the constraints of brief visual display and multielement processing were met in most studies, differences in the implementation of these paradigms may have had a non-trivial impact on performance and explain some discrepancy between the reported findings, which will be discussed below. Of course, performance on tasks that require the processing of a single target whose location in the string is fully predictable [48] or those that do not limit presentation time enough to ensure parallel processing [49] cannot be taken as evidence pro or against the VAS deficit hypothesis.

3. How to interpret performance on VAS tasks?

Behavioral evidence from alphanumeric strings.

There is a relative consensus that dyslexic individuals, as a group, are impaired on VAS oral report tasks [4, 10, 11, 17, 19, 20, 21, 22, 23, 24, 25, 26, 29, 30, 45, 50, 51, 52, 53, but 16]. Most of the concerns were about the interpretation of impaired performance on these tasks. Because of their verbal dimension, the locus of the deficit may not reside in impaired visual attention but rather in a verbal short-term memory (STM) or visual-to-verbal mapping deficit [16, 19].

A verbal STM account of poor performance on VAS tasks makes several predictions that might be experimentally assessed. Two straightforward predictions are that the VAS deficit should be found in individuals with impaired STM and should be higher in the whole than in partial report condition, since the former requires the oral report of the whole set of items. To our knowledge, no group study directly addressed these issues. However, available data do not provide strong support for these predictions. First, several case studies have shown that a VAS deficit could occur in dyslexic individuals who had preserved language and verbal STM skills [21, 22, 24, 54, 55] while other dyslexic individuals showed normal VAS despite impaired verbal STM [22, 56]. Second, the deficit where observed in the whole report condition was further found in partial report [4, 10, 11, 25] and scores on the two tasks were substantially correlated (correlation coefficients from .44 to .71 [10, 11, 25, 31, 32, 57, 58]. Unfortunately, no study provided direct comparison between performance in whole and partial report. Inspection of scores does suggest slightly higher performance in partial than in whole report [4, 10, 11, 26]. However, even if proved significant, a partial report over whole report advantage should not be taken as straightforward evidence that verbal STM affects performance in VAS tasks. A partial report advantage might reflect purely visual mechanisms. Indeed, in the absence of backward masking, information on the whole letter string remains active in iconic memory in both the whole and partial report conditions. Presentation of the post-cue immediately at the offset of the letter string might yield attention shifting towards target location on the iconic memory trace [59], which might induce slightly better target identification in partial than in global report. Further investigation is required to check reliability of the partial report advantage and, if any, whether this advantage can be abolished by presentation of a backward mask preventing further processing in iconic memory at the offset of the letter string.

Three studies were designed to more directly address the verbal, STM and visual-to-verbal account of poor VAS performance. In the first study, dyslexic participants were administered both the standard whole letter report task and a variant of the task with concurrent counting to prevent online verbal encoding [23]. It was reasoned that if performance in whole report was due to verbal coding and/or verbal rehearsal, then the concurrent verbal condition would greatly reduce VAS performance in typical readers. Furthermore, dyslexic performance would be only minimally affected by the concurrent verbal task assuming that their performance was already impacted by impaired STM in the standard version of the task. In disagreement with these predictions, typical readers only showed slightly lower performance in the task with concurrent counting and the deficit was of similar amplitude with or without concurrent verbalization in the dyslexic population. The second study compared performance on two tasks that similarly involved rapid mapping of letters onto phonology and maintenance of letter names in STM but required either simultaneous or sequential multi-element visual processing [53]. It was assumed that a verbal account would predict similar poor performance regardless of variations in visual presentation. Against this prediction, the dyslexic participants were as efficient as typical readers to report letter names when the letters were sequentially presented one at a time but their performance drastically dropped when the letters were simultaneously displayed. In the third study, the standard whole report paradigm was administered using either letters, digits or colors [23]. Although the three versions of the tasks similarly required rapid naming and maintenance of stimuli names in STM, dyslexic children were not similarly impaired whatever stimuli type. A deficit was reported in the report tasks using alphanumeric material but dyslexic participants performed like typical readers in the color report task. In showing that VAS performance is only minimally affected by suppression of verbal coding and verbal rehearsal and that poor VAS performance does not extend to all the tasks that involve oral report and verbal STM, the overall findings provide little support to the verbal account of VAS performance.

However, one might argue that these findings are not any more in support of the visual account. If the deficit was specific to simultaneous multi-element processing as suggested by the second study and the VAS deficit hypothesis, then against evidence from the third study, similarly worse performance should be expected in every task involving multi-element simultaneous processing. Although these findings are intriguing and may appear contradictory at first glance, it is worth noting that similar performance as typical readers for color strings does not reflect the fact that dyslexic individuals processed color strings more efficiently than letter or digit strings. Actually, performance was very similar regardless of stimuli type in the dyslexic population, which contrasts with the pattern of performance of typical readers who found more challenging to process strings of colors than of letters or digits (see also [33]). An alternative interpretation that would deserve further investigation might be that typical readers are more sensitive to the visual familiarity of multielement strings than dyslexic readers.

Behavioral evidence from symbol string processing

Since the definition of the VAS deficit encompasses all types of visual stimuli, dyslexic individuals should perform worse than typical readers not only on letter or digit report tasks but further on non-verbal tasks using non-alphanumeric stimuli [17, 18, 19, 32]. Impairment on symbol-strings would sideline any phonological/verbal interpretation and provide strong support for the VAS theory.

A series of studies was designed to test the ability of dyslexic individuals to process strings of unknown, non-nameable, items (like pseudo-letters, unknown geometrical shapes, characters from foreign alphabets…, referred to as "symbols" here after). Results were rather inconsistent. Some studies reported worse symbol-string processing performance in dyslexic than typical readers [38, 40, 41, 45] while others failed to find a deficit on symbol-strings [16, 18, 33] and so, even when the same participants did exhibit a deficit on alphanumeric strings [17, 19, 33]. An overview of relevant studies (see supplementary material) highlights the large variety of paradigms that were used and non-trivial differences in the implementation of each paradigm.

Different paradigms of visual-1back [16, 33, 38], two-alternative forced-choice [17, 18, 19, 40, 41] and categorization [45] were adopted across studies to explore symbol-string processing. This variety contrasts with the relative consistent use of similar oral report tasks to explore alphanumeric multielement simultaneous processing. However, the use of different paradigms would unlikely account for the reported inconsistencies. Indeed, evidence for a deficit in symbol-string processing comes from as many different paradigms as evidence of preserved symbol-string processing. Moreover, opposite results have been reported despite using the same paradigm. For example, both Yeari et al. [18] and Jones et al. [40] used the two-alternative forced-choice (2AFC) paradigm, initially proposed by Pammer et al. [41,42], in which a target five-symbol string was briefly displayed followed by a mask; then two symbol-strings were presented and the participant was asked to select the string that strictly matched the target (motor response). Using this same paradigm and identical instructions, Yeari et al. [18] reported no deficit in the dyslexic population while Jones et al. [40] found worse performance in dyslexic than typical readers, as previously reported by Pammer et al. [41].

An alternative explanation of contradictory results may reside in the way the different paradigms were implemented. To go back to the previous example, Jones et al. (2008) administered a task that was strictly identical to that of Pammer et al. [41] while the task administered by Yeari et al. [18] differed from the original one in the way the alternative strings were generated. Far from being trivial, this had for consequence that accurate performance on two third of the trials could follow from accurate processing of the sole symbol at fixation in the former studies while the same strategy would only marginally affect performance in the latter. Given that the symbol at fixation is best identified in fast symbol-string processing [60], differences in the way the paradigm was implemented made the task easier in Pammer et al. [41] and Jones et al. [40] than in Yeari et al. [18]. This is attested by the report of higher task sensitivity in the former two studies and close to chance level performance for both typical and dyslexic readers in the latter. Differences in task difficulty/sensitivity may well be the factor that best account for opposite reports of the presence or absence of deficits in dyslexic individuals. Although specific studies comparing performance between different versions of the tasks would be useful to strengthen this hypothesis, inspection of task designs and reported levels of performance suggests that failure to report a deficit in the dyslexic population cooccurs with the use of challenging tasks yielding very low performance in typical readers. An excessively high level of errors characterized typical readers' performance on symbol strings in Collis et al. [17]'s study (from 60% to 80% errors). Dyslexic performance was close to chance level on all string positions except at fixation in the 2AFC task used in Ziegler et al. [19]'s study.

