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Fractionating the multi-character processing deficit in developmental dyslexia: Evidence
from two case studies

Matthieu Dubois^{†,§}, Søren Kyllingsbæk[‡], Chloé Prado[§], Serban C. Musca*, Elsa Peiffer[¶],
Delphine Lassus-Sangosse^{¶,§}, and Sylviane Valdois[§]

[†] Cognition and Development Lab, Catholic University of Louvain, Louvain-La-Neuve, Belgium

[‡] Centre for Visual Cognition, Department of Psychology, University of Copenhagen, Denmark

[§] Laboratoire de Psychologie et NeuroCognition (CNRS UMR 5105), Grenoble Universités,
Grenoble, France

* LAPSCO (CNRS UMR 6024), Université Blaise Pascal, Clermont-Ferrand, France

[¶] Centre Référent pour le diagnostic des troubles du langage et des apprentissages, Service de
pédiatrie, CHU Nord, Grenoble, France

Corresponding author: Matthieu Dubois

Present address: Department of Psychology, New York University

6 Washington Place, Room 959 — New York, NY 10003

e-mail: matthdub@gmail.com tel: (+1) 212-998-3864 fax: (+1) 815-642-0407

Abstract

While there is growing evidence that some dyslexic children suffer from a deficit in simultaneously processing multiple visually displayed elements, the precise nature of the deficit remains largely unclear. The aim of the present study is to investigate possible cognitive impairments at the source of this visual processing deficit in dyslexic children. The visual processing of simultaneously presented letters was thus thoroughly assessed in two dyslexic children by means of a task that requires the report of briefly presented multi-letters arrays. A computational model of the attentional involvement in multi-object recognition (Bundesen, 1990, 1998) served as framework for analysing the data. By combining psychophysical measurements with computational modelling, we demonstrated that the visual processing deficit of simultaneously displayed letters of the two dyslexic individuals reported in the current study stems from at least two distinct cognitive sources: a reduction of the rate of —letter— information uptake, and a limitation of the maximal number of elements extracted from a brief visual display and stored in visual short term memory. Possible relations between these impairments and learning to read proficiently are discussed.

Keywords: developmental dyslexia, visual attention, visual short-term memory (VSTM), multi-element processing, letter identification

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1. Introduction

A growing number of studies suggest that visual and attentional limitations in processing letter-strings may constrain visual word recognition and its development (see Boden and Giaschi, 2007, for a review of how visually related processes may influence reading). Accordingly, difficulties in processing multi-character strings have recently been documented (Bosse et al., 2007; Hawelka et al., 2006; Hawelka and Wimmer, 2005; Lassus-Sangosse et al., 2008; Pammer et al., 2004b; Prado et al., 2007; Valdois et al., 2003).

1.1. Multi-element processing in dyslexia

The multi-element processing deficit has been studied in dyslexic participants by means of report tasks. First introduced by Sperling (1960; see also Averbach and Coriell, 1961; Averbach and Sperling, 1968), whole and partial report paradigms are measures of information extraction from brief visual displays. In whole report, the task is to report the identity of as many stimuli as possible from a briefly visually displayed array. Typically, unrelated letters (or digits) are presented and both the number of displayed stimuli and exposure duration are varied. In partial report, the stimuli are divided into two classes: targets and distractors. The task is to report as many of the target stimuli as possible while ignoring the distractors.

Evidence for a multi-letter string processing deficit in some dyslexic children was obtained in a series of experiments by Valdois and co-workers (Bosse et al., 2007; Valdois et al., 2003, 2004). In these experiments, arrays of five consonants were shown to the

participants for a fixed exposure duration of 200 msec, under whole and partial report conditions. Using a single-case methodology, Valdois et al. (2003) contrasted the performance of two young boys suffering from developmental dyslexia. The first child, Laurent, demonstrated poor phonemic awareness skills but good letter whole and partial report abilities, while Nicolas showed the reverse pattern with severe difficulties in the visual report tasks but good phonemic awareness. These results suggest that phonological and visual multi-letter processing disorders can dissociate in developmental dyslexia. More recently, the same tasks were administered to two large samples of French and British dyslexic children (Bosse et al., 2007). Participants were further submitted to a comprehensive reading and phonological test battery. A similar pattern of results emerged from both groups: the dyslexic participants reported on average less letters than chronological age-matched control participants in both (whole and partial) report conditions. Using the factorial scores derived from a principal components analysis, Bosse et al. (2007) found that the phonological and report skills were significant and independent predictors of the dyslexic children reading scores. Scores on report tasks accounted for a substantial amount of unique variance in irregular word and pseudo-word reading, independently of phonological skills. Finally, most dyslexic children exhibited a single, selective disorder: either phonological (19% and 34.5%, respectively from the French and British dyslexic group) or in letter report (44% and 34.5%, respectively). Also, Prado et al. (2007) reported significant negative correlations between report scores and the number of rightward fixations in text reading in a group of French dyslexic teenagers without obvious phonological problems. Similar results were described by Hawelka and Wimmer (2005; see also Hawelka et al., 2006), with a partial report task. In their studies, participants were required to identify a single element in response to a position cue after brief presentation of either digit or letter strings. Presentation times were systematically varied in order to measure an identification time threshold, the exposure duration required

for the dyslexic participants to identify target items according to a given accuracy criterion. While dyslexic children and control group mean thresholds did not differ for 2-digit strings, the dyslexic group needed significantly longer exposure durations than control participants for longer (4- and 6-) digit strings. Furthermore, a substantial correlation was reported between the dyslexic participants' number of eye movements in single word and pseudo-word reading and their ability to process multi-element arrays, independently of their pseudo-word repetition and rapid naming skills. Finally, a deficit in processing simultaneously displayed letters was also observed in a dyslexic group using a non-verbal change detection task (Rutkowski et al., 2003). However, whether the deficit extends to material other than alphanumeric characters (or letter-like symbols: Pammer et al., 2004b) remains to be empirically investigated. Since only letters were used as stimulus material in the present investigations, we will use the term 'multi-character processing' throughout, instead of the more general 'multi-element processing', which remains to be assessed.

All these findings suggest that at least some dyslexic people suffer from a multi-character processing deficit, which influences their reading performance independently of metaphonological factors. Following Valdois et al. (2004), these difficulties would reflect a limitation in the amount of distinct visual elements that can be simultaneously extracted from a multi-element array and are available for further processing in reading. These authors argue that such a deficit, called by Bosse et al. (2007) the *visual attention span* deficit hypothesis, might be a second core deficit in dyslexia, independent of the phonological deficit. However, the precise nature of this deficit remains unclear. Indeed, report tasks involve various processes and components. Different—and possibly not mutually exclusive—deficits could thus potentially account for these results.

Indeed, the ability to encode and maintain visual information is restricted by two related processes that are capacity limited: visual attention enhances visual processing

and visual working memory supports the maintenance of encoded information (Awh et al., 2006). Accordingly, performance on letter report tasks is known to be related to the processing rate of single letters, which rely upon visual attention limited resources (Gegenfurtner and Sperling, 1993; Shibuya and Bundesen, 1988). A reduced processing speed (either general or specific to alphanumeric characters) could thus account for the multi-character processing deficit in dyslexia. Visual working memory storage capacities also constrain the number of elements than can be reported when multiple items are displayed simultaneously (e.g. Luck and Vogel, 1997; Vogel et al., 2001; Xu and Chun, 2006). An impairment at this storage level may also be a plausible cause of the multi-character processing deficit observed in dyslexia. Finally, in addition to a possible reduction in visual processing speed and visual short-term memory storage capacity, report performance could also be affected by a particular imbalance of the processing resources in dyslexic individuals. Indeed, Hari et al. (2001) have proposed that dyslexic readers might be affected by a left mini-neglect (see also Buchholz and Aimola Davies, 2005; Facoetti and Turatto, 2000; Sireteanu et al., 2005). This deficit, supposed to result from a right parietal lobe dysfunction, is characterised by an attentional visual field asymmetry (left hemifield inattention and right hemifield over-distractibility) and was taken as a sign of an underlying attentional problem (Hari and Renvall, 2001). This left mini-neglect might be particularly detrimental in learning string-specific processing mechanisms (Whitney and Cornelissen, 2005).

In this paper, we investigated the underlying deficits at the source of the multi-character processing disorder observed in some dyslexic participants. As in the above mentioned studies, multi-element processing was investigated through letter report paradigms. However, the previous findings were extended in a number of ways. First, our investigation method is theoretically grounded in a computational model. Bundesen's (1990; 1998) Theory of Visual Attention (TVA) provides an integrated framework within

which several accounts of the multi-character deficit in dyslexia can be formalised, related, and tested. Second, the various accounts were simultaneously assessed within the same task. Different aspects of the individual performance were further related to a number of parameters such as sensory effectiveness, processing capacity, attentional weighting and visual short-term memory capacity, most of which are directly related to specific accounts. Finally, multi-character processing was investigated through a case study approach. This allows us to take into account the well known heterogeneity of the dyslexic pathology.

1.2. Bundesen's Theory of Visual Attention

TVA is a formal model of visual attention and (multi) object recognition. Contrary to most other theories in the field, TVA yields direct quantitative predictions in different paradigms, including whole and partial report tasks. The estimation of the various model parameters is allowed in individual participants by fitting data obtained with adequate psychophysical paradigms. Actually, report tasks were already used in conjunction with TVA to investigate visual attention and visual multi-element recognition in normal participants (Bundesen, 1987; Bundesen and Harms, 1999; Finke et al., 2005; Hung et al., 2005; Shibuya and Bundesen, 1988) as well as brain damaged patients (Bublak et al., 2005; Duncan et al., 1999, 2003; Gerlach et al., 2005; Habekost and Bundesen, 2003; Habekost and Rostrup, 2006, 2007; Habekost and Starrfelt, 2006; Peers et al., 2005) and degenerative pathologies (Finke et al., 2006, 2007). Furthermore, whereas the original TVA model was framed at a cognitive description level, its principles have been shown to have a strong analogy at the single cell level (Bundesen et al., 2005).

In contrast to many serial models of attention (e.g. Treisman and Gelade, 1980), TVA is based on parallel, competitive processing (Duncan et al., 1997; Rumelhart, 1970). Objects or elements in the visual field compete for access to a visual short-term memory (VSTM) with limited storage capacities, in a K -winners-take-all process. Objects in the

visual field can be processed in parallel, and the objects that are selected (and, therefore, can be reported) from a briefly exposed visual display are those objects whose encoding processes complete before the sensory representation of the display vanishes and before VSTM has been filled up with other objects. In normal participants, the storage capacity of VSTM is limited to K objects, where K is about 4, so up to four objects can be reported from a brief display (e.g. Luck and Vogel, 1997; Sperling, 1960; Vogel et al., 2001). Competition is thus considered as a race: recognised elements are those who were processed faster. TVA summarises visual recognition and selection in terms of different parameters (see Appendix B for mathematical details), three of which are of interest to our study: (a) *the visual processing speed*, C : the total number of visual elements processed per second from a given display (b) *the storage capacity of visual short-term memory (VSTM)*, K : the maximum number of objects that can be extracted from a brief visual display, and (c) *the spatial bias*, w_{lat} : the relative attentional weighting of stimuli in different parts of the visual field (here: left versus right hemifield) .