The very low level of performance of typical readers reported for symbol-strings in these studies contrasts with the reasonable level of performance they reached in the study of Lobier et al. [45]. Discrepancy between Lobier et al. [45]'s findings and the other studies is not surprising. There is now ample evidence that even expert readers cannot identify briefly presented symbol-strings efficiently [28, 48, 61]. To improve performance in single symbol processing prior to administrating the experimental task, participants in the Lobier et al. [45]'s study were not only familiarized with the different categories of symbols but further trained to attribute each individual symbol to the appropriate category. Furthermore, assuming that visual processing entails accumulating evidence that a stimulus belongs to a visual category (based on within-category shared general features) before being able to identify a specific stimulus within each category (based on target-specific features), participants were asked to categorize target symbols as belonging to a given category rather than identifying them among distractors, as typically done in the other studies. As a result, typical readers were as efficient at processing symbol- as letter- or digit-strings, which left room to highlight poorer performance in dyslexic individuals.

Overall, one can hardly draw solid conclusions in support or against the VAS deficit hypothesis from these inconsistent findings. Further studies are needed to explore to what extent the poor performance of typical readers for symbol-strings would primarily reflect low visual familiarity with symbols and whether the gap between dyslexic and typical readers' performance depends on whether the task is more or less challenging for typical readers. Another important issue to clarify the debate would require controlling that the symbols presented within strings do not correspond to known verbal labels. Indeed, the use of nameable stimuli --like color patches [33], known geometrical shapes [33] or keyboard characters (like %, ?, @, <, &, ! or }; [17, 19])—as symbols is rather puzzling.

The VAS relationship with other reading-related cognitive skills

The verbal or visual interpretation of VAS performance further makes different predictions on the deficits that should accompany the VAS deficit in developmental dyslexia. If verbally-driven, the VAS deficit would be prone to overlap with phonological deficits. The relationship between VAS and PA was the most often investigated. Most of the studies that measured both PA skills (through tasks of phoneme deletion, segmentation or acronyms, or tasks of alliteration or rhyme fluency), and VAS performance through letter report tasks very consistently concluded to the absence of relationship between the two measures [10, 11, 26, 30, 31, 50, 51, 52]. However, strong relationships were reported between VAS and some specific PA tasks. For example, Bosse et al. ([11], study 2) reported significant correlations between VAS and performance on the spoonerism task – a task that requires exchanging the onsets of two given words-- but not between VAS and the PA tasks of alliteration or rhyme fluency. Several other studies that based their PA assessment on spoonerisms also reported significant correlations with VAS performance [25, 33, 57, 62]. In the same way, van den Boer et al. [63] found significant correlations between VAS and phoneme deletion but only for the most challenging version of the task. No significant relationship was found when the task required to delete a single phoneme from a pseudo-word (e.g., say *tral* without *r*) but the relationships were found significant when the phoneme to be deleted occurred twice in the pseudo-word (e.g., say *gepgral* without *g*). In the same way, significant correlations were reported in all subsequent studies that used this phoneme double deletion task [64,65,66]. As a phonological interpretation of the VAS-PA relationship would extend to all PA tasks, the overall findings suggest that the two measures of PA and VAS tap different cognitive processes and that performance on letter report VAS tasks would unlikely reflect the phonological processes involved in PA tasks. Evidence for a relationship with some specific PA tasks requires further investigation to identify what are the mechanisms involved in the tasks of spoonerisms and double deletion that might explain the reported relationship with VAS performance.

Common features between VAS and PA would further predict comorbidity of the phonological and VAS deficits in the dyslexic population. Contrary to this expectation, the share of dyslexic individuals who exhibited both deficits was very consistently found lower than the share exhibiting one single deficit on either the phonological or VAS measures [10, 11, 25, 26, 51]. However, a larger overlap was reported between phonological and VAS deficits when both PA and rapid automatized naming (RAN) were taken as markers of the phonological deficit [4].

It is worth noting that the visual-to-verbal mapping account of VAS performance would predict privileged links between VAS and RAN, since RAN requires rapid naming of arrays of visual elements. Although nonsignificant relationships between VAS and RAN were sometimes reported [41, 50], most studies concluded to the existence of substantial correlations between the two skills [4, 25, 30, 33, 40, 62, 63, 64, 65, 66, 67]. In a recent paper, de Jong & van den Boer [67] examined the nature of the relationship between VAS and RAN in typical readers. They estimated VAS using the whole report paradigm and examined its relation with two formats of RAN. In the discrete format, letters and digits were presented one at a time and had to be successively named. In the serial format, they were simultaneously displayed in rows, following the original paradigm of Denckla & Rudel [68]. The authors reported moderate correlations between VAS and serial RAN but no significant correlations between VAS and discrete RAN. As both discrete and serial RAN involve similar rapid retrieval of verbal codes from visual alphanumeric characters, their findings suggest that the relationship between VAS and serial RAN, when observed, cannot be attributed to the mapping between visual elements and phonological codes. To the contrary, their investigation suggests that the VAS paradigm and serial RAN might share common visual processes. In particular, the overlap might be due to the involvement of parallel processing of multiple visual elements in serial RAN as in VAS tasks (for converging evidence, see Valdois, Zaher, Mandin & Bosse [69]).

On the other hand, if it was visually-driven, we would expect VAS performance to relate with performance on purely visual tasks, in particular those that relate with reading development [70, 71, 72]. The results of two studies support this prediction. Germano et al. [51] reported substantial correlations between performance on the letter whole report VAS task and tasks of visual perception that required the matching of visual shapes that differed in size or orientation. Lallier, Donnadieu & Valdois [73] showed that performance on the whole and partial letter report VAS tasks related to visual search performance, but only when the target did not pop-out, thus requiring serial attentional processing of subsets of visual elements. Further studies are required to explore more in depth the relationship between VAS and purely visual tasks. In particular, these studies would assess whether the relationship is specific to the visual tasks that involve multi-element parallel processing, as expected following the VAS theory.

Evidence from neuroimaging studies

Some neuroimaging studies were designed to identify the neural underpinnings of VAS in order to contribute to the debate on the visual *or* phonological account of poor VAS performance in developmental dyslexia. The rational was that a phonologically-driven VAS deficit should be found associated with atypical functioning of the brain regions of the language network while involvement of the attentional network brain regions would support a visual attentional account.

Decades of research in neurosciences have led to identify the different brain networks that are associated with either language skills or visual attentional processing. Language abilities relate to the perisylvian brain network within the left hemisphere, including inferior frontal areas, the superior temporal cortex and the inferior parietal lobule [74]. Reduced activation of these brain regions has been highlighted in relation with phonological and visual-verbal mapping deficits in developmental dyslexia [75, 76, 77, 78, 79]. Otherwise, neuroimaging studies have revealed that visuo-spatial attention relates to posterior brain areas bilaterally, including the temporal parietal junction, the superior parietal lobule and the frontal eye fields [80,81]. Because of its implication in selective attention and in the binding of features for the recognition of visual stimuli, the parietal cortex might be more specifically involved in learning to read and developmental dyslexia [82,83].

The studies carried out to identify the cerebral correlates of VAS in typical readers (adults or children) showed involvement of the superior parietal lobules (SPLs) bilaterally during the simultaneous processing of multiple visual elements [43, 44, 46, 84, 85]; see supplementary material for an overview). Parietal activations were very consistently reported either using tasks of categorization [43, 46], oral report [84] or string comparison [85]. Moreover, parietal involvement in typical readers did not differ whether the elements within strings were symbols or alphanumeric characters [43]. Assuming that a VAS deficit only characterizes a subset of the dyslexic population [10, 11, 26, 51], fMRI studies were administered to dyslexic individuals who were *a priori* selected to show a VAS deficit on the standard oral report tasks behaviorally. Reduced SPLs activation was systematically reported in VAS-impaired dyslexic readers [24, 44, 46, 84, 85]. Critically, fMRI investigation revealed similar under-activation of the SPLs regardless of character type, either alphanumeric characters or symbols. In support of the VAS deficit attention-based interpretation, the available findings suggest that multielement simultaneous processing deficit at the behavioral level relates to atypical activation of brain regions (the SPLs) that belong to the dorsal attentional network. Furthermore, against the verbal interpretation, the verbal or non-verbal nature of the stimuli does not modulate parietal involvement in multi-character simultaneous processing.

Stronger evidence to disentangle the verbal *versus* attention account of poor performance on VAS tasks would require demonstrating first that VAS-impaired dyslexic individuals with parietal under-activation do show normal language brain network activity; second, that individuals with a unique phonological deficit show preserved activation of the SPLs. A single research reporting neuroimaging data from two case-studies addressed this issue [47]. The participants were selected to show double dissociation of phonological and VAS deficits at the behavioral level. Neuroimaging investigation revealed contrasted patterns of brain activation that mirrored the reported cognitive double-dissociation. The participant with a unique VAS deficit showed reduced activity of the SPLs in multielement processing but normal perisylvian functioning during phonological processing. The participant with a unique phonological deficit showed the reverse pattern, namely perisylvian underactivation but preserved SPLs functioning. If replicated through larger samples, such findings should be of critical significance to strengthen the attention-based interpretation of VAS performance.

Two further findings from the follow-up of a VAS-impaired dyslexic child and from assessment of a brain-damaged patient who suffered bilateral damage of the SPLs at the adult age provide further support for an attention-based VAS interpretation. The dyslexic child exhibited a unique VAS-deficit associated with under-activation of the parietal regions at initial testing. Intensive VAS-targeted training yielded improvement of her VAS oral report performance that was accompanied by bilateral activation increase of the SPL [24]. Investigation of the adult patient revealed a severe VAS deficit on letter oral report tasks following bilateral damage of the SPLs but preserved oral language and verbal short-term memory skills [86]. Furthermore, as previously reported for VAS-impaired dyslexic children, the patient demonstrated preserved ability in the verbal STM taxing task of sequential report in which she had to orally recall the names of series of letters that were presented sequentially one at a time. She only failed when oral naming relied on parallel processing of letters within strings. Results from these two studies support a specific link between VAS performance, even when measured on oral report tasks, and the dorsal attention network.

The overall findings suggest that VAS performance relates to the activation of parietal regions within the dorsal attention network, that these parietal regions are similarly activated by VAS tasks either using verbal or non-verbal material, and that variations in SPLs functioning do impact performance on VAS oral report tasks without affecting verbal or STM skills. Interestingly, the activation of the SPLs was found to covary with activation of the visual word form area [44, 85, 87, 88; see also 89], suggesting that the VAS neurobiological underpinnings relate to the orthographic hub of the reading neuronal network, well in agreement with evidence for a privileged relationship between orthographic knowledge and VAS skills [62, 66, 69, 90, 91]. A VAS deficit in dyslexic individuals might thus reflect abnormal functioning of a cerebral network that is dedicated to the simultaneous processing of multielement visual arrays and is in particular involved in word-specific orthographic knowledge.

What kind of visual deficit?

Independently of the verbal issue, there is no doubt that performance on VAS tasks relies on a variety of visual processes for the analysis of the input multi-character string. Hence, another important issue is to identify the visual mechanisms at play. This would help defining the experimental conditions required to specifically assess the visual-attention-based account of poor VAS performance in dyslexic individuals.

In line with evidence that word recognition in reading is letter-based [92], the ability to process letter/digit or symbol strings depends on how efficiently each letter, digit or symbol can be recognized within strings. Accurate recognition of characters within strings is modulated by three factors: character complexity, visual similarity between targets and competitors, and crowding. Each of these three factors might affect performance on VAS tasks.

There is evidence that identification efficiency closely relates to visual complexity [28]. In the case of letters, some written languages use visually more complex letters than others; this is in particular true for the Arabic language [93]. If letter visual complexity impacts letter string processing, then strings of Roman letters should be easier to identify than strings of Arabic letters. This is indeed the case; Arabic skilled readers have lower performance in Arabic-letter-string processing than French or Spanish skilled readers in Roman-letter-string processing, which yields lower VAS in Arabic [94]. Assuming that VAS performance is modulated by the visual complexity of characters, any attention-based interpretation of differential performance depending on character type, would require strict matching of alphanumeric and symbol strings in visual complexity, which was not systematically done [16, 17, 33].

Visual similarity driven by shared features is another factor that affects letter recognition [95]. In reading, delayed recognition of letters that share more visual features with competitor letters contributes to slow down word recognition [96, 97, 98, 99, 100; for a review, see 101]. In the same way, we would expect performance in symbol strings to vary depending on the visual similarity between targets and distractors. Visual similarity was manipulated by Yeari et al. [18], showing that performance in symbol-string recognition (2AFC paradigm) was significantly lower when the distractor string was visually more similar to the target. Control of visual similarity between the target and the competitor string or between the target character and the other characters within string or among the set of possible responses should help clarifying whether poor VAS performance reflects visual similarity effects rather than a visual attention deficit. Control of visual similarity is also required for familiar alphanumeric characters. Some dyslexic children have difficulty to discriminate visually similar letters (or digits) in isolation [102, 103], which might affect letter/digit string processing independently of any simultaneous processing deficit. This control is further critical when VAS tasks are administered to beginning readers who have not yet developed efficient letter recognition skills [104, 105]. It is worth noting that those studies that controlled for single character visual identification efficiency reported as accurate and fast processing of single letters or symbols in dyslexic participants as in typical readers of the same chronological age [55, 61], suggesting that poor VAS performance was specific to multielement processing.

A third factor that affects letter visibility within strings is crowding [60, 106]. Crowding is a general property of the visual system that extends to all types of visual objects and results from feature integration between the target and surrounding similar elements [107]. Crowding affects letter and digit string processing differently than symbol string processing, the latter being subject to higher levels of crowding [60]. Furthermore, several studies suggest that dyslexic individuals suffer from crowding more than typical readers of the same age [108, 109, 110; for a review, see 111]. In the absence of control for crowding effects, lower performance for symbols than letters/digits in typical readers might follow from crowding effects and the lower performance of dyslexic individuals on alphanumeric characters from excessive crowding. Increasing the distance between adjacent characters is known to compensate for crowding effects. [109, 110, 112]. An increase of inter-character spacing in VAS tasks is thus required to address the attention-based interpretation of performance while minimizing crowding effects, which was done in most previous studies, but not all [17, 19, 63]. Although inter-character spacing was not systematically manipulated (see however, [86]), evidence for a deficit in conditions of increased spacing [4, 10, 11, 26, 34, 43, 44, 45, 50] and similar poor performance in spatial configurations that minimize crowding [55] makes unlikely any crowding interpretation of poor dyslexic performance on VAS tasks.

Several studies explored whether the poor performance of dyslexic children in VAS whole report tasks stemmed from limited visual STM storage capacity or a limitation in the amount of visual attention resources available for processing. These studies were carried out within the mathematical framework of the Theory of Visual Attention (TVA; [113, 114]; for a review [115]). A visual processing speed deficit was systematically documented in individuals with developmental dyslexia as evidence of limited attentional resources while a storage capacity reduction of visual STM was only found in some participants [55, 61, 116, 117]. Interestingly, processing speed was similarly reduced in dyslexic individuals either using letters or symbols as stimuli, as expected following a purely visual attention deficit [61]. In typical readers, exploration of the relationship between VAS performance in letter whole report task, TVA parameters and reading revealed that whole report VAS performance was modulated by both attentional resources and verbal STM capacity [12]. However, the amount of attentional resources alone predicted reading speed and this relationship was mediated by VAS abilities. The overall findings suggest that a visual attention capacity reduction underlies the VAS deficit in developmental dyslexia. Interestingly, the use of the TVA framework in adult brain-damaged patients showed that similar visual attention capacity limitation was associated with neglect, simultanagnosia and letter-by-letter reading, that is to say with forms of peripheral acquired dyslexia that relate to visual attentional processing but not to phonological or language deficits [118, 119, 120].

4. Conclusion

Although it might be premature to conclude that the VAS deficit in developmental dyslexia unambiguously reflects poor visual attentional processing, most current evidence at both the behavioral and neurobiological level speaks in favor of a visually-driven rather than a verbal deficit. The review further highlights some methodological issues that are critical to minimize potential effects of crowding, letter discrimination, visual complexity and/or visual familiarity, thus making interpretation of performance on VAS tasks easier. It further highlights the fields in which additional evidence would be required and makes new predictions that might be experimentally addressed to inform the debate on the visual versus verbal interpretation of the VAS deficit. How VAS performance relates to reading skills and the debate on the causal issue were considered as outside the scope of the present overview. Clarifying the interpretation of VAS performance is a first essential step before addressing these critical issues.