All these parameters are best estimated in a whole report paradigm. When the number of accurately reported items is measured as a function of exposure duration, performance follows a characteristic pattern (Bundesen and Harms, 1999; Duncan et al., 1999; Finke et al., 2005; Habekost and Bundesen, 2003; Shibuya and Bundesen, 1988) illustrated in Figure 2. Below a minimal exposure duration t_0 (the visual threshold) no items are reported. Above this threshold, the curve begins to rise sharply, but gradually flattens to approach an asymptotic value. This asymptote is interpreted as the maximum storage capacity of VSTM: K . The slope of the whole report function at the visual threshold (t_0) corresponds to the processing speed (C). C is highly dependent on the degree of pattern match between the stimuli and representations in long-term memory. As a consequence, processing speed is affected by the sensory properties and general discriminability of the stimuli, but also by learning which may affect the quality of

long-term representations. When stimuli are presented unmasked, the effective exposure duration is prolonged by a constant, μ (Bundesen, 1990). This parameter is necessary for curve fitting, but will not receive independent interest. In sum, given a sufficient number of observations at different exposure durations (ranging from near threshold to near-ceiling performance) the parameters t_0 , C and K can be estimated from whole report data. As the *attentional weights* represent the way the total processing capacity is distributed across the different displayed elements, a further systematic variation of the number of displayed elements is required to estimate the w_{lat} . The w_{lat} parameter represents a pure estimate of spatial attentional bias, controlled for sensory factors (for further details see Appendix B).

To summarise, TVA suggests a range of separate basic deficits that could underlie or contribute to the multi-character processing deficit observed in some dyslexic participants. The different possible underlying impairments are indexed by different parameters within the TVA model. A letter processing speed disorder should manifest itself in a reduction of the C parameter (the visual processing speed). Alternatively, in the case of a reduction of the maximal number of elements simultaneously extracted, a deficit on K (the VSTM storage capacity) is expected. Finally, left mini-neglect would induce a bias towards the right visual hemifield, indexed by a deviation of the w_{lat} index (Duncan et al., 1999; Habekost and Rostrup, 2006; Peers et al., 2005).

2. Case reports

AB et PA are two right-handed male native French speakers of 9 years and 9 years 1 month respectively who were in 3rd grade at the time of testing. Both AB and PA are of average intelligence¹. None of them reported any history of neurological disorder or severe problems in speech and language development. Hearing was found to be normal in both of them. Vision was normal (in PA) or corrected to normal (in AB) after diagnosis of slight hypermetropia of one eye. AB's relatives reported no family history of learning disabilities

or psychiatric illness. On the contrary, difficulties in learning to read were reported in some of PA's family members. Both dyslexic participants received conventional reading instruction when attending primary school. However, there has been concerns about their progress in reading and spelling since early primary school. Both children repeated a grade (Grade 1 for AB, Grade 2 for PA) due to difficulties in learning to read and entered a reading remediation program at the same time (at the start of AB's second first Grade and PA's first second Grade). AB and PA were addressed to the Grenoble University Hospital clinical centre. Both complained of strong and persistent reading and spelling difficulties, despite two years of remedial reading instruction. On the "Alouette" French standardised reading test² (Lefavrais, 1963, 1965), AB and PA achieved respectively a reading age of 6 years 9 months and 6 years 8 months, revealing a retardation of respectively 27 and 29 months in reading acquisition. Thus, both AB and PA performed significantly below average for their age, demonstrating the severity of their reading difficulties.

AB and PA were further submitted to standardised reading, spelling and phonological test batteries, as well as to Valdois et al.'s (2003; 2004) whole and partial report tasks. As the normative data was obtained on sufficiently large groups ($n > 50$), participants' performance was transformed into z -scores.

2.1. Reading and spelling

AB and PA's reading and spelling skills were estimated by means of subtests of the ODEDYS French test battery (Jacquier-Roux et al., 2005)³. This test battery was standardised on a large sample of children, selected to be representative of the French population. Table 1 displays a summary of AB and PA's results.

2.1.1. Word and pseudo-word reading. Participants were asked to read two lists of 20 consistent words of high (HF) or low (LF) frequency, two lists of 20 HF and LF inconsistent words, and a list of 40 pseudo-words. All lists were matched for number of

letters and syllables. Consistent and inconsistent words were also matched for grammatical class and frequency (from MANULEX, a lexical database from French elementary school books: Lété et al., 2004). Each list was printed in column, in lower-case letters (Times font, 14-point). Children were asked to read each list as quickly and accurately as possible. Accuracy and reading times were recorded. AB and PA made both significantly more errors and their reading was markedly slowed on all types of items (each $p < .01$; remain significant after Bonferroni correction for multiple comparisons, with the only exception of AB' inconsistent LF word reading score).

The pattern of errors was similar in both dyslexic children (see Appendix A for examples of errors). A qualitative analysis of errors revealed that misreadings of inconsistent words corresponded predominantly to regularisations (AB: 17/28, 61%; PA: 16/28, 57%). Those errors reflect the consistent application of grapheme-to-phoneme mappings to inconsistent items. The remaining misreadings on inconsistent words were essentially visual in nature (AB: 10/13, 77%; PA: 11/14, 79%). Visual errors were also the main error type in AB and PA on consistent words as well as pseudo-words (AB: 30/33, 91%; PA: 29/33, 88%). Their production was visually similar to the target, and characterised by a large number of confusions between visually similar letters (AB: 12; PA: 10) and letter omissions (AB: 12; PA: 11). Notice that none of the participants produced semantic or morphological paralexias. Finally, two lexicalisations of pseudo-words were noted in AB.

2.1.2. Single grapheme processing. Knowledge of the grapheme-to-phoneme mapping rules was assessed by presenting AB and PA with 46 different isolated French graphemes and asking them to sound these graphemes out. AB correctly sounded 40 graphemes and PA 41 graphemes. These scores were well within the range of normal readers of the same chronological age ($p = .18$ and $p = .29$, respectively).

2.1.3. Word and pseudo-word spelling. AB and PA were asked to spell two lists of 10 highly consistent and 10 exception words. Highly consistent words could be spelled accurately by application of the most frequent phoneme-to-grapheme mapping rules, while exception words required access to specific orthographical knowledge. Two lists of 10 bi-syllabic and 10 tri-syllabic pseudo-words were also given. The four lists were successively dictated, one word at a time and without time constraints. AB's spelling performance was significantly impaired on all types of items (each $p < .02$). PA also demonstrated severe spelling deficits on consistent and exception words (each $p < .01$) as well as on tri-syllabic pseudo-words ($p = .006$). A qualitative analysis of the errors revealed a similar pattern in both participants (see Appendix A for examples). Errors made when spelling words were characterised by a predominance of phonologically plausible errors⁴ (AB: 11/15, 73.3% and PA: 8/12, 66.7%). Pseudo-word spelling errors were mostly due to the omission of a grapheme (AB: 6/11, 54.5% and PA: 4/7, 57.1%) and to confusions (AB: 3/11, 27.3%; PA: 1/7, 14.3%) between phonologically and/or visually similar letters (e.g. /j/ was spelled /ʒ/, /b/ and /ʒ/ were written /d/).

2.2. Verbal short-term memory and metaphonology

According to the phonological hypothesis of dyslexia (Snowling, 2001), a phonological deficit is assumed to be at the source of developmental dyslexia. This phonological deficit is usually described as having different main components, including poor phoneme awareness (i.e. the ability to identify and manipulate speech sounds consciously) and poor verbal short-term memory. AB and PA were thus given verbal short-term memory and research-made phoneme awareness tasks (Bosse et al., 2007; Valdois et al., 2003). For the metaphonological tasks, 101 age-matched participants (chronological age, in months: $M = 106.24$, $SD = 4.25$, range: [99–116]; reading age, in months: $M = 107.17$, $SD = 14.48$, range: [83–146]) were selected from a large sample

study (Bosse and Valdois, 2009) to serve as normative data.

2.2.1. Verbal short-term memory. AB accurately reported 5 digits forward and 4 digits backward, a performance within the range of normal participants (see Table 2). Similarly, PA obtain normal span sizes (forward: 6; backward: 3).

2.2.2. Phoneme awareness. AB and PA were submitted to three different phoneme awareness tasks. In the *phoneme deletion task*, participants were required to delete the first sound of a word and to produce the resulting pseudo-word. Twenty words were chosen as stimuli: seven began with a multi-letter vocalic grapheme, nine with a consonantal cluster. The last four began with a singleton. A set of 15 different words were used for the *phoneme segmentation task*, in which auditory presented words have to be orally segmented into their constitutive phonemes. Finally, 10 *acronyms* from the BELEC (Mousty et al., 1994) were proposed. For each acronym, two words were successively pronounced by the experimenter. Participants were asked to extract the first phoneme of each word, combine them and produce the resulting syllable. Each task was preceded with unscored practice items for which feedback was given. As can be seen in Table 2, AB performed significantly below the norms for two of the three tasks (phoneme deletion and acronyms). Contrarily to AB, PA's performance on the three phoneme awareness tasks felt well within the range of normal readers' achievement.

2.3. Multi-character processing screening

Valdois et al.'s (2003; 2004) whole and partial report tasks (see also Bosse et al., 2007) were given to AB and PA as a first screening of multi-character processing deficit.

Random five-letter strings were build up from ten consonants [BPTFLMDSRH]. The letters were presented in upper-case (Geneva 24, .8° high and .63° wide) in black on a white background. The strings contained no repeated letters. The centre-to-centre distance between adjacent letters was of 1.2° and the whole string subtended a visual

angle of approximately 5.4° . Twenty 5-letter strings were successively presented in whole report. Fifty random 5-letter strings were presented in partial report. Each letter appeared the same number of times in each position. On each trial, a letter string was displayed at the centre of a CRT screen for 200 ms. The letter string was preceded by a central fixation point lasting for 1000 msec, immediately followed by a blank screen which lasted for 50 msec. In partial report, a probe—a vertical bar—indicating the letter to be reported was presented for 50 msec, 1.1° below the target letter, at the offset of the letter string. Each letter was used as target once in each position. The participants' task was to report verbally either as many of the letters as possible (in whole report) or the cued letter only (in partial report), immediately after the letter string disappeared. For each participant, experiments began with 10 unscored warm-up trials for which they received feedback. No feedback was given during experimental tasks. Letters were scored independently of report order.

Results are displayed in Table 2. AB and PA accurately reported respectively 51 and 55 letters in the whole report task, which is a very poor performance in comparison to non-dyslexic children matched for chronological age ($p = .002$ and $p = .007$, respectively). In partial report, AB and PA performed similarly, both reporting accurately only 30 letters ($p = .042$).

2.4. Summary

AB and PA are closely matched in terms of chronological age, Grade and overall reading level. They demonstrate highly similar performance patterns in reading and when spelling single words under dictation. Regardless of the type of items, they made lots of reading and spelling errors and their reading speed was impressively slowed down. Some reading related skills were further assessed. No verbal short-term memory impairment was observed on the basis of digit spans. AB exhibited impaired performance on phoneme

awareness tasks, but PA did not. However, the hypothesis of an initial phonological deficit in PA cannot be ruled out on the basis of the current data. Indeed, PA received a reading remediation program prior to the current assessment, probably including metaphonological training. Finally, both dyslexic participants exhibit a strong multi-character processing deficit, as evidenced in whole and partial report tasks.

3. Experimental measure: Multi-letter processing

We further investigated AB and PA’s multi-letter processing within the TVA framework. More specifically, our purpose was to evaluate various —and possibly not mutually exclusive— accounts of the multi-character processing deficit in dyslexia: (i) a limitation of the visual working memory storage capacity; (ii) a letter processing speed deficit and (iii) particular spatial attentional distribution and mini-neglect. These three hypotheses are indexed in TVA by three different parameters: (i) K , the VSTM capacity; (ii) C , the total processing speed and (iii) w_{lat} , the distribution of the attentional weights.