5. References

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

https://doi.org/10.1111/jcpp.12029
[2] Melby-Lervåg, M., Lyster, S. A. H. & Hulme, C. (2012). Phonological skills and their role in learning to read: A meta-analytic review. *Psychological Bulletin, 138*(2), 322-352. https://doi.org/10.1037/a0026744
[3] Ramus, F., Rosen, S., Dakin, S. C., Day, B. L., Castellote, J. M., White, S., & Frith, U. (2003). Theories of developmental dyslexia: insights from a multiple case study of dyslexic adults. *Brain*, 126(4), 841–865. doi: 10.1093/brain/awg076
[4] Saksida, A., Ianuzzi, S., Bogliotti, C., Chaix, Y., Démonte, J.F., Bricout, L., Billard, C., N'Guyen-Morel, M.A., Le Heuzey, M.F., Soares-Boucaud, I., George, F., Ziegler, J. & Ramus, F. (2016). Phonological skills, visual attention span and visual stress in developmental dyslexia. *Developmental Psychology*, *52*(10), 1503-1516. https://doi.org/10.1037/dev0000184
[5] Snowling, M.J. (2000). *Dyslexia*. 2nd ed. Oxford: Blackwell.
[6] Vellutino, F.R., Fletcher, J.M., Snowling, M.J. & Scanlon, D.M. (2004) Specific reading disability (dyslexia). What have we learned in the past four decades? *Journal of Child Psychology and Psychiatry*, 45, 2–40. https://doi.org/10.1046/j.0021-9630.2003.00305.x
[7] Menghini, D., Finzi, A., Benassi, M., Bolzani, R., Facoetti, A., Giovagnoli, S., et al. (2010). Different underlying neuro- cognitive deficits in developmental dyslexia: a comparative study. *Neuropsychologia*, 48, 4, 863–872. https://doi.org/10.1016/j.neuropsychologia.2009.11.003
[8] Pennington, B.F., Santerre-Lemmon, L., Rosenberg, J., McDonald, B., Boada, R., Friend, A., Leopold, D.R., Samuelson, S., Byrne, B., Willcutt, E.G. & Olson, R.K. (2012). Individual prediction of dyslexia by single versus multiple deficits models. *Journal of Abnormal Psychology*, *121*(1), 212-224. https://doi.org/10.1037/a0025823
[9] Perry, C., Zorzi, M., & Ziegler, J. C. (2019). Understanding Dyslexia Through Personalized Large-Scale Computational Models. *Psychological Science*, 30(3), 386–395. DOI : 10.1177/0956797618823540
[10] Zoubrinetzky, R., Bielle, F. & Valdois, S. (2014). New insights on developmental dyslexia subtypes: Heterogeneity of mixed reading profiles. *Plos One*, *9*(6) Article e99337. • https://doi.org/10.1371/journal.pone.0099337
[11] Bosse, M.L., Tainturier, M.J. & Valdois, S. (2007). Developmental dyslexia: the visual attention span deficit hypothesis. *Cognition, 104*, 198-230. https://doi.org/10.1016/j.cognition.2006.05.009
[12] Lobier, M., Dubois, M. & Valdois, S. (2013). The role of visual processing speed in reading speed development. *Plos One*, 8, 4, e58097. doi:10.1371/ journal.pone.0058097
[13] Goswami, U. (2015a). Sensory theories of developmental dyslexia: three challenges for research. *Nature Reviews Neuroscience, 16*, 43–54. https://doi.org/10.1038/nrn3836
[14] Goswami, U. (2015b). Visual attention span deficits and assessing causality in developmental dyslexia. *Nature Reviews Neuroscience, 16*, 225–226. https://doi.org/10.1038/nrn3836-c2
[15] Lobier, M. & Valdois, S. (2015). Visual attention deficits in developmental dyslexia cannot be ascribed solely to poor reading experience. *Nature Reviews Neuroscience*, 16, 4, 225. doi:10.1038/nrn3836-c1
[16] Banfi, C., Kemény, F., Gangl, M., Schulte-Körne, G., Moll, K. & Landerl, K. (2018). Visual attention span performance in German-speaking children with differential reading and spelling profiles: No evidence of group differences. *PloS One*, 13, 6, e0198903. DOI 10.1007/s11881-016-0132-4
[17] Collis, N. L., Kohnen, S., & Kinoshita, S. (2013). The role of visual spatial attention in adult developmental dyslexia. *The Quarterly Journal of Experimental Psychology*, 66, 245–260. http://dx.doi.org/10.1080/17470218.2012.705305
[18] Yeari, M. Isser, M., & Schiff, R. (2017). Do dyslexic individuals present a reduced visual attention span? Evidence from visual recognition tasks of non-verbal multi-character arrays. *Annals of Dyslexia*, 67, 128-146. DOI 10.1007/s11881-016-0132-4
[19] Ziegler, J. C., Pech-Georgel, C., Dufau, S., & Grainger, J. (2010). Rapid processing of letters, digits and symbols: What purely visual-attentional deficit in developmental dyslexia? *Developmental Science*, 13 (4), F8–F14. https://doi.org/10.1111/j.1467-7687.2010.00983.x
[20] Prado, C., Dubois, M. & Valdois, S. (2007). Eye movements in reading aloud and visual search in developmental dyslexia: Impact of the VAS. *Vision Research*, 47, 2521-2530. https://doi.org/10.1016/j.visres.2007.06.001
[21] Valdois, S., Bidet-Ildei, C., Lassus-Sangosse, D., Reilhac, C., N'Guyen-Morel, M. A., Guinet, E., et al. (2011). A visual processing but no phonological disorder in a child with mixed dyslexia. *Cortex*, 47, 1197e1218.

http://dx.doi.org/10.1016/j.cortex.2011.05.011

[22] Valdois, S., Bosse, M. L., Ans, B., Zorman, M., Carbonnel, S., David, D., et al. (2003). Phonological and visual processing deficits are dissociated in developmental dyslexia: evidence from two case studies. *Reading and Writing*, 16, 543e572. https://doi.org/10.1023/A:1025501406971

[23] Valdois, S., Lassus-Sangosse, D., & Lobier, M. (2012). Impaired letter string processing in developmental dyslexia: what visual-to-phonological code mapping disorder? *Dyslexia*, 18(2), 77e93. https://doi.org/10.1002/dys.1437

[24] Valdois, S., Peyrin, C., Lassus-Sangosse, D., Lallier, M., Démonet, J.F. & Kandel, S. (2014). Dyslexia in a French-Spanish bilingual girl: Behavioral and neural modulations following a specific visual-attention span intervention program. *Cortex*, *53,* 120-145. https://doi.org/10.1016/j.cortex.2013.11.006

[25] Valdois, S., Reilhac, C., Ginestet, E. & Bosse, M.L. (2021). Varieties of Cognitive Profiles in Poor readers: Evidence for a visual-attention span impaired subtype. *Journal of Learning Disabilities, 54 (3), 221-233.* DOI: 101177/0022219420961332

[26] Zoubrinetzky, R., Collet, G., Serniclaes, W., N'Guyen-Morel, M.A., Valdois, S. (2016). Relationships between categorical perception of phonemes, phonological awareness, and visual attention span in developmental dyslexia. *PLoS One 11*(3), Article e0151015. https://doi.org/10.1371/journal.pone.0151015

[27] Zoubrinetzky, R., Collet, G., N'Guyen-Morel, M.A., Valdois, S. & Serniclaes, W. (2019). Remediation of allophonic perception and visual attention span in developmental dyslexia: a joint assay, *Frontiers in Psychology*, *10*, Article 1502. https://doi.org/10.3389/fpsyg.2019.01502

[28] Pelli, D. G., Burns, C.W., Farell, B., & Moore-Page, D. C. (2006). Feature detection and letter identification. *Vision Research,* 46, 4646-4674. doi:10.1016/j.visres.2006.04.023

[29] Hawelka, S., Huber, C., & Wimmer, H. (2006). Impaired visual processing of letter and digit strings in adult dyslexic readers. *Vision Research,* *46*, 718-723. https://doi.org/10.1016/j.visres.2005.09.017

[30] Hawelka, S., & Wimmer, H. (2005). Impaired visual processing of multi-element arrays is associated with increased number of eye movements in dyslexic reading. *Vision Research*, 45, 855-863. DOI:10.1016/j.visres.2004.10.007

[31] Holmes, V. & Dawson, G. (2014). Visual attention span and lexical decision in skilled adults. *Journal of Research in Reading*, 37, 4, 331-355. doi: 10.1111/j.1467-9817.2012.01543.x

[32] Chan, K.S.C & Yeung, P.S. (2020). Prediction of Chinese Reading Fluency by Verbal and Non-verbal Visual Attention Span Measures. *Frontiers in Psychology, 10: 3049. doi: 10.3389/fpsyg.2019.03049*

[33] Cheng, C., Yao, Y., Wang, Z. & Zhao, J. (2021). Visual attention span and phonological skills in Chinese developmental dyslexia. *Research in Developmental Disabilities*, 116. https://doi.org/10.1016/j.ridd.2021.104015

[34] Huang, C., Lorusso, M.L., Luo, Z. & Zhao, J. (2019). Developmental Differences in the Relationship Between Visual Attention Span and Chinese Reading Fluency. *Frontiers in Psychology,* 10:2450. doi: 10.3389/fpsyg.2019.02450

[35] Lallier, M., Abu Mallouh, R., Mohammed, A.M.,Khalifa, B., Perea, M. & Carreiras, M. (2018). *Scientific Studies of Reading*, 22, 2, 181-190. https://doi.org/10.1080/10888438.2017.1421958

[36] Lallier, M., Acha, J. & Carreiras, M. (2016). Cross-linguistic interactions influence reading development in bilinguals: a comparison between early balanced French-Basque and Spanish-Basque bilingual children. *Developmental Science*, 19, 1, 76-89. https://doi.org/10.1111/desc.12290

[37] Zhao, J., Kwok, R.K.W., Liu, M., Liu, H., Huang, C. (2017). Underlying skills of oral and silent reading fluency in Chinese: Perspective of visual rapid processing. *Frontiers in Psychology*, 7:2082. doi: 10.3389/fpsyg.2016.02082

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

[39] Zhao, J., Liu, M. Liu, H. & Chen, H. (2018b). The visual attention span deficit in Chinese children with reading fluency difficulty. *Research in Developmental Disabilities*, 73, 76-86. https://doi.org/10.1016/j.ridd.2017.12.017

[40] Jones, M.W., Branigan, H.P., & Kelly, L. (2008). Visual deficits in developmental dyslexia: Relationships between non-linguistic visual tasks and their contribution to components of reading. *Dyslexia*, 14, 95-115. https://doi.org/10.1002/dys.345

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

https://doi.org/10.1016/j.bandl.2004.01.009

[42] Pammer, K., Lavis, R., Cooper, C., Hansen, P.C., & Cornelissen, P.L. (2005). Symbol-string sensitivity and adult performance in lexical decision. *Brain and Language*, 94, 278-296. doi:10.1016/j.bandl.2005.01.004

[43] Lobier, M., Peyrin, C., Le Bas, J. F., & Valdois, S. (2012). Pre-orthographic character string processing and parietal cortex: A role for visual attention in reading? *Neuropsychologia*, 50, 195–204. https://doi.org/10.1016/j.neuropsychologia.2012.05.023.

[44] Lobier, M., Peyrin, C., Pichat, C., Le Bas, J.F. & Valdois, S. (2014). Visual processing of multiple elements in the dyslexic brain: evidence for a superior parietal dysfunction. *Frontiers in Human Neuroscience*, 8, 479.https://doi.org/10.3389/fnhum.2014.00479

[45] Lobier, M., Zoubrinetzky, R. & Valdois, S. (2012). The visual attention span deficit in developmental dyslexia is visual and not verbal. *Cortex*, 48, 6, 768–773. https://doi.org/10.1016/j.cortex.2011.09.003

[46] Peyrin, C., Démonet, J.F., Baciu, M., Le Bas, JF & Valdois, S. (2011). Superior parietal lobe dysfunction in a homogeneous group of dyslexic children with a single visual attention span disorder. *Brain & Language*, *118*, 128-138. https://doi.org/10.1016/j.bandl.2010.06.005

[47] Peyrin, C., Lallier, M., Démonet, J.F., Pernet, C., Baciu, M., LeBas, J.F. & Valdois, S. (2012). Neural dissociation of phonological and visual attention span disorders in developmental dyslexia: fMRI evidence from two case studies. *Brain & Language*, *120*(3), 381-394. https://doi.org/10.1016/j.bandl.2011.12.015

[48] Shovman, M. M., & Ahissar, M. (2006). Isolating the impact of visual perception on dyslexics' reading ability. *Vision Research, 46*, 3514-3525. https://doi.org/10.1016/j.visres.2006.05.011

[49] Hawelka, S., & Wimmer, H. (2008). Visual target detection is not impaired in dyslexic readers. *Vision Research*, 48, 850-852. https://doi.org/10.1016/j.visres.2007.11.003

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

[51] Germano, D.G., Reilhac, C., Capellini, A.S. & Valdois, S. (2014). The phonological and visual bases of developmental dyslexia in Brazilian Portuguese. *Frontiers in Psychology*, 5, 1169. http://www.frontiersin.org/Psychology/editorialboard

[52] Lallier, M., Valdois, S., Lassus-Sangosse, D., Prado, C., & Kandel, S. (2014). Impact of orthographic transparency on typical and atypical reading development: Evidence in French–Spanish bilingual children. *Research in Developmental Disabilities*, 35, 1177–1190. http://dx.doi.org/10.1016/j.ridd.2014.01.021

[53] Lassus-Sangosse, D., N'Guyen-Morel, M.A., & Valdois, S. (2008). Sequential or simultaneous visual processing deficit in developmental dyslexia. *Vision Research*, 48, 979–988. https://doi.org/10.1016/j.neuropsychologia.2010.09.027

[54] Bouvier-Chaverot, M., Peiffer, E., N'Guyen Morel, M.A. & Valdois, S (2012). Un cas de dyslexie développementale avec trouble isolé de l'empan visuo-attentionnel. *Revue de Neuropsychologie*, 4, 1, 24-35. DOI : 10.3917/rne.041.0024.

[55] Dubois, M., Kyllingsbaek, S., Prado, C., Peiffer, E., Lassus-Sangosse, D. & Valdois, S. (2010). Fractionating the multi-element processing deficit in developmental dyslexia: Evidence from two case studies. *Cortex,* 46, 6, 717-738. doi:10.1016/j.cortex.2009.11.002

[56] Lallier, M., Donnadieu, S., Berger, C. & Valdois, S. (2010). A case study of developmental phonological dyslexia: Is the attentional deficit in rapid stimuli sequences processing amodal? *Cortex,* 46, 231-241. https://doi.org/10.1016/j.cortex.2009.03.014

[57] Bosse, M.L. & Valdois, S. (2009). Influence of the visual attention span on child reading performance: a cross-sectional study. *Journal of Research in Reading*, 32, 2, 230-253. doi: 10.1111/j.1467-9817.2008.01387.x

[58] Chen, C., Schneps, M.H., Masyn, K.E. & Thomson, J.M. (2016). The effects of visual attention span and phonological decoding in reading comprehension in dyslexia: A path analysis. *Dyslexia*, 22, 322-344. doi: 10.1002/dys.1543

[59] Lachter, J., Forster, K. I., & Ruthruff, E. (2004). Forty-five years after Broadbent (1958): Still no identification without attention. *Psychological Review*, 111 (4), 880–913. doi: 10.1037/0033-295X.111.4.880

[60] Tydgat, I., & Grainger, J. (2009). Serial position effects in the identification of letters, digits, and symbols. *Journal of Experimental Psychology: Human Perception and Performance*, *35*(2), 480–98. doi: 10.1037/a0013027