3.1. Methods

3.1.1. Control group. The performance of AB and PA was compared to that of an age-matched control group of 9 participants (3 male and 6 female), with a mean age of 110.78 months ($SD = 3.11$, range: [108–118]). They were all average or good French readers (reading age, in months: $M = 114.67$, $SD = 9.70$, range: [97–127]). Vision was reported to be normal in all participants. The experiments were undertaken with the understanding and written consent of both the children and their parents. Normal reading participants were assessed at school while the two dyslexic participants were tested in the Lab.

3.1.2. Design. The task was driven by the E-prime software (Version 1.1 SP 3: Schneider et al., 2002) and run on an IBM-compatible computer. Participants were seated

in front of a CRT computer screen, refreshed at 100 Hz. Two different CRT screens were used, one at school for control participants, the other in the lab for the dyslexic participants. Viewing distance was adapted to keep visual size constant. The stimulus presentation was locked to the refresh rate of the computer monitor. As no chin rest was used for precise control of viewing distance, reported visual angles are approximate.

The setup of the task is schematically shown in Fig. 1*a*. Each trial began with the presentation of a fixation cross, displayed at the centre of the screen. When the participant was fixating the cross, he pressed a mouse button and the fixation point disappeared. After a 100 msec gap, one, three or five uppercase letters randomly chosen without replacement from the ten most frequent French consonants [RNSTLCPMDV]⁵ (from the French database LEXIQUE 2.6: New et al., 2004) were briefly displayed (10–200 msec). Each selected letter, subtending a maximal area of $.64^\circ \times .7^\circ$ visual angle, was randomly presented at one of six equally distant positions. Each position was drawn at the circumference of a 3.3° radius virtual circle centred at fixation, with three positions within each hemifield (see Fig. 1*b*). Letters were displayed in white (RGB: 256, 256, 256) on a dark grey (RGB: 64, 64, 64) background⁶. The stimulus was followed either by a black screen or a 500 msec mask, a white box sustaining the same area as the biggest letter and fulfilled with randomly chosen white and dark grey pixels. Participants were instructed to report *as many letters as possible*, but refrain for guessing. No time pressure was imposed.

Three individually set exposure durations were specified. The lowest exposure duration was determined during individual practice sessions of the experimental task. It was defined as the minimal exposure duration required by the participant to accurately report on average .5 letter on each trial (participant's near threshold exposure duration). To avoid eye movements, the maximal exposure duration was set at 200 msec (near ceiling duration). An intermediate exposure was further determined by adding 70 msec to the participant's near threshold exposure duration. AB and PA's three exposure durations

were respectively set at 20, 90, 200 and 40, 110, 200 msec. For each of the nine control participants, the three exposure durations were in the range 10–20, 80–90, and at 200 msec, respectively. All three exposure durations were used in a masked condition, but only near threshold and near ceiling exposure durations were proposed in an unmasked condition. The unmasked condition was designed to prolong the effective exposure duration without allowing eye movements, yielding to a total of five different *effective exposure durations*. Critical timing of the experiment was pre-tested and verified with an external exposure duration checking system developed at the Catholic University of Louvain, Belgium⁷.

Testing was organised in blocks of 2 repetitions of the 15 conditions (5 durations * 3 display sizes). Participants were given 16 items per condition⁸, which allows robust parameter estimates in whole report paradigm (Finke et al., 2005). Conditions were randomised in each block. The requirement for accurate fixation and report of letters without guessing was emphasised at the beginning of each block. To reduce tiredness, rest periods and other standard reading and writing tests were given between blocks. The whole testing, including the reading and spelling assessment, was completed within three-to-four sessions of maximally 1 hour length, including breaks. In addition, participants were given 30 unscored warm-up trials at the beginning of each session. Before the experiment, participants were also shown the whole set of stimuli used in the experiment.

3.1.3. Data analysis. For each participant, the best-fitted TVA parameters were estimated from individual data by a maximum likelihood fitting algorithm (mathematical details and the custom software used are described in Kyllingsbæk, 2006). The following parameters were derived from the basic TVA fits: K , C , w_{lat} , t_0 and μ (see Appendix B for further details). To improve the robustness of the fits, K values were not allowed to be higher than the maximum number of letters reported from a trial by the participant. The

reliability of each parameter estimate was evaluated by 1,000 bootstrap repetitions (Efron, 1979; Efron and Tibshirani, 1993), a sample size that allows the construction of confidence intervals (Chernick, 1999). Each bootstrap sample was constrained to include at least one trial with the participant's maximum score (Habekost and Rostrup, 2006).

Dyslexics' parameter estimates were then compared to those obtained by control participants by means of a method based on the t distribution proposed by Crawford et al. (1998) that was proven highly robust for evaluating single-case results against control groups of limited size (Crawford and Garthwaite, 2006a,b; Crawford et al., 2006). Dissociation between two tasks was quantified with the Bayesian Test for Standardised Differences (hereafter BTSD: Crawford and Garthwaite, 2007). Significance was assessed through one-tailed tests for deficits (unless otherwise stated) and bilateral tests for dissociations. *Log* transformation of data was used when required to satisfy the normality assumption underlying the use of t -tests. Finally, in order to quantify the reliability of our conclusions in front of possible measurement errors, we further computed 95% confidence intervals (*CI*s) of the rarity of the patients' scores (Crawford and Garthwaite, 2002, 2007). The rarity of scores is an estimate of the percentage of the control population that would obtain a score lower than the patient. It corresponds to the one-tailed p -value of the test, expressed in percents. *CI*s thus quantify the degree of confidence that should be placed in the estimation of the abnormality of the patient's score, due to sample size limitation and measurement error. All statistical analyses were realised with the *singlecase* package (Dubois, 2008) for the R statistical environment (Ihaka and Gentleman, 1996; R Development Core Team, 2008) and graphical output was produced using *ggplot2* (Wickham, 2009).

3.2. Results

3.2.1. Raw data. On average, control participants reported accurately 1.95 letters ($SD = .16$, range=[1.74–2.25]). Dyslexic participants' mean raw score was 1.73 for AB and 1.81 for PA. None differed significantly from the control group (AB: $t_8 = -1.3$, $p = .12$, CI: [1.15%–33.74%]; PA: $t_8 = -.79$, $p = .22$, CI: [5.62%–47.95%])⁹. AB never reported correctly all of the letters from a five letter display, contrarily to PA and each control participant. Regarding the visual hemifields, control participants' mean letter recognition performance in the left and right sides was 61.86% ($SD = 6.6$, range: [52–73]) and 68.35% ($SD = 5.3$, range: [62–76]) respectively, with a mean score was significantly higher for letters displayed in the right side (paired t -test: $t_8 = -3.69$, $p = .006$). This finding is consistent with previous studies showing a slight left hemisphere advantage for perception of letters (Habekost and Bundesen, 2003). On the contrary, both dyslexic participants exhibited slightly better letter recognition scores in the left than in the right hemifield (AB: left 62.2%, right 52.75%; PA: left 61.4%, right 59.21%). The imbalance between left and right scores significantly differed from the control participants in AB (BTSD, $p = .01$, CI: [95%–100%]), but failed to reach significance in PA (BTSD, $p = .096$, CI: [78%–100%]). No significant difference was observed between dyslexic participants and controls in the left side (AB: $t_8 = .05$, $p = .48$; CI: [27%–76%]; and PA: $t_8 = -.07$, $p = .47$, CI: [24%–72%]), but AB reported significantly less letters presented in the right side ($t_8 = -2.78$, $p = .01$, CI: [0%–8%]). This difference was only marginal in PA ($t_8 = 1.631$, $p = .07$, CI: [0%–25%]). However, mean raw scores are composite measures that do not indicate whether the observed differences relate to processing speed, short-term memory capacity or lateral attentional imbalance. TVA analysis provides more specificity.

Some participants' data is shown in Figure 2 as a function of display size and exposure duration. Congruently with other whole report studies (Bublak et al., 2005; Bundesen and Harms, 1999; Duncan et al., 1999, 2003; Finke et al., 2005; Habekost and

Bundesen, 2003; Sperling, 1960), performance rose sharply after a minimal exposure duration, t_0 , below which no letter is reported. After a few hundred milliseconds, performance gradually flattened and progressively reached an asymptote. The value of the asymptote depends on the display size. If a sufficiently large number of letters is provided (as in our 5-letters condition), the asymptote is interpreted as the storage capacity of the visual short-term memory, K . For displays in which the storage capacity exceeds the number of elements (as in our 1- and 3-letters conditions), performance asymptotically reaches the display size. Finally, due to visual persistence (parameter μ), the effective exposure duration was prolonged in the case of unmasked conditions. The three control participants showed in Figure 2 are representative of the inter-subject variability within the control group. Participant BC exhibited the smaller curve rise rate (the processing speed parameter, C), and SI the largest. SP's performance illustrates an average rising rate. Turning to the asymptote of the five letters curve (the VSTM storage capacity parameter, K), the smallest value was observed for control participant SP. Other displayed control participants obtained values close to the control group mean. Finally, SP and SI exhibited respectively one of the smallest and one of the largest visual persistence estimate, yielding important variations in the *effective* exposure durations. While dyslexic participants exhibited qualitatively the classical whole report pattern of results, Figure 2 also illustrates quantitative differences between the dyslexic and control participants. The slope of AB and PA's whole report function was more shallow and performance reached asymptote later. Moreover, the asymptotic value of AB's 5 letter whole report curve was lower. These deficits are accurately captured by TVA parameter estimates.

3.2.2. TVA fits. As illustrated in Figure 2, TVA fits in each of the 15 experimental conditions were fairly close to the empirical data. The Pearson product-moment correlation coefficient between theoretically predicted and currently observed position probabilities (i.e. the probability of reporting a letter at a given position in a certain

experimental condition) was .90 on average¹⁰ in the control group (range: [.84–.95]). AB and PA raw data were also closely fitted, with respective correlation coefficients of .84 and .86. Table 3 shows the best-fit parameter estimates. Bootstrap estimates distributions were generally close to the normal function, allowing the computation of *SDs* (see Figure 3). These bootstrap *SDs*, also shown in Table 3, allow an estimation of the reliability of each parameter estimate. Individual parameters were reliably estimated, with small bootstrap *SDs*. As an example, the standard error related to the dyslexic participants' *K* estimate was only .13 (AB) and .25 (PA) and both AB and PA's *C* estimate standard errors were in the range 1–3 elements/sec. Finally, a large *SD* was obtained for AB's μ estimate, which will be discussed later.

3.2.3. Processing speed. In TVA, processing speed is indexed by the *C* parameter, which corresponds to the slope of the whole report curve at the minimal exposure duration, t_0 . In the control group, the average *C* value was 41.2 letters/sec. Dyslexic participants demonstrate a two-fold reduction in processing rate (22.9 and 23.3 letters/sec, respectively), significantly below control participants for AB ($t_8 = -1.92$, $p = .046$, CI: [.07%–20.25%]). The difference just failed to reach significance for PA ($t_8 = -1.85$, $p = .051$, CI: [.1%–21.5%]). Finally, the distributions of bootstrap estimates were used to directly compare both dyslexic participants (see Figure 4 *Left*). Bootstrap distributions reflect the probability density associated with the different possible values of a given parameter in a given subject. The almost complete overlap observed between AB and PA indicates a high probability that the 'true', but unknown, value of the processing speed parameter *C* is in fact identical for these dyslexic participants.