[61] Stefanac, N., Spencer-Smith, M., Brosnan, M., Vangkilde, S., Castles, A. & Bellgrove, M. (2019). Visual processing speed as a marker of immaturity in lexical but not sublexical dyslexia. *Cortex*, 120, 567-581.https://doi.org/10.1016/j.cortex.2019.08.004
[62] Niolaki, G.Z., Vousden, J., Terzopoulos, A.R., Taylor, L.M., Hall, S. & Masterson, J. (2021). Predictors of single word spelling in English speaking children: A cross sectional study. *Journal of Research in Reading*. doi:10.1111/1467-9817.12330
[63] Van den Boer, M., de Jong, P.F., Haentjens-van Meeteren, M.M. (2013). Modeling the length effect: Specifying the relation with visual and phonological correlates of reading. *Scientific Studies of Reading*, 17,4, 243–256. http://www.tandfonline.com/loi/hssr20
[64] Van den Boer, M. & de Jong, P.F. (2018). Stability of visual attention span performance and its relation with reading over time. *Scientific Studies of Reading*, 22, 5, 434-441. https://doi.org/10.1080/10888438.2018.1472266
[65] Van den Boer, M., van Bergen, E. & de Jong, P.F. (2014). Underlying skills of oral and silent reading. *Journal of Experimental Child Psychology*, 128, 138-151. http://dx.doi.org/10.1016/j.jecp.2014.07.008
[66] Van den Boer, M., van Bergen, E. & de Jong, P.F. (2015). The specific relation of visual attention span with reading and spelling in Dutch. *Learning and Individual differences*, *39*, 141-149. https://doi.org/10.1016/j.lindif.2015.03.017
[67] De Jong, P. & van den Boer, M. (2021). The relation of visual attention span with serial and discrete rapid automatized naming and reading. *Journal of Experimental Child Psychology*, 207. https://doi.org/10.1016/j.jecp.2021.105093
[68] Denckla, M.B. & Rudel, R.O. (1974). 'Rapid automatized naming' of pictured objects, colors, letters, and numbers by normal children, *Cortex*, *10*, 186–202. https://doi.org/10.1016/S0010-9452(74)80009-2
[69] Valdois, S., Zaher, A., Mandin, S. & Bosse, M.L. (submitted). Are phonological awareness and visual attention span, two cognitive mechanisms behind the rapid-automatized-naming-literacy relationship?
[70] Plaza, M. & Cohen, H. The contribution of phonological awareness and visual attention in early reading and spelling. *Dyslexia*, 13, 67-76. doi: 10.1002/dys.330
[71] Rayner, K. (2009). Eye movements and attention in reading, scene perception and visual search. *The Quarterly Journal of Experimental Psychology*, 62, 8, 1457-1506. https://doi.org/10.1016/j.ridd.2021.104015
[72] Zhou, Y., McBride-Chang, C. & Wong, N. (2014). What is the role of visual skills in learning to read? Frontiers in Psychology, 5: 776. https://doi.org/10.1016/j.ridd.2021.104015
[73] Lallier, M., Donnadieu, S. & Valdois, S. (2013). Investigating the role of visual and auditory search in developmental dyslexia. *Frontiers in Human Neuroscience*. **7**, 597, 1-12. doi: 10.3389/fnhum.2013.00597
[74] Price, C. (2012). A review and synthesis of the first 20 years of PET and fMRI studies if heard speech, spoken language and reading. *Neuroimage*, 62, 816-847. doi:10.1016/j.neuroimage.2012.04.062
[75] Blomert, L. (2011). The neural signature of orthographic-phonological binding in successful and failing reading development. *Neuroimage, 57*(3), 695-703. http://dx.doi.org/10.1016/j.neuroimage.2010.11.003
[76] Démonet, J. F., Taylor, M. J. et Chaix, Y. (2004). Developmental dyslexia. *The Lancet*, 363(9419), 1451- 1460. https://doi.org/10.1016/S0140-6736(04)16106-0
[77] Richlan, F. (2012). Developmental dyslexia: dysfunction of a left hemisphere reading network, *Frontiers in Human Neuroscience*, 6-120. doi: 10.3389/fnhum.2012.00120
[78] Richlan, F. (2019). The Functional Neuroanatomy of Letter-Speech Sound Integration and Its Relation to Brain Abnormalities in Developmental Dyslexia. *Frontiers in Human Neuroscience,* 13, 21. doi: 10.3389/fnhum.2019.00021
[79] Xu, W., Kolozsvari, O.B., Oostenveld, R. & Hämäläinen, J.A. (2020). Rapid changes in brain activity during learning of grapheme-phoneme associations in adults. *NeuroImage*. http://doi.org/10.1016/j.neuroimage.2020.117058 .
[80] Behrmann, M., Geng, J.J. & Shomstein, S. (2004). Parietal cortex and attention. *Current Opinion in Neurobiology*, 14, 2, 212-217. DOI 10.1016/j.conb.2004.03.012
[81] Carrasco, M. (2011). Visual attention: The past 25 years. *Vision Research*, 51, 1484–1525. https://doi.org/10.1016/j.visres.2011.04.012
[82] Vidyasagar, T. R. (1999). A neuronal model of attentional spotlight: Parietal guiding the temporal. *Brain Research Reviews*, 30, 66–76. https://doi.org/10.1016/S0165-0173(99)00005-3
[83] Vidyasagar, T.R. & Pammer, K. (2010).

Dyslexia : a deficit in visuo-spatial attention, not in phonological processing. *Trends in Cognitive Sciences*, 14, 2, 57-63. doi:10.1016/j.tics.2009.12.003

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

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

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

[87] Vogel, A. C., Church, J. A., Power, J. D., Miezin, F. M., Petersen, S. E., and Schlaggar, B. L. (2013). Functional network architecture of reading-related regions across development. *Brain and Language*, 125, 231–243. doi: 10.1016/j.bandl.2012.12.016

[88] Vogel, A. C., Miezin, F. M., Petersen, S. E., and Schlaggar, B. L. (2012). The putative visual word form area is functionally connected to the dorsal attention network. *Cerebral Cortex*, 22, 537–549. doi: 10.1093/cercor/bhr100

[89] Pleish, G., Karipidis, I., Brauchli, C., Röthlisberger, M., Hofstetter, C., Stämpfli, P., Walitza, S. & Brem, S. (2019). Emerging neural specialization of the ventral occipitotemporal cortex to characters through phonological association learning in preschool children. *NeuroImage*, 189, 813-831. https://doi.org/10.1016/j.neuroimage.2019.01.046

[90] Ginestet, E., Valdois, S., Diard, J. & Bosse M.L. (2020). Orthographic learning of novel words in adults: Effect of exposure and visual attention on eye movements. *Journal of Cognitive Psychology*. https://doi.org/10.1080/20445911.2020.1823987

[91] Valdois, S., Phénix, T., Fort, M. & Diard, J. (submitted). Atypical viewing position effect in developmental dyslexia: A behavioral and modeling exploration.

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

[93] Eviatar, Z. & Ibrahim, R. (2014). Why is it hard to read Arabic ? In E. Saiegh-Haddad & R. M. Joshi (Eds.). *Handbook of Arabic literacy: Insights and Perspectives* (pp. 77-98). NY: Springer-Verlag.

[94] Awadh, F., Phénix, T., Antzaka, A., Lallier, M., Carreiras, M. & Valdois, S. (2016). Cross-language modulation of the VAS: A Spanish-French-Arabic comparison in adult skilled readers. *Frontiers in Psychology*, 7, 307. doi: 10.3389/fpsyg.2016.00307

[95] Grainger, J., Rey, A. & Dufau, S. (2008). Letter preception: from pixels to pandomenium. *Trends in Cognitive Sciences*, 12, 10, 381-387. doi:10.1016/j.tics.2008.06.006

[96] Coltheart, M., Rastle, K., Perry, C., Langdon, R., & Ziegler, J. C. (2001). DRC: A dual route cascaded model of visual word recognition and reading aloud. *Psychological Review*, *108*(1), 204–256. doi: I0.1037//0033-295X.108.1.204

[97] McClelland, J. L., & Rumelhart, D. E. (1981). An interactive activation model of context effects in letter perception: Part 1. an account of basic findings. *Psychological Review*, *88*(5), 375–407. https://doi.org/10.1037/0033-295X.88.5.375

[98] Perry, C., Ziegler, J. C., & Zorzi, M. (2007). Nested incremental modeling in the development of computational theories: The CDP+ model of reading aloud. *Psychological Review*, *114*(2), 273–315. doi: 10.1037/0033-295X.114.2.273

[99] Perry, C., Ziegler, J. C., & Zorzi, M. (2010). Beyond single syllables: Large-scale modeling of reading aloud with the Connectionist Dual Process (CDP++) model. *Cognitive Psychology*, *61*(2), 106–51. doi:10.1016/j.cogpsych.2010.04.001

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

[101] Phénix, T., Diard, J. & Valdois, S. (2016). Les modèles computationnels de lecture. In M. Sato & S. Pinto (Eds). *Traité de Neurolinguistique* (p. 167-182). De Boeck supérieur.