3.2.4. Visual short-term memory. On average, the visual short-term memory storage capacity, *K*, was about 4.6 letters in the control group (range: [4.25–5]). This real value represents a probability mixture of VSTM capacity at four and five elements,

occurring respectively with 40% and 60% probability. Though slowed processing was the most conspicuous aspect of AB's deficit, his VSTM capacity K , estimated at only 3.81 letters, was also reduced compared to the controls ($t_8 = -3.38$, $p = .005$, CI: [0%–4%]). On the contrary, PA's 4.44 K value was similar to those of the control participants ($t_8 = -.7$, $p = .25$, CI: [7%–50%]). The difference between AB and PA is made clear when looking at their bootstrap distributions for parameter K (see Figure 4 *Right*). However, the lower storage capacity observed in AB remains well within the typical range of VSTM capacity estimates for normal participants (3–5 items), as reported in other studies using a similar paradigm (Duncan et al., 1999, 2003; Finke et al., 2005, 2006; Habekost and Bundesen, 2003). We will return to this in the discussion.

3.2.5. Attentional distribution between hemifields. Non classical attentional distribution between the hemifields has sometimes been reported in dyslexic individuals, yielding to the hypothesis of a left mini-neglect. In the control group, the ratio between left and right attentional weights, w_{lat} , was .43 on average (range: [.34–.56]). This indicates a small but significant tendency to pay more attention to the right hemifield (tested against .5: $t_8 = -2.9$, $p = .02$). Contrary to the hypothesis of a left mini-neglect, AB and PA tended to direct *more* attention to the *left hemifield* (respective w_{lat} : .59 and .56). The w_{lat} value of AB and PA deviated respectively 2.3 and 1.9 SD from the mean of the control group, a difference just failing to reach significance (AB: $t_8 = -2.15$, bilateral $p = .064$, CI: [83.7%–99.9%]; PA: $t_8 = -1.78$, bilateral $p = .11$, CI: [77.2%–99.9%]). The individual w_{lat} bootstrap distributions were further used to test the deviation from symmetrical attentional deployment at an individual level. Indeed, the bootstrap distribution of a given parameter reflects the measurement error of this parameter. As a consequence, this distribution can be used to test whether a given parameter estimate “truly” differs from a given value. Percentiles 95% bootstrap confidence intervals were computed for each participant (see Figure 3). A w_{lat} value was

considered significantly deviating from symmetry if .5 was not included within the bounds of the bootstrap CI. Six out of the 9 control participants demonstrated a significant trend to allocate more attention towards the right hemifield. On the contrary, AB exhibited a significant trend to pay more attention to the left hemifield. As 3 control participants, PA's w_{lat} value failed to reach significance, attesting a symmetrical attentional distribution.

3.2.6. Timing parameters. Finally, two different timing parameters are provided by the TVA fits: t_0 , the minimal exposure duration, and μ , the visual persistence. As in some previous studies (Duncan et al., 1999, 2003), t_0 was estimated at 0 msec in both dyslexic participants, as well as in most control participants¹¹. When stimuli were not masked, the effective exposure duration was on average prolonged by about 160 msec (μ parameter) in control participants (range: [105–255]). PA's μ parameter, estimated at 238 msec, fell within the range of the control participants ($t_8 = 1.62$, bilateral $p = .14$, CI: [73.8%–99.7%]). On the contrary, AB exhibited a significantly larger μ estimate (313 msec, $t_8 = 2.66$, bilateral $p = .03$, CI: [90.3%–100%]), indicating a prolonged visual persistence. However, the bootstrap SD was more than 20% of the μ estimate in AB. As indicated by a bootstrap 95% percentile interval, AB's true μ estimate was in the range 230–500 msec. This questions the reliability of his μ value and also of the significance of the difference with control participants. As a consequence, we will not further discuss this result.

However, the estimation of the other parameters, especially C , may also partly depend on the estimation of μ . Indeed, despite being mainly constrained by the shorter exposure duration conditions, the estimation of C also partly relies on unmasked displays. For these displays, the effective exposure duration in turn is based on the estimation of the additional parameter μ . Therefore, an “unreliable” estimation of μ , as in patient AB, may in turn lead to greater uncertainty on C . We thus ran for this patient additional data

fits in which unmasked conditions were excluded. When only masked displays were considered, AB's processing speed was estimated at 24.21 letters/sec (bootstrap SD : 2.33), which is very close to the estimate obtained on the whole data (22.9 letters/sec, bootstrap SD : 2.1). When computed from the masked displays only, the other parameter estimates were also in large agreement with those from the whole data set (bootstrap SD s are given in parentheses: t_0 : 0 (3.5); K : 3.71 (.45); and W_{lat} : .61 (.05)). There is thus no sign of any impact of AB's less reliable μ estimate on the other parameters.

4. Discussion

The aim of the present study was to investigate the nature of the cognitive impairments at the source of the multi-character visual processing deficit observed in two dyslexic participants. TVA, a computational model of attentional involvement in (multi) object recognition served as framework for this investigation. More specifically, three—not mutually exclusive—hypotheses were assessed, each of them related to a specific TVA parameter. It was first hypothesised that the multi-letter processing deficit could stem from a reduction in the speed at which elements are extracted from a brief visual display. Such an impairment would result in a reduction of processing speed, captured by the C parameter estimate. Visual processing is further constrained by the storage capacity of VSTM, K , another plausible source of multi-character processing deficit. Finally, particular spatial attentional distribution might also impair performance on report tasks. This third hypothesis was captured by the laterality index of attentional weights, w_{lat} .

Two developmental French dyslexic children were thus a priori selected for having a similar deficit in processing simultaneously displayed letters. Both dyslexic participants were closely matched with respect to chronological age and Grade level, and demonstrated a similar level of reading impairment. They demonstrated highly similar performance patterns in reading and spelling. Regardless of the type of items, they made lots of

reading and spelling errors and their reading speed was impressively slowed down. Verbal short-term memory was further shown to be preserved in both dyslexic participants. The only major difference between them was observed on phoneme awareness, which was within the normal range in PA but impaired in AB. Multi-letter processing was further assessed through the coupling a psychophysical methodology with the TVA computational framework. A number of visual parameters, including sensory and attentional aspects, were measured. Applied for the first time to children, the TVA model accurately captured the participants' performance.

Turning to the different TVA parameter estimates, the data suggest two main types of deficits, both related to limited capacities. First of all, the most prominent result was a similar significant reduction in visual processing speed for both dyslexic children. In addition, VSTM storage capacity was found to be reduced in AB but preserved in PA. Finally, the two dyslexic participants did not significantly differ from controls on measures of spatial distribution of visual attention between visual hemifields. However, AB tended to pay more attention to the left hemifield, a pattern observed in none of the control participants. Each of these findings will be discussed in turn.

4.1. Processing capacity limitations

Overall, the current findings suggest a reduction of visual processing speed as the most plausible cause of both dyslexic participants' multi-letter processing disorder. Indeed, processing speed alone was affected in both dyslexic participants, and in a similar way.

Suggestive evidence for a link between slow visual processing and poor reading has been provided by Duncan et al. (2003). Using TVA in two participants with dorsal and ventral simultanagnosia, Duncan et al. found an impressively slowed visual processing speed as the most prominent impairment. The authors argued that, in front of multiple elements simultaneously competing for processing, a massive reduction in processing speed may

cause perceptual failure for all but the most prominent element. An efficient way to minimise competition would be to process one element at a time by top-down selection. Accordingly, Finke et al. (2007) recently reported a negative correlation between the C parameter and the number of errors produced when identifying multiple —overlapping— figures in a group of patients suffering from Huntington’s disease. Such results suggest that the marked slowed processing speed observed in these patients may lead to impaired simultaneous perception of multiple stimuli. Duncan et al. (2003) further argued that a slowed processing speed may also affect the processing of letters in words in ventral simultagnosia (Kinsbourne and Warrington, 1962; Levine and Calvanio, 1978), leading to the characteristic pattern of letter-by-letter reading.

Is such an account relevant with respect to the clinical features showed by our dyslexic participants? A processing speed deficit may result in only a few letters to be processed simultaneously, thus yielding reading impairments. Hence, we recently provided evidence that the number of letters simultaneously processed constrains visual word recognition in a dyslexic child (Dubois et al., 2007). The processing speed impairment is also consistent with Valdois et al.’s (2004) interpretation of the multi-element deficit in dyslexia, later called by Bosse et al. (2007) the visual attention span deficit hypothesis of developmental dyslexia. These authors argue that a reduction in the number of elements simultaneously processed might be a second core deficit in developmental dyslexia. Accordingly, a slow processing speed may result in a limitation of the number of letters simultaneously processed, in accordance with the visual attention span deficit hypothesis. This hypothesis is theoretically based on the connectionist multi-trace memory model for polysyllabic word reading proposed by Ans et al. (1998, hereafter MTM model). Interestingly, the MTM model offers a theoretical framework accounting for a possible causal relationship between the number of letters simultaneously processed and proficient reading. A key component of the MTM model is a focal processing window through which

information from the orthographic input is extracted. In simulating skilled reading and acquired disorders, the MTM model suggests that a selective reduction in the amount of information extracted from the orthographic input through the focal window might impact reading acquisition (Valdois et al., 2004). A detailed account on how the number of simultaneously processed letters is related to reading deficiencies within the MTM framework is provided in Bosse et al. (2007). Accordingly, multi-character processing performance predicts variations in learning to read, independently of the influence of phoneme awareness. This contribution to reading performance is observed from the beginning of literacy instruction and remains present over grades, suggesting that it might have a long-term influence on specific orthographic knowledge acquisition (Bosse and Valdois, 2009).

While the MTM model emphasises the constraints set by the number of letters from which information is extracted, other aspects of visual information extraction from letters in strings may also play a role in the reading deficit of some dyslexics. Letter position information extraction had been relatively neglected until recently. However, encoding the position of letters within a word as well as the identity of individual letters is crucial for word recognition. Acquiring the letter position encoding mechanism required to process letters in parallel is not straightforward (Dehaene et al., 2005). Accordingly, beginning readers exhibit large transposed-letters effects, in which pseudo-words composed by transposing two internal letters are read as the original word (e.g. Acha and Perea, 2008; Perea and Estévez, 2008). Based on the SERIOL model of expert reading (Whitney, 2001, 2008), Whitney and Cornelissen (2005) point out difficulties in acquiring the complex position encoding mechanism as a potential source of developmental dyslexia. In line with this, it has been shown that dyslexic individuals exhibit impaired sensitivity to position in briefly presented symbol-strings (Pammer et al., 2004b). In addition, performance on this task is related to reading (Pammer et al., 2005, 2004a). Moreover, developmental

analogues of the acquired letter position dyslexia have been recently described (Friedmann and Gvion, 2001; Friedmann and Rahamim, 2007). The letter position dyslexics' reading pattern is characterised by the predominance of letter migration errors within words. Unfortunately, letter transposed-position effects and migration errors are largely beyond the scope of most classical formal models of reading (Ans et al., 1998; Coltheart et al., 2001; Perry et al., 2007; Plaut et al., 1996; Seidenberg and McClelland, 1989). Indeed, those models have been essentially designed to deal with higher order processes of reading. They often presuppose a case- and location-invariant representation, without specifying the mechanisms to achieve it (but see Davis and Bowers, 2006; Gomez et al., 2008; Whitney, 2001, 2008, for recent attempts). Also, positional encoding was besides the scope of this study. Indeed, items were not formatted in strings, in order to avoid any effect of reading direction and report order onto the attentional spatial distribution. Nevertheless, position extraction seems a promising complementary line of research (Boden and Giaschi, 2007).