[102] Corballis, M.C. (2018). Mirror-Image equivalence and interhemispheric mirror-image reversal. *Frontiers in Human Neuroscience*, 12, 140. doi: 10.3389/fnhum.2018.00140

[103] Fernandes, T., Vale, A.P., Martins, B., Morais, J. & Kolinsky, R. (2014). The deficit of letter processing in developmental dyslexia :

combining evidence from dyslexics, typical readers and illiterate adults. *Developmental Science*, 17, 1, 125-141. doi: 10.1111/desc.12102
[104] Pegado F., Comerlato, E., Ventura, F., Jobert, A., Nakamura, K., Buiatti, M., Ventura, P., Dehaene-Lambertz, G., Kolinsky, R., Morais, J., Braga, L.W., Cohen, L. & Dehaene, S. (2014). Timing the impact of literacy on visual processing. *Proceedings of the National Academy of Science*, 24, E5233-E5242.
[105] Torres, A.R., Mota, N.B., Adamy, N., Naschold, A., Lima, T.Z., Copelli, M., Weissheimer, J., Pegado, F. & Ribeiro, S. (2021). Selective inhibition of mirror invariance for letters consolidated by sleep doubles reading fluency. *Current Biology*, 31, 1-11. https://doi.org/10.1016/j.cub.2020.11.031
[106] Huckauf, A., Heller, D., & Nazir, T. A. (1999). Lateral masking: Limitations of the feature interaction account. *Perception & Psychophysics*, *61* (1), 177–189. doi: 10.3758/BF03211958
[107] Pelli, D. G., & Tillman, K. A. (2008). The uncrowded window of object recognition. *Nature Neuroscience*, *11*(10), 1129–1135. https://doi.org/10.1038/nn.2187
[108] Callens, M., Whitney, C., Tops, W., & Brysbaert, M. (2013). No deficiency in left-to-right processing of words in dyslexia but evidence for enhanced visual crowding. The *Quarterly Journal of Experimental Psychology*, 66 (9), 1803–1817. http://dx.doi.org/10.1080/17470218.2013.766898
[109] Martelli, M., Di Filippo, G., Spinelli, D., & Zoccolotti, P. (2009). Crowding, reading, and developmental dyslexia. *Journal of Vision*, *9* (4), 1–18. doi: 10.1167/9.4.14

[110] Spinelli, D., de Luca, M., Judica, A. & Zoccolotti, P. (2002). Crowding effects on word identification in developmental dyslexia. *Cortex*, 38, 179-200. doi: 10.1016/s0010-9452(08)70649-x
[111] Gori, S. & Facoetti, A. (2015). How the visual aspects can be crucial in reading acquisition? The intriguing case of crowding and developmental dyslexia. *Journal of Vision*, 15(1), 1-20. doi: 10.1167/15.1.8
[112] Bouma, H. (1970). Interaction effects in parafoveal letter recognition. *Nature*, 226(5241), 177–178. https://doi.org/10.1038/226177a0
[113] Bundesen, C. (1990). A theory of visual attention. *Psychological Review*, 97, 4, 523–547. https://doi.org/10.1037/0033-295X.97.4.523
[114] Bundesen, C., Vangkilde, S. & Petersen, A. (2015). Recent developments in a computational theory of visual attention (TVA). *Vision Research*, 116, 210-218. http://dx.doi.org/10.1016/j.visres.2014.11.005
[115] Bogon, J., Finke, K., & Stenneken, P. (2014b). TVA-based assessment of visual attentional functions in developmental dyslexia. *Frontiers in Psychology*, 5, 1172. doi: 10.3389/fpsyg.2014.01172
[116] Bogon, J., Finke, K., Schulte-Körne, G., Müller, H. J., Schneider, W. X., and Stenneken, P. (2014a). Parameter-based assessment of disturbed and intact components of visual attention in children with developmental dyslexia. *Developmental Science*. 17, 697–713. doi: 10.1111/desc.12150
[117] Stenneken, P., Egetemeir, J., Schulte-Körne, G., Müller, H.J., Schneider, W.X. & Finke, K. (2011). Slow perceptual processing at the core of developmental dyslexia: A parameter-based assessment of visual attention. *Neuropsychologia*, 49, 3454-3465. doi:10.1016/j.neuropsychologia.2011.08.021
[118] Duncan, J., Bundesen, C., Olson, A., Humphreys, G., Chavda, S., & Shibuya, H. (1999). Systematic analysis of deficits in visual attention. *Journal of Experimental Psychology: General*, *128*(4), 450–478. https://doi.org/10.1037/0096-3445.128.4.450
[119] Habekost, T., Petersen, A., Behrmann, M., and Starrfelt, R. (2014). From word superiority to word inferiority: visual processing of letters and words in pure alexia. *Cognitive Neuropsychology*, 31, 413–436. doi: 10.1080/02643294.2014.906398
[120] Habekost, T. (2015). Clinical TVA-based studies: a general review. *Frontiers in Psychology*, 6: 290. doi: 10.3389/fpsyg.2015.00290

Papers investigating verbal and non-verbal VAS : Comparison Dyslexic and Control groups									
Study			Characteristics of the Task				Results		
Reference	Language	Participants	Paradigm	Strings	Time	Processing	Verbal	Non verbal	Relationship with other cognitive skills
Banfi et al. 2018	German	26 DYS - 43 CTL Children G3-G4	Visual 1-back	Letters Unknown geometrical figures	200ms	position	DYS = CTL	DYS = CTR	_______
Castet et al., 2019	French	20 DYS – 20 CTL Adults	Non-oral report: PR	Letters Symbols	94ms + mask	Identity	DYS < CTL	DYS < CTL	_______
Cheng et al., 2021	Chinese	45 DYS - 43 CTL Children 8-11 years old	Visual 1-back	Chinese characters – digits Colors – geometrical shapes	200ms	identity	DYS < CTL	DYS=CTL	Partial correlation of verbal VAS with PA (.29), RAN (.55) and verbal STM (.27).
Collis et al., 2013	English	19 DYS-23 CTL Adults	Non-oral Partial report	Letters – digits Symbols (% ? < / @...)	93ms + mask	Identity and position	DYS < CTL	DYS = CTL	_______
Hawelka et al., 2008	German	18 DYS – 18 CTL Adults	Visual target detection	Letters Pseudo-letters	Estimated	Identity	DYS = CTL	DYS = CTL	_______
Lobier et al., 2012a	French	14 DYS – 109 CTL Children G4-G5	Categorisation	Letters – digits Pseudo-letters, hiragana characters, geometrical shapes	200ms	Category membership	DYS < CTL	DYS < CTL	_______
Ziegler et al., 2010	French	28 DYS – 29 CTL Children G3-to-G7	2 AFC characters	Letters-digits Symbols (% ? < / @...)	200ms + mask	Identity	DYS < CTL	DYS = CTL	A RAN deficit in the DYS but no PA deficit
Papers investigating verbal and non-verbal VAS in typical readers									
Chan & Yeung, 2020	Chinese	101 university students	Visual 1-Back	Letters Pseudo-letters	200ms	Identity and position	_______	_______	_______
			Oral Report	Letters	200ms	Identity	_______	_______	_______

Papers using only non-verbal material : Comparison Dyslexic and Control groups									
Study			Characteristics of the Task				Results		
Reference	Language	Participants	Paradigm	Strings	Time	Processing	Verbal	Non verbal	Relationship with other cognitive skills
Pammer et al. 2004 Study 2	English	13 DYS – 13 CTL children	2 AFC String recognition	Unfamiliar symbols	100ms + mask	Position	_______	DYS < CTL	Correlation with PA (..52) but not RAN
Jones et al., 2008	English	19 DYS – 19 CTL Adults	2 AFC String recognition	Unfamiliar symbols	100ms + mask	Position	_______	DYS < CTL	Correlation with RAN (.28)
Yeari et al., 2017 Exp. 1	Hebrew	24 DYS -26 CTL Adults	2 AFC characters and strings	Unfamiliar symbols	200ms + mask	Identity	_______	DYS = CTL	_______
Yeari et al., 2017 Expé. 2	Hebrew	16 DYS - 19 CTL Adults	2 AFC characters and strings	Unfamiliar symbols	100 or 200 ms + mask	Identity	_______	DYS = CTL	_______
Zhao et al., 2018a	Chinese	57 DYS – 54 CTL G2 to G6	Visual 1-Back	Unfamiliar symbols	200ms	Identity	_______	DYS < CTL in higher grades	_______
Zhao et al., 2018b	Chinese	14 DYS – 14 CTL	Visual 1-Back	Unfamiliar symbols	200ms.	Identity	_______	DYS < CTL	_______
Papers using only non-verbal material in typical readers									
Pammer et al., 2004 Study 1	English	38 children Primary school	2 AFC String recognition	Unfamiliar symbols	100ms + mask	Position	_______	_______	Correlation with PA (..40) but not RAN
Pammer et al., 2005	English	50 adults	2 AFC String recognition	Unfamiliar symbols	100ms + mask	Position	_______	_______	No correlation with digit span
Huang et al., 2019	Chinese	292 participants G1 to expert readers	Visual 1-Back	Unfamiliar symbols	200ms	Identity	_______	_______	_______
Zhao et al., 2017	Chinese	58 adults	Visual 1-Back	Unfamiliar symbols	200ms	Identity	_______	_______	_______

Papers using only verbal material : Comparison Dyslexic and Control groups									
Study			Characteristics of the Task				Results		
Reference	Language	Participants	Paradigm	Strings	Time	Processing	Verbal	Non verbal	Relationship with other cognitive skills
Bosse et al., 2007 Study 1	French	68 DYS – 55 CTL G5	Oral report: GR & PR	Letters	200ms	Identity	A subset of DYS < CTL	_______	No partial correlations with PA
Bosse et al., 2007 Study 2	French	29 DYS – 23 CTL G3 to G5	Oral report: GR & PR	Letters	200ms	Identity	A subset of DYS < CTL	_______	No partial correlation with PA except spoonerism
Chen et al., 2019	Chinese	25 DYS – 25 CTL G5	Oral report: GR	Letters – Radicals -Digits	200ms	Identity	DYS < CTL	_______	No partial correlations with PA or RAN
Germano et al., 2014	Brazilian Portuguese	33 DYS – 33 CTL G3 to G6	Oral report: GR	Letters	200ms	identity	A subset of DYS < CTL	_______	No correlation with PA Significant correlations with form constancy (.55)
Hawelka et al., 2005	German	15 DYS – 15 CTL G9	Non-Oral PR	Digits	Estimated	Identity & position	DYS < CTL	_______	No correlation with PA but with RAN (.37)
Hawelka et al., 2006	German	12 DYS – 14 CTL Adults	Non-Oral PR	Letters	Estimated	Identity & position	DYS < CTL	_______	_______
Lallier et al., 2014	Spanish-French	9 DYS- 9 CTL G5	Oral report: GR & PR	Letters	200ms	Identity	DYS < CTL	_______	No correlation with PA
Lassus-Sangosse et al., 2008	French	26 DYS – 13 CTL. G5	Oral report: GR	Letters	200ms	Identity	A subset of DYS < CTL	_______	_______
Prado et al., 2007	French	14 DYS- 14 CTL	Oral report: GR & PR	Letters	200ms	identity	DYS < CTL	_______	A PA deficit in DYS
Saksida et al., 2016	French	164 DYS -118 CTL. G3 to G7	Oral report: GR & PR	Letters	200ms	Identity	DYS < CTL	_______	Correlation with phonological accuracy (PA accuracy and digit span) and phonological speed (mainly RAN)
Valdois et al. 2012	French	22 DYS- 22 CTL G4-G5	Oral report: GR	Letters, digits, colors	200ms	identity	DYS < CTL for letters and digits	_______	No PA or verbal STM deficit in the DYS participants
Valdois et al. 2021	French	162 DYS -119 CTL. G6	Oral report: GR & PR	Letters	200ms	identity	A subset of DYS < CTL	_______	Partial correlations with PA (from .17 to .27) and RAN (.30)
Zoubrinetzky et al., 2014	French	71 DYS – 71 CTL G3 to G7	Oral report: GR & PR	Letters	200ms	Identity	A subset of DYS < CTL	_______	No correlation with PA
Zoubrinetzky et al., 2016	French	63 DYS – 63 CTL G3 to G7	Oral report GR & PR	Letters	200ms	Identity	A subset of DYS < CTL.	_______	No correlation with PA

Papers using only verbal material in either DYS or typical readers									
Study			Characteristics of the Task				Results		
Reference	Language	Participants	Paradigm	Strings	Time	Processing	Verbal	Non verbal	Relationship with other cognitive skills
Bosse & Valdois 2009	French	417 typical readers G1, G3 and G5	Oral report GR & PR	letters	200ms	identity	_______	_______	Partial correlations with phoneme deletion and spoonerisms No corelation with phoneme segmentation and acronyms
Chen et al., 2016	English	105 DYS Adults	Oral report: GR & PR	Letters	200ms	Identity	_______	_______	Correlation with PA (.30); no correlation with verbal STM
De Jong & van den Boer, 2021	Dutch	108 typical readers Children	Oral report: GR	letters	200ms	Identity and position	_______	_______	Correlation with serial RAN (from .22 to .37) but no significant correlation with discrete RAN
Holmes et al., 2014 Study 1	English	85 typical readers Adults	Non-oral partial report	Letters	200ms	Position	_______	_______	Correlation of partial VAS with PA (.28)
Holmes et al., 2014 Study 2	English	75 typical readers Adults	Oral report: GR & PR	Letters	200ms	Identity	_______	_______	No correlation of PR with PA Significant correlation of GR with PA (.29)
Lallier et al., 2015	bilinguals	74 typical readers G2 or G5	Visual 1-Back	Letters	200ms	Identity	_______	_______	_______
Lobier et al., 2013	French	49 children G2-G3	Oral report: GR	Letters	200ms	Identity	_______	_______	Correlation with visual STM capacity (.66)
Niolaki et al., 2020	English	258 children G2-G4	Oral report: GR	Letters	200ms	Identity	_______	_______	Correlation with PA (.25) in advanced spellers and with RAN digits (.31) in novice spellers. No correlation with VSTM
Valdois et al., 2019	French	126 children Kindergarten – G1	Oral report: GR & PR	Digits	200ms	Identity	_______	_______	Partial correlation with PA (.41) but not with verbal STM.
Van den Boer et al., 2013	Dutch	184 children G2	Oral report: GR	Letters	200ms	Identity and position	_______	_______	Correlations with PA (.31), verbal STM (.33) and RAN (.20)
Van den Boer et al., 2014	Dutch	255 children G4	Oral report: GR	Letters	200ms	Identity and position	_______	_______	Corelation with PA (from .11 to .49), verbal STM (.11 to .49) and RAN (from .26 to .42)
Van den Boer et al., 2015 Study 1	Dutch	228 children G2 or G5	Oral report: GR	Letters	200ms	Identity and position	_______	_______	Correlation with PA (from .20 to .33), with verbal STM (.30 to .35) and with RAN (.28) but only in Grade 2
Van den Boer et al., 2015, Study 2	Dutch	255 children G4	Oral report: GR	Letters	200ms	Identity and position	_______	_______	Correlation with PA (.42), verbal STM (.32) and RAN (.37)
Van den Boer et al., 2018	Dutch	180 children G3	Oral report: GR	Letters	200ms	Identity and position	_______	_______	Correlation with PA (from .43 to .44) and RAN (from .20 to .34)

Papers exploring the neuronal underpinnings of VAS									
Study			Characteristics of the Task under fMRI				Results		
Reference	Language	Participants	Paradigm	Strings	Time	Processing	Verbal	Non verbal	Neural underpinnings
Lobier et al., 2012	French	14 expert readers Adults	Categorisation	Verbal Letters-Digits non-verbal Pseudo-Letters-Hiragana characters	200ms	Category membership	_______	_______	Specific involvement of the SPLs in multi-element processing (as compared to single element categorisation). Similar involvement of the SPLs regardless of stimli type (verbal or non-verbal)
Lobier et al., 2014	French	12 DYS with a VAS deficit - 12 CTL Adults	Categorisation	--- idem ----	200ms	Category membership	Accuracy & RTs DYS < CTL	Accuracy DYS < CTL	Reduced Right SPL activation in the DYS regardless of stimli type (verbal or non-verbal).
Peyrin et al., 2011	French	12 DYS with a VAS deficit - 12 CTL Children	Categorisation	Letters Geometrical shapes	180ms	Same or different category	_______	_______	Bilateral SPL activation during multi-element processing Reduced Left SPL activation in DYS than CTLs.
Peyrin et al., 2012	French	1 DYS with a PA deficit 1 DYS with VAS deficit 14 CTL	Categorisation	Letters Geometrical shapes	180ms	Same or Different category	_______	_______	Bilateral SPL underactivation in the participant with a VAS deficit (but normal activation of the perisylvian regions). Normal SPL activation in the DYS participant with a PA deficit but underactivation of the perisylvian brain regions.
Reilhac et al., 2013	French	12 DYS with VAS deficit – 12 CTL Adults	2 AFC String recognition	Letters	200ms	Same - Different	DYS < CTL	_______	Reduced activation of the left SPL and left ITG
Valdois et al., 2014	French - Spanish	1 DYS with a VAS deficit – 12 CTL	Categorisation	Letters Geometrical shapes	180ms	Same or Different category	_______	_______	Reduced activation of the SPLs and IPLs bilaterally Significant activation increase of the SPLs following VAS training
Valdois et al., 2019	French	1 DYS with a bilateral SPL damage	Oral Report GR - PR	Letters	200ms	Identity	DYS < CTL	_______	An adult patient with bilateral SPL damage shows poor oral report performance in a letter-string processing task