Where does this slow processing speed stem from? In TVA, the interpretation of the C parameter, the visual processing speed, is two-fold (Bundesen, 1990; for a similar discussion of C interpretations in the context of neuropsychological case studies, see Duncan et al., 1999). In a sense, C is the total visual processing capacity shared out among the different elements in the array. On the other hand, C is obviously a sensory parameter, dependent on such factors as discriminability and retinal eccentricity¹². Whereas the original TVA model was framed at a cognitive description level, its principles have been shown to have a strong analogy at the single cell level (the Neural Theory of Visual Attention, NTVA: Bundesen et al., 2005). In NTVA, visual processing capacity is distributed across stimuli by dynamic remapping of receptive fields of cortical cells (Moran and Desimone, 1985). Accordingly, the total processing capacity, C , is proportional to the total activation of neurones at a level of processing at which the classical receptive fields of

neurons are so large that each one covers the entire stimulus display. The activation of these neurons in turn depends on the activation of neurons in lower level cortical areas (Kyllingsbæk et al., 2007). C is thus the product of a whole series of processes, starting from basic feature detection, up to object recognition.

While a basic perceptual deficit account cannot be definitely ruled out, the task was designed to avoid some perceptual confounding effects that were found in at least some dyslexic people. We used high-contrast, easily identifiable letters in a font familiar for children. Letters were not centrally displayed, but Klein et al. (1990) demonstrated that identification scores of peripherally viewed single letters in dyslexic participants were similar to those of normal readers. Also, using six possible positions in a circular display minimises *crowding* between displayed letters. Indeed, identification of a letter displayed in the periphery is generally reduced by the presentation of nearby, surrounding, letters (i.e. crowding; for a recent review, see Levi, 2008; see also Kyllingsbæk et al., 2007; Pelli and Tillman, 2008). This phenomenon has been demonstrated to be increased in some dyslexics (Bouma and Legein, 1977, 1980; Pernet et al., 2006; Spinelli et al., 2002). In normal participants, the isolation field (the area in which crowding occurs) has an elliptic form with a circumferential critical spacing roughly equivalent to a quarter of the target eccentricity (Toet and Levi, 1992). However, Martelli et al. (2009) recently reported a mean *radial* critical spacing of about 0.93 times the eccentricity in a group of sixth Grade dyslexic participants. Nevertheless, the *circumferential* critical spacing is about half the radial critical spacing (Pelli et al., 2007; Toet and Levi, 1992). Accordingly, the spacing between adjacent items, which strictly corresponds to the visual eccentricity, seems sufficient to minimise the impact of crowding on letter identification.

Alternatively, the observed processing speed reduction may stem from either a general visual processing capacity reduction or a more specific disturbance in visually processing letters. The present results do not allow to unambiguously disentangle these

two alternatives and the scientific literature does not provide strong clues. Evidence in favour of an impairment of visual letter recognition in dyslexia is sparse and inconsistent. Peculiarities have been recently reported in the way dyslexic participants visually process symmetric letters (Lachmann and van Leeuwen, 2007) and letters surrounded by a congruent or incongruent shape (Lachmann and van Leeuwen, 2008). Shovman and Ahissar (2006) attempted to isolate the impact of visual perception on dyslexics' reading ability. In their study, control and dyslexic participants achieved similarly in a non-verbal symbol identification task, in which various basic visual properties were manipulated. Recently, Ziegler et al. (2008) investigated the different representational levels of the Dual Route Cascaded model (Coltheart et al., 2001) in a group of dyslexic participants. As a group, dyslexic children showed reduced accuracy in a letter-in-string search task. On the contrary, Hawelka and Wimmer (2008) did not find any impairment in a group of young adult dyslexic on the same kind of task. A number of data nevertheless suggest that the multi-element deficit is not specific to letters (Hawelka et al., 2006; Hawelka and Wimmer, 2005). For example, Hawelka and Wimmer (2005) showed that individual recognition thresholds on multi-digit arrays were associated with dyslexic and normal-readers' number of eye movements in reading. Nevertheless, the question remains whether dyslexic participants' multi-element processing difficulties are specific to alphanumerical characters or generalise to other objects. This topic is of particular relevance to the visual attention span hypothesis (Bosse et al., 2007). Bosse et al. defined the visual attention span as "the amount of distinct visual elements which can be processed in parallel in a multi-element array" (p. 198). This definition strongly suggests that a reduction of the visual attention span would apply to all types of material, provided that the different visual elements are processed in parallel (Prado et al., 2007; Lassus-Sangosse et al., 2008).

A number of processing speed deficits have been theoretically and empirically associated with developmental dyslexia. Amongst these are the automatisisation deficit

(Moores et al., 2003; Nicolson and Fawcett, 1990; van der Leij and van Daal, 1999), the temporal processing deficit (Au and Lovegrove, 2001; Farmer and Klein, 1995; Stein and Walsh, 1997), a more general processing speed deficit (Breznitz and Misra, 2003; Catts et al., 2002; Wolf and Bowers, 1999), and a sluggish attentional shifting (Facoetti et al., 2008; Hari and Renvall, 2001). However, there is no ‘gold standard’ definition of processing speed as a construct (Shanahan et al., 2006). As a consequence, though there are some clear similarities between these and our observation of a reduced speed at which letters are visually processed, we would be cautious in proposing any direct correspondence (Duncan et al., 2003). For instance, an increased attentional blink has been observed in some dyslexic people (Buchholz and Aimola Davies, 2007; Facoetti et al., 2008; Hari et al., 1999; Visser et al., 2004; but see Lacroix et al., 2005). The attentional blink refers to the finding that after people have identified the first target in a sequence, they are far less accurate at identifying a second target that succeeds the first one in close temporal proximity. The attentional blink reflects constraints on temporal visual processing (Gillard-Crewther et al., 2007; Marois and Ivanoff, 2005) and has been taken as a sign of sluggish and prolonged attentional dwell time in dyslexia. Nevertheless, “in normal subjects, for example, ‘processing’ in the sense defined by TVA —entry of a stimulus description into VSTM— typically completes over tens of milliseconds from stimulus onset, while the attentional blink lasts hundreds of milliseconds.” (Duncan et al., 2003, p. 700). In line with this, Lallier et al. (2009) recently reported a dissociation between prolonged attentional dwell time and preserved multi-letter processing (assessed by means of a global and partial report tasks) in a young adult dyslexic participant. Further work is thus required to address the relations between these temporal processing mechanisms and various hypothesised causes of developmental dyslexia.

4.2. Storage capacity limitations

Patient AB exhibited a small but significant reduction on the K parameter. This parameter indexes the maximal number of elements that can be extracted from a short visual display and stored in visual short-term memory. VSTM storage capacity sets an upper limit for the number of objects that can be perceived simultaneously and has been considered as one of the major bottlenecks of visual information processing (Marois and Ivanoff, 2005).

In the last few years, there has been growing interest in investigating the cognitive and neural properties of VSTM (Alvarez and Cavanagh, 2004; Awh et al., 2007; Luck and Vogel, 1997; Todd and Marois, 2004; Vogel et al., 2001; Vogel and Machizawa, 2004; Xu and Chun, 2006; for recent reviews, see D'Esposito, 2007; Postle, 2006) as well as their links with other cognitive abilities, such as visual attention (for a review, see Awh et al., 2006). Recently, Vogel et al. (2005) provided evidence that low VSTM capacity individuals also have low efficiency at excluding irrelevant items from being processed and stored in memory. Their study is of relevance here, since VSTM capacity was estimated using a change detection paradigm (Luck and Vogel, 1997), which provides fairly close estimates to those obtained by whole report paradigms (Vogel et al., 2001). The inability to inhibit or suppress the influence of distractor stimuli on performance has also been reported in dyslexic individuals. Roach and Hogben (2007) recently used the combination of a spatial cueing procedure with a single fixation visual search task to investigate visual information selection (see also Roach and Hogben, 2004). Contrary to the control participants, the dyslexics' search performance was markedly affected by the set size in the cued condition. Using signal detection theory to model the participants' search performance, Roach and Hogben convincingly demonstrated that the cueing deficit observed in dyslexic individuals reflects their inability to filter out the distractor stimuli. There is also evidence that some dyslexics are unable to focus visual attention normally

(Facoetti et al., 2000, 2003; Lorusso et al., 2004), which may be particularly detrimental when learning to read (Whitney and Cornelissen, 2005; see Vidyasagar, 1999, 2004 for similar proposals; Skottun and Skoyles, 2006, for a critical discussion).

These results potentially suggest that AB's low storage capacity might have broader implications. However, these proposals remains at the current stage largely speculative. AB and PA showed a similar reading level, but only AB exhibited reduction on the K parameter. This discrepancy suggests that this measure is not of primary relevance for the explanation of the reading pattern. One would also note that memory capacity vary considerably across normal individuals, classically ranging from 3 to 5 (Duncan et al., 1999, 2003; Habekost and Bundesen, 2003; Vogel and Machizawa, 2004; Vogel et al., 2005) and that AB's storage reduction is relatively small, well within the classical range. Taken together, these different elements question the behavioural significance of such a small deficit.

4.3. Attention allocation, left mini-neglect and parietal deficit

The final aim of our study was to assess a possible contribution of a particular attentional imbalance to multi-character processing deficit in dyslexic participants. Signs of left mini-neglect were indeed reported in dyslexic participants by Hari et al. (2001). They tested dyslexic adults with two tasks known to be affected in neglect patients. In the *temporal order judgement task*, two bars are presented, one in each visual field. Participants are required to indicate which of the two appeared first. The Stimulus Onset Asynchrony (SOA) between the stimuli was systematically varied. At short SOAs, dyslexic participants tended to report more right than left stimulus precedence. Hari et al. reported similar results in a *line motion illusion task*. Left mini-neglect was further observed in line bisection (Sireteanu et al., 2005). Hari et al. (2001; see also Hari and Renvall, 2001) interpreted this left mini-neglect as reflecting a visual attentional problem,

possibly stemming from a mild right parietal lobe dysfunction. In line with these results, some dyslexic children were shown to exhibit left inattention in flanker and cue-target reaction time tasks, associated with over-distractibility in the right visual field (Buchholz and Aimola Davies, 2005, 2006; Facoetti and Molteni, 2001; Facoetti and Turatto, 2000; Facoetti et al., 2001). Also in agreement are the reports of prolonged attentional dwell time in dyslexic children (Buchholz and Aimola Davies, 2007; Hari et al., 1999; Visser et al., 2004; but see Lacroix et al., 2005). However, in contradiction to the left mini-neglect hypothesis, AB and PA did not exhibit a preference for letters displayed in the right hemifield. On the contrary, AB tended to allocate more attention to the left hemifield, a result already reported in some adult control participants (Bublak et al., 2005; Duncan et al., 2003; Finke et al., 2005; Habekost and Bundesen, 2003; Habekost and Rostrup, 2006). In accordance with other studies (Judge et al., 2007; Rutkowski et al., 2003; Sireteanu et al., 2006), we did not find any sign of left mini-neglect in AB and PA.

Various other aspects of our data may be seen at first glance as congruent with a mild parietal lobe dysfunction. Indeed, Duncan et al. (1999) reported a bilateral reduction of the VSTM storage capacity and a reduction of processing speed, similar to those observed in AB and PA, in 9 brain-damaged patients with right inferior parietal lobule lesions (see also Peers et al., 2005). Accordingly, there is now growing evidence that neglect patients exhibit bilateral attention deficit, in addition to the classical lateralised attentional impairment (see Husain and Rorden, 2003, for a review). Moreover, Hari and Renvall (2001) did not consider the left mini-neglect as the core attentional problem in dyslexia, but rather as a marker of an underlying attentional deficit. They instead propose that the key impairment —at least in the attentional domain— could be a *Sluggish Attentional Shifting* mechanism (i.e. the SAS theory): a slowing of attention engagement/disengagement. The idea is that, once engaged, the attention of dyslexic children cannot easily disengage. The sluggish attentional capture would thus impair

processing of rapid stimulus sequences (for a review on fast temporal processing in dyslexia, see Farmer and Klein, 1995). Though a deficit in attention engagement is not easily captured by the TVA framework, in which processing is conceived as a parallel race, the SAS theory may seem to offer a plausible alternative explanation of the processing speed deficit observed in AB and PA. This interpretation rely on a sequential processing of the displayed elements. However, Lassus-Sangosse et al. (2008) recently described an impaired ability to process simultaneously displayed letter-strings in a group of dyslexic children, whose performance was similar to control participants when the same letter-strings were presented sequentially. In addition, only the performance on the simultaneous task was predictive of reading. Kyllingsbæk and Bundesen (2007) recently provided strong evidence in favour of parallel processing in whole report. They designed a multi-feature whole report paradigm, in which the displayed elements have multiple features to be reported (e.g. coloured letters). Authors demonstrated perfect stochastic independence of feature reports in various experimental conditions, a result that is incompatible with purely serial models but well captured by parallel models such as TVA (see also Bundesen et al., 2003; see Bundesen and Habekost, 2005 for a review about sequential versus parallel attentional processing). Additionally, K and/or C reductions were also reported after various lesions outside the parietal cortex (Duncan et al., 2003; Habekost and Bundesen, 2003; Habekost and Rostrup, 2007). This had lead Habekost and Rostrup (2007) to suggest that reductions in both K and C could manifest after damage in relevant parts of the white matter, specifically the long-range posterior-anterior or cortico-thalamic connections, which may be critical for successful integration of the large cerebral network underlying visual conscious perception and short-term maintenance.

Nevertheless, dyslexic participants showed a slight tendency towards attention imbalance. This is clearer for AB. Indeed, he tends to pay more attention to the left hemifield as opposed to the control participants. He also demonstrated better letter

identification scores in the left than in the right hemifield, contrary to the control participants. To assess whether this tendency to imbalance is reflected in spatial asymmetries in reading and/or spelling, we ran a reanalysis of his reading and spelling errors. We distinguished between errors affecting left versus right part of the word. However, no particular sign of imbalance was observed at this level. In reading, 34 errors affected the left part of the item, and 35 errors were localised on the right side. The same pattern emerges in spelling, 23 on each side. This is coherent with the fact that a small leftward bias is sometimes observed in normal participants processing letters in conditions similar to ours (Bublak et al., 2005; Habekost and Bundesen, 2003; Habekost and Rostrup, 2006; Finke et al., 2005, 2006).

4.4. Multi-letter processing and phonology

Are the observed deficits related to the oral report procedure and possible phonological problems in our dyslexic participants? The oral report method used in the whole report task is of immediate relevance for reading. Moreover, this non-speeded procedure is well suited for dyslexic children, in which motor problems were often reported (e.g. Ramus et al., 2003). However, whole report performance might reflect more than the ability to extract visual information. The potential contribution of oral or phonological abilities to the whole report performance has been a matter of debate in both normal adult participants and dyslexic children (Habekost and Bundesen, 2003; Vogel et al., 2001; Hawelka and Wimmer, 2008). However, the current findings support the fact that the poor performance of dyslexic children in processing simultaneously displayed letters cannot be attributed to phonological or verbal short-term memory problems. Indeed, despite important differences in performance between AB and PA on metaphonological tasks, both dyslexic participants demonstrated a highly comparable impairment on the most prominent parameter: the letter visual processing speed. Also, AB demonstrated a

small visual short-term memory storage capacity impairment, contrasting with his preserved phonological short-term memory. This conclusion is in line with previous research. It has been shown that performance in the global report task is barely affected by a concurrent verbal task (Pelli et al., 2006). The VSTM storage estimates obtained by means of match-to-sample tests (e.g. Vogel et al., 2001), which do not require a verbal recoding operation, are closely in line with the results found by fitting TVA to whole report data (Habekost and Bundesen, 2003; Habekost and Rostrup, 2007; Finke et al., 2005). The minimal involvement of phonological processes in the letter report task is further supported by data on developmental dyslexia. A deficit in processing simultaneously displayed letters was observed in dyslexic people using a non-verbal change detection task (Rutkowski et al., 2003). Letter report disorders were typically reported in dyslexic children who exhibited no phonological problems whereas a phonological impairment was not found to affect multi-character processing abilities in developmental dyslexia (Bosse et al., 2007; Hawelka and Wimmer, 2005; Lallier et al., 2009; Valdois et al., 2003). Moreover, performance on the report tasks was further found to relate to reading performance (Bosse and Valdois, 2009) and eye movements in text reading (Prado et al., 2007), independently of phoneme awareness.

It nevertheless remains that the report tasks do require the secondary activation of verbal names of the initially encoded information in visual short-term memory (Shih and Sperling, 2002). This has led Shovman and Ahissar (2006) to hypothesise that the poor report performance observed in dyslexic children might potentially reflect a sluggish activation of the phonological information of letter names, instead of visual processing deficiencies. This might be particularly detrimental for the estimation of the VSTM storage capacity. Indeed, the time required for verbal recoding of the visually encoded items might be longer than the duration of the VSTM trace, thus leading to artificially low estimates of VSTM capacity (Vogel et al., 2001; Schweickert and Boruff, 1986).

However, no deficit was observed on parameter K in PA; and the reduced VSTM storage observed in AB, albeit significant, remained well in the typical range of normal VSTM estimates. Accordingly, Lassus-Sangosse et al. (2008) recently reported poor performance in global and partial report tasks in the absence of letter naming or verbal short term memory problems.

It can thus be assumed that the observed impairments primarily reflect deficiencies in those visual and attentional processes involved in the extraction and storage of visual information from a brief visual display.

5. Conclusion

This study applied an original method derived from the formal modelling field to investigate the multi-letter visual processing deficit observed in some dyslexics. Individual letter report performance of young dyslexic participants were fractionated into theoretically-driven components, by means of the combination of psychophysical measurements and computational modelling. The present results demonstrate the power of such combined approach. They strengthen the initial observation of a multi-letter processing deficit in some dyslexic people. Taken together, the results point to a prominent role of the speed of parallel processing of visual information (at least for letters).

These results also highlight the need of a better understanding of the visual front-end of reading. How and to which degree visual mechanisms contribute to reading difficulties in developmental dyslexia remains largely to be understood. Future research is required to clarify the prevalence, precise nature and role of the deficits we identified at the source of the multi-letter processing impairment in our dyslexic participants.

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Appendix A

Examples of errors made by the participants

A.1. Errors in reading aloud

	Target item	Target translation	Target pronunciation	Response pronunciation	Comments
Regularisations	femme	woman	/fam/	/fəm/	
	monsieur	mister	/məsjø/	/mɔ̃sjøer/	
	seconde	second	/səgɔ̃d/	/səkɔ̃d/	
	écho	echo	/eko/	/eʃo/	
Confusions	caravelle	caravel	/karavel/	/garavel/	
between	asile	asylum	/azil/	/ozil/	
letters	rac		/rak/	/kak/	
	taubage		/tobaz/	/tubaz/	/u/ is spelled 'ou' and resulted from a confusion between 'a' and 'o'
Omissions	toir		/twar/	/twa/	
	mission	mission	/misjɔ̃/	/misɔ̃/	
Lexicalisations	courlone		/kurlɔ̃n/	/kuløer/	production of the French word 'couleur' (colour)
	mic		/mik/	/pik/	production of the French word 'pic' (peak)

A.2. Errors in spelling

	Target item	Target translation	Target pronunciation	Response	Response pronunciation
Phonologically	tabac	tobacco	/taba/	taba	/taba/
plausible	août	august	/ut/	oute	/ut/
	femme	woman	/fam/	fame	/fam/
	ville	city	/vil/	vile	/vil/
Omissions	flocachin		/fɔka fɛ̃/	focachin	/fɔka fɛ̃/
	verdulin		/vɛrdylɛ̃/	erdulin	/ɛrdylɛ̃/
Confusions	datoir		/datwar/	tatoir	/tatwar/
	bracho		/braʃo/	brajo	/braʒo/

Appendix B

The TVA model

B.1. General theory

TVA is a joint theory of attentional selection and visual recognition. In TVA, visual recognition and attentional selection consist in making perceptual categorisations. A perceptual categorisation has the form “ x belongs to i ”; where x is an element in the visual field and i is a perceptual category (such as a letter type). As an example, “the element displayed at the upper left position is a B” is a perceptual categorisation.

A given element from the visual field is selected (and simultaneously recognised) if and when a perceptual categorisation for this element enters a limited-capacity visual short-term store: the visual short-term memory (VSTM). In contrast to many serial models of attention (e.g. Treisman and Gelade, 1980), TVA is based on parallel, competitive processing (Rumelhart, 1970). Objects or elements in the visual field compete for access to the VSTM, in a K -winners-take-all process. Selection is determined by temporal characteristics of processing. Objects in the visual field can be processed in parallel, and the objects that are selected (and, therefore, can be reported) from a briefly exposed visual display are those objects whose encoding processes complete before the sensory representation of the display vanishes and before VSTM has been filled up with other objects. Competition is thus considered as a race: recognised elements are those who were processed faster.

For each element in a given display, the rate at which a particular categorisation “ x belongs to i ” is encoded into VSTM, $v(x, i)$, is given by Equation 1 of TVA:

$$v(x, i) = \eta(x, i) \beta_i \frac{w_x}{\sum_{z \in S} w_z} \quad (1)$$

where $\eta(x, i)$ is the strength of the sensory evidence that element x belongs to category i ,

β_i is the perceptual bias to classify any element as belonging to category i , and $w_x/\sum_{z \in S} w_z$ is the relative attentional weight allocated to element x (i.e. the weight of object x , w_x , divided by the sum of the weights across all objects in the visual display S). The ratio of attentional weights is the way by which competition between elements is “biased”, based on “bottom-up” and “top-down” factors.

Within most experimental set-ups, $\eta(x, i)$ and β_i values may be assumed to be constant. As a practical consequence, they can not be distinguished from each other and form a compound estimate:

$$s(x, i) = \eta(x, i)\beta_i.$$

The $s(x, i)$ parameter represents the degree of pattern match between element x and a template i in long-term memory. This parameter is affected by the sensory properties and general discriminability of the stimuli, but also by learning which may lead to change in or even development of new representations (For more details, see Bundesen, 1990).

Consider the case when the VSTM storage capacity exceeds the number of displayed elements. In this case, the time taken to encode x in VSTM is exponentially distributed. Specifically, the probability that element x gets encoded into VSTM at time t equals

$$P(t) = \begin{cases} 0 & \text{for } t < t_0 \\ 1 - \exp[-v(x, i)(t - t_0 + \mu)] & \text{for } t \geq t_0 \end{cases}$$

where t_0 denotes the *minimal effective exposure duration*, below which no information is extracted from the display, and μ captures the prolongation of the effective exposure duration in the case of unmasked displays. Thus, $(t - t_0 + \mu)$ is the *effective exposure duration* of the stimulus. After a minimal exposure duration, t_0 , processing follows the exponential distribution with a rate parameter corresponding to $v(x, i)$. When x is displayed alone, $v(x, i)$ is the sensory effectiveness of object x , $s(x, i)$. When multiple elements are displayed, the sensory effectiveness of each element $s(x, i)$ is scaled by their relative attentional weights $w_x/\sum_{z \in S} w_z$, as expressed in Equation 1. When more than one

element is displayed, the total processing capacity C for the display could be computed as the sum of v values across all perceptual categorisations of all elements in the visual field

$$C = \sum_{x \in S} \sum_{i \in R} v(x, i)$$

where R is the set of all perceptual categorisations. Thus, C is a measure of the total rate of information uptake (in objects per second). Also, the balance between attentional weights was estimated by

$$w_{lat} = \frac{w_{left}}{w_{left} + w_{right}}$$

where w_{left} and w_{right} are the means of the attentional weights w respectively in the left and right hemifields. As a consequence, a w_{lat} value at .5 indicates a symmetrical attention distribution. When the attention allocation is asymmetrical, w_{lat} deviates toward 0 (in the case of a right hemifield advantage) or 1 (in the case of a left hemifield advantage).

Matters are mathematically more complicated when the VSTM capacity K is a limiting factor. In this situation, categorisation processing times remain obviously exponentially distributed and are still mutually independent, but only categorisations from the first K stimuli will be encoded in VSTM. Details may be found in Kyllingsbæk (2006).

B.2. Experimental paradigms and parameters estimation

The main paradigms modelled by TVA have been whole and partial report tasks (Sperling, 1960, see text for details). However, the choice of the experimental settings had implications on the model's parameters that can be estimated. If the exposure duration is kept constant, it is not possible to separate v from the effective exposure duration ($t - t_0 + \mu$). As a consequence, no pure estimation of *processing speed* is allowed. On the other hand, if the display size is kept constant, v -values can not be decomposed in sensory effectiveness s and attentional weights w . Our experimental paradigm thus involved a systematic variation of both exposure duration and set size to allow the distinction between processing speed and attentional weighting.

Before fitting the data, a decision has to be taken concerning the number of parameters to be estimated. Indeed, TVA allows the fitting of various sets of parameters. Parameters K , t_0 and μ could vary from 1 to the number of experimental conditions. This is particularly useful for the study of neurological patients with unilateral lesions. In this case, experimental conditions in which stimuli are displayed unilaterally are required. Though essential in data fitting, t_0 and μ parameters were not directly linked to the various theoretical accounts of the multi-element processing deficit in dyslexia (but see Habekost and Bundesen, 2003, for a demonstration of the usefulness of the t_0 parameters in sub-clinical attentional disturbances). They were thus constrained to be identical across conditions. Also, K was shown to be highly bilateral in normal control participants, as well as in patients with parietal (Bublak et al., 2005; Duncan et al., 1999), occipital or occipito-parietal (Duncan et al., 2003) and frontal-subcortical lesions (Habekost and Bundesen, 2003). This lead Habekost and Bundesen (2003, p. 1178) to state that “damage to VSTM is typically nonspecific, reducing capacity uniformly in the visual field” (see also Habekost and Rostrup, 2007). As a consequence, our experimental conditions did not included unilateral displays. Processing rate $s(x)$ and attentional weight $w(x)$ could vary from 1 to the number of different position in the display. Previous results emphasised that processing speed was highly correlated between the hemifields in normal participants as well as in neglect and simultagnosic patients (Bublak et al., 2005; Duncan et al., 1999, 2003), thus arguing for s as constant between hemifields in dyslexic participants. However, Habekost and Rostrup (2006, 2007) recently reported a unilateral processing speed deficit in the contralesional visual hemifield of patients with anterior right hemisphere lesions. We thus fitted 6 different parameterisations to the data, resulting from the combination of 1, 2 (one for the left hemifield, one for the right) or 6 (one for each position) s -values and 2 or 6 w -values. Because we were interested in the attentional imbalance between hemifields in dyslexic participants, at least 2 different w -values were required. We then

chose the best fitted model as the model that minimised the Bayesian Information Criterion (BIC: Schwarz, 1978) across the participants. The selected model includes only one s -value and six w -values, one for each possible position in the display. Data was thus best explained by a model in which processing speed is the same for the different possible positions. Interestingly this model is also the one that minimises the bootstrap SDs , indicating highest reliability in the individual parameter estimates.

Author Note

The research reported in this article was supported by a grant from the Belgian Fonds National de la Recherche Scientifique (FNRS) to M. Dubois. Chloé Prado was supported by a fellowship from the French Research Ministry. Søren Kyllingsbæk was supported by grants from the Danish Research Council for the Humanities, the Danish Strategic Research Council, and the University of Copenhagen. We are grateful to Claus Bundesen and Thomas Habekost for in-depth discussions on methodological and data analysis aspects. We thank Pierre Mahau for developing the critical timing accuracy checker software and performing the assessment. We are also grateful to William Maki for providing feature and pixel letter similarity matrices. We thank the teachers and children of the “Saint Boniface-Parnasse” school for their help and participation in this research. We are particularly grateful to AB and PA for their patience.

Requests for reprints should be addressed to Matthieu Dubois, E-mail: matthdub@gmail.com or to Sylviane Valdois, E-mail: Sylviane.Valdois@upmf-grenoble.fr.

Footnotes

¹AB's non verbal reasoning was assessed through the Raven's Coloured Progressive Matrices, for which he achieved normal performance (percentile 50–75). PA obtained a 99 performance IQ on the WISC-IV.

²In this test, children are required to read a 265 words text, as accurately and quickly as possible. By including very unfamiliar words, the text forces one to avoid guessing based on lexical knowledge. Reading level is established on the basis of both accuracy and reading speed.

³The ODEDYS test battery is a subset of a standardised, but not yet published, French reading and writing assessment battery, called BALE. The normative data we used in fact came from the BALE, which provides additional normative informations that are not always included in the ODEDYS.

⁴Errors were considered as phonologically plausible when the written word could be pronounced like the dictated word by applying grapheme-to-phoneme conversion rules, irrespective of the orthographical context.

⁵The averaged feature chi-square dissimilarity (Maki et al., 2003) within the stimuli set was similar to those of the whole alphabet (stimuli set: $M = 10.36$, $SD = 1.89$; whole alphabet: $M = 10.65$, $SD = 1.73$).

⁶Stimuli and background colours were characterised for the CRT screen used for dyslexic participants' assessment only. In the CIE *LaB* space, Stimuli were characterised as follows: *Luminance*: 85.4 cd.m^{-2} , *a*: 1.84, *B*:-30.37; and background: *Luminance*: 19 cd.m^{-2} , *a*: 5.72, *B*:-8.72.

⁷This system is composed by a computer, a 8-channel logical analyser SDA810 connected to photosensors and custom data acquisition software.

⁸ Due to an error of administration, both AB and PA did 1 block less than scheduled, yielding 14 items per condition.

⁹The same results stem from an analysis by stimulus size (1, 3 or 5 letters). In the control group, the average number of reported letters was respectively .84 ($SD = .06$, range: [.76 – .95]), 2.19 ($SD = .17$, range: [1.86 – 2.41]), and 2.83 ($SD = .31$, range: [2.54 – 3.48]). AB achieved respectively .81, 2, and 2.39 letters, and PA .89, 2.13, and 2.44 letters (all $p > .05$ after *log*-transformation).

¹⁰The mean was computed after applying a Fisher z -transform to correlation coefficients.

¹¹In TVA, t_0 refers to the threshold exposure duration, that is, the minimal exposure duration below which no letter is reported. More specifically, t_0 reflects the difference of time required by the stimulus and the mask to be perceived.

¹²The two properties follow from Equation 1, in Appendix B. When sensory effectiveness is kept constant, Equation 1 imply that C is constant across variations in both the number of objects in the display and their attentional weights. Thus, C may be regarded as a fixed total processing capacity divided among the different objects in the display, and the weight ratio $w_x / \sum_{z \in S} w_z$ may be regarded as the proportion of the total processing capacity C that is allocated to element x . However, when sensory effectiveness vary between elements, C reflects this variation. This is the reason why C is estimated separately for each hemifield in the case of —unilateral— brain damage, in which sensory effectiveness may be affected differentially across the hemifields (Habekost and Rostrup, 2006; Peers et al., 2005).

Table 1

Clinical characteristics of the two participants — Test of reading and spelling abilities

	Norms		AB		PA	
	Mean (<i>SD</i>)	Range	score	<i>z</i>	score	<i>z</i>
Reading scores						
Cons. HF	19.7 (0.7)	17–20	16	-5.0 ^{***}	16	-5.0 ^{***}
Cons. LF	18.4 (2.0)	11–20	9	-4.7 ^{***}	10	-4.2 ^{***}
Inc. HF	18.2 (1.5)	12–20	8	-6.7 ^{***}	10	-5.4 ^{***}
Inc. LF	13.2 (3.9)	2–20	4	-2.4 ^{**}	2	-2.9 ^{**}
Pseudo-w.	33.9 (3.9)	21–40	22	-3.0 ^{**}	21	-3.3 ^{***}
Reading times (sec)						
Cons. HF	18.7 (5.7)	8–42	56	6.5 ^{***}	82	11.0 ^{***}
Cons. LF	26.5 (8.1)	13–51	67	5.0 ^{***}	109	10.2 ^{***}
Inc. HF	20.3 (6.5)	9–47	66	7.0 ^{***}	101	12.3 ^{***}
Inc. LF	30.2 (10.4)	14–70	66	3.4 ^{***}	116	8.3 ^{***}
Pseudo-w.	60.6 (16.8)	34–103	127	3.9 ^{***}	191	7.7 ^{***}
Mapping rules	42.6 (2.9)	33–46	40	-0.9	41	-0.6
Spelling						
Cons.	9.4 (0.8)	7–10	4	-6.4 ^{***}	7	-2.9 ^{**}
Inc.	7.9 (1.7)	4–10	1	-4.1 ^{***}	1	-4.1 ^{***}
Pseudo-w. bi	9.2 (1.1)	4–10	7	-2.1 [*]	8	-1.1

Table 1

(continued)

	Norms		AB		PA	
	Mean (<i>SD</i>)	Range	score	<i>z</i>	score	<i>z</i>
Pseudo-w. tri	8.8 (1.5)	4–10	2	-4.4 ^{***}	5	-2.5 ^{**}

Notes – HF stems for High Frequency and LF for Low Frequency; Cons. and Inc. for consistent and inconsistent words; Pseudo-w. for pseudo-words; bi and tri are respectively for bi-syllabic and tri-syllabic. Normative data are from the ODEDYS test battery ($N = 116$).

* one-tailed $p < .05$; ** one-tailed $p < .01$; *** one-tailed $p < .001$. Applying a Bonferroni correction for 15 tests reduces the critical p -value from .05 to .0033 (the critical z -value became -2.7), rendering three comparisons insignificant (AB: inconsistent low frequency word reading score and bi-syllabic pseudo-word spelling score; PA: tri-syllabic pseudo-word spelling score).

Table 2

Clinical characteristics of the two participants — Phonological skills and Multi-element processing screening

	Norms		AB		PA	
	Mean (<i>SD</i>)	Range	score	<i>z</i>	score	<i>z</i>
Verbal short-term memory: digit span						
Forward	4.7 (0.5)	2–5	5	.6	6	2.6
Backward	3.6 (1.9)	1–5	4	.2	3	-0.3
Metaphonology						
Phon. del.	15.1 (4.4)	3–20	7	-1.8*	10	-1.2
Phon. segm.	6.6 (4.4)	1–15	1	-1.3	7	0.1
Acronyms	7.4 (2.4)	1–10	0	-3.1***	5	-1.0
Multi-element processing screening						
whole report	80.4 (10.4)	51–99	51	-2.8**	55	-2.4**
partial report	41.3 (6.6)	9–50	30	-1.7*	30	-1.7*

Notes – Phon. del. stems for phoneme deletion and Phon. segm for phonemic segmentation.

Normative data ($N = 101$) are from Bosse and Valdois (2009).

* one-tailed $p < .05$; ** one-tailed $p < .01$; *** one-tailed $p < .001$. Whole report results and AB's acronym performance survived a Bonferroni-corrected significance of $p < .0071$ (the critical z -value became -2.4).

Table 3

Best-fitted TVA parameter estimates

	t_0	μ	K	C	W_{lat}
Dyslexic participants					
AB	0	313 (65)*	3.81 (.13)**	22.9 (2.1)*	.59 (.04)
PA	0	238 (33)	4.44 (.25)	23.3 (1.7)†	.56 (.03)
Controls					
BC	0	152 (20)	4.69 (.26)	27.0 (2.3)	.40 (.04)
RDF	5	145 (21)	4.59 (.22)	40.3 (4.5)	.40 (.03)
LB	4	157 (33)	4.25 (.15)	45.7 (4.4)	.34 (.03)
NT	0	173 (24)	4.66 (.26)	36.5 (2.8)	.56 (.04)
SP	0	186 (24)	4.32 (.12)	40.4 (2.9)	.52 (.04)
KK	0	105 (20)	4.74 (.16)	52.2 (3.9)	.40 (.04)
MM	0	131 (17)	4.60 (.22)	34.0 (2.8)	.41 (.03)
SI	0	134 (32)	4.60 (.12)	64.7 (8.6)	.47 (.04)
WP	1	255 (41)	5.00 (.16)	29.6 (2.9)	.39 (.04)
Mean	1.06	159.64	4.6	41.16	.43
<i>SD</i>	1.92	42.93	.22	11.76	.07

Table 3

Continued

Notes — t_0 : minimal effective exposure duration (msec); μ : additional effective exposure duration for unmasked displays (msec); K : visual short-term memory storage capacity (number of elements); C : total processing speed (elements.sec⁻¹); and w_{lat} : laterality index of attentional weights. Standard errors of each estimate are given in parentheses (as estimated by the *Standard Deviation* of the 1,000 bootstrap repetitions). As no variability was observed for t_0 in most cases, no *SD* has been computed. *Log*-transformed μ and C parameter estimates were used in statistical analyses to satisfy the normality assumption underlying the use of *t*-tests.

† $p = .051$; * $p < .05$; ** $p < .01$; *** $p < .001$.

Figure Captions

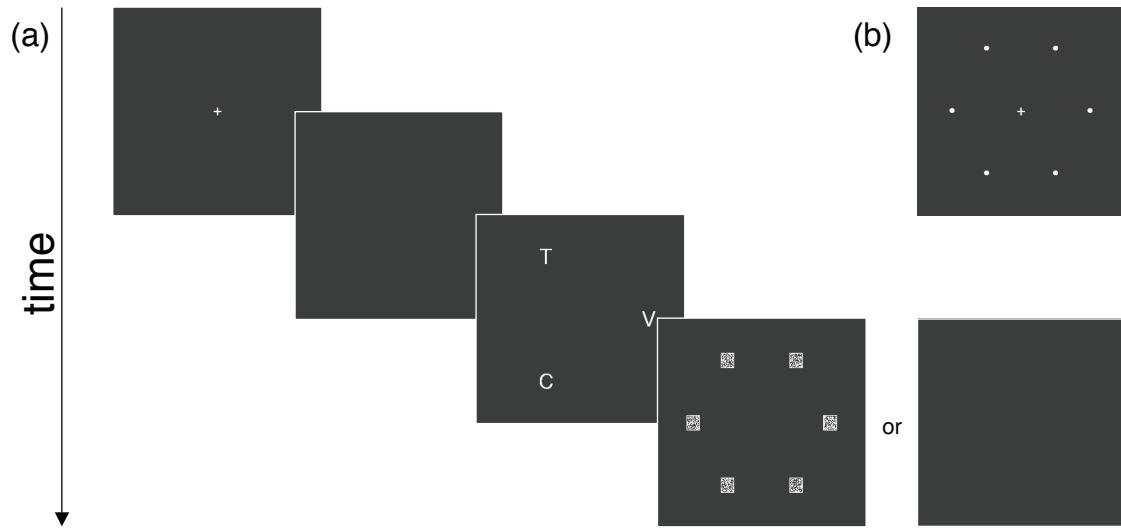
Figure 1. Experimental settings. (a) Schematic illustration of the set-up of the multi-element processing task. (b) The six possible display locations.

Figure 2. Whole report performance for dyslexic participants AB and PA (upper panels) and three representative control participants (lower panels, see text or details). Each panel shows the mean number of correctly reported letters as a function of the effective exposure duration (msec) and the stimulus size. Circles, triangles and squares are for 1, 3 and 5 letters stimuli, respectively. The effective exposure duration was computed for the unmasked conditions by adding μ , the visual persistence estimate, to the physical exposure duration. TVA maximum likelihood fits are represented by solid curves. K , the visual short-term memory parameter estimate, is indicated by a horizontal dashed line.

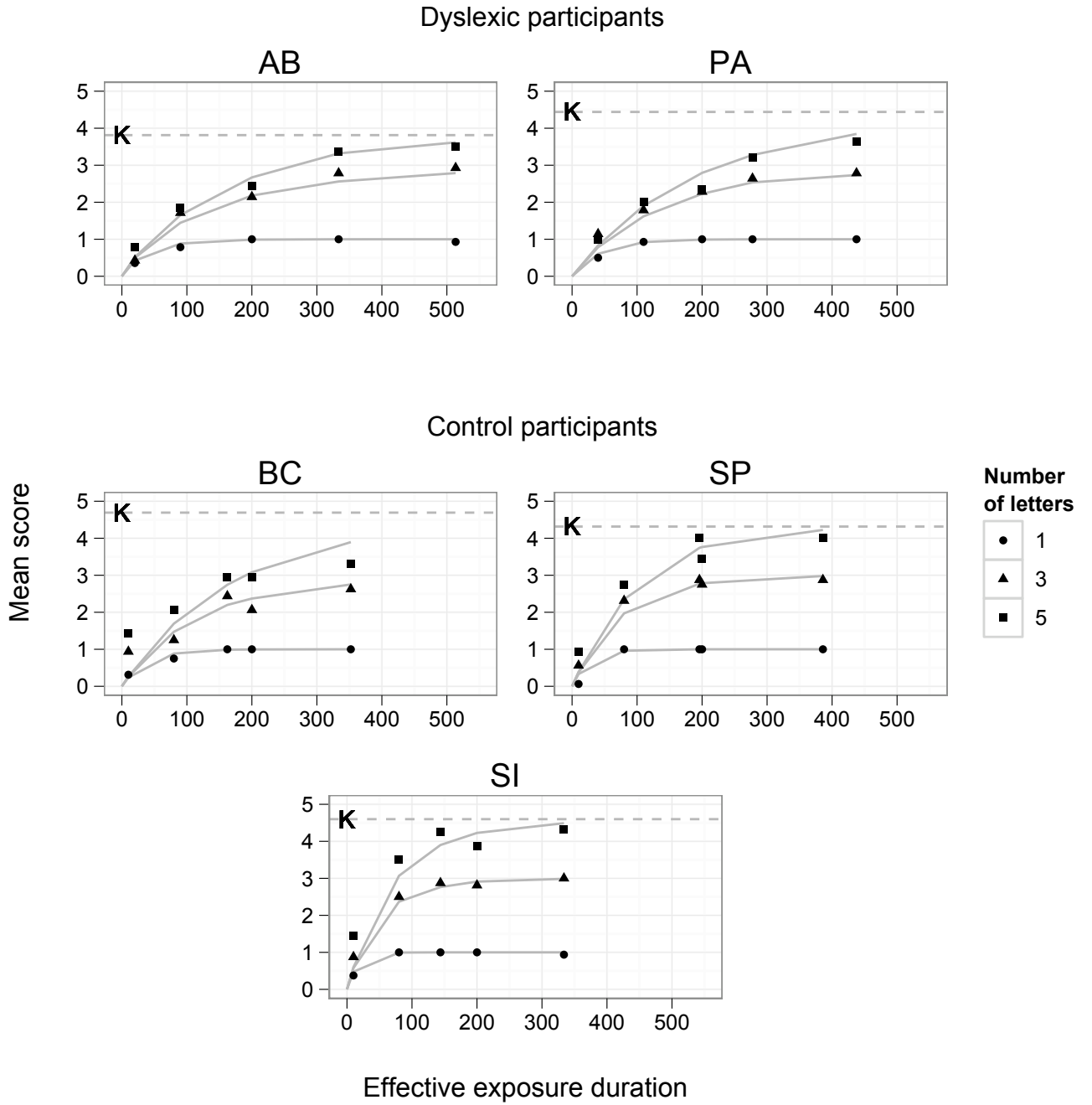
Figure 3. Distributions of the 1,000 bootstrap estimates of parameter w_{lat} for dyslexic participant AB. Solid and dotted curves respectively indicate kernel density estimation and normal distribution. As can be seen, the bootstrap distribution is close-to-normal. The 95% percentile confidence interval (CI) is also illustrated by means of a grey box around the mean (+): $0.53 \leq w_{lat} \leq 0.66$.

Figure 4. Differences between AB and PA. Each panel shows the kernel density estimate of the bootstrap probability distribution for parameters C (*Left*) and K (*Right*). Overlap between distributions represents the probability of both dyslexic participants having the same ‘true’ parameter estimate.

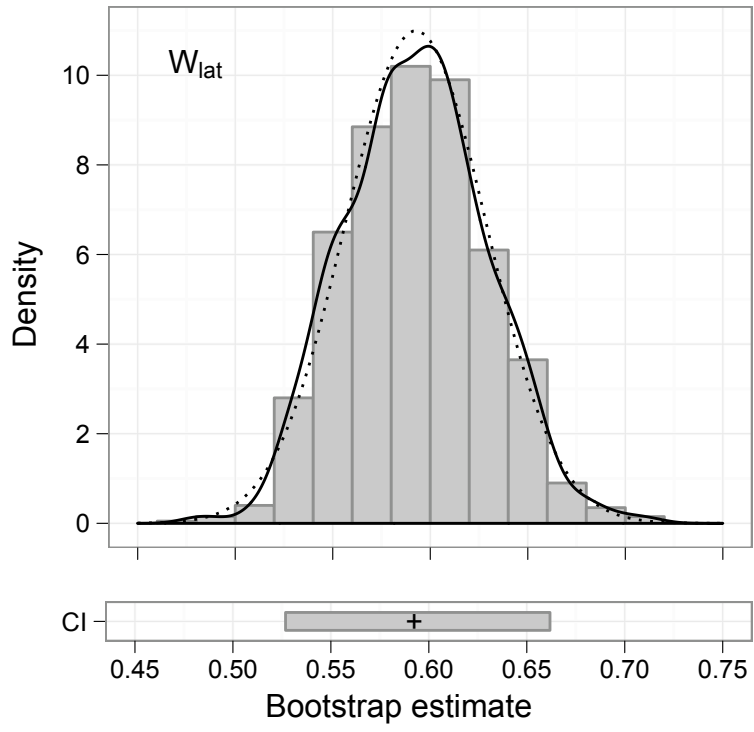
Multi-character processing in dyslexia, Figure 1



Multi-character processing in dyslexia, Figure 2



Multi-character processing in dyslexia, Figure 3



Multi-character processing in dyslexia, Figure 4

