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Pre-Orthographical Constraints on Visual Word recognition: Evidence from a Case Study of Developmental Surface Dyslexia

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Abstract

In the present article, we investigated the visual word recognition ability of MT, a young boy with surface dyslexia, by means of a paradigm that measures performance as a function of the eye fixation position within the word, known as the “viewing position effect” paradigm. In well-achieving readers, the viewing position effect is mainly determined by factors affecting letter visibility and by lexical constraints on word recognition. We further quantified MT’s sensory limitations on letter visibility by computing visual span profiles, i.e. the number of letters recognizable at a glance. Finally, in an ideal-observer’s perspective, MT’s performance was compared with a parameter-free model combining MT’s letter visibility data with a simple lexical matching rule. The results showed that MT did not use the whole visual information available on letter identities to recognize words and that pre-orthographical factors constrained his word recognition performance. The results can be best accounted for by a reduction of the number of letters processed in parallel.

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Pre-Orthographical Constraints on Visual Word recognition: Evidence from a Case Study of Developmental Surface Dyslexia

Introduction

In addition to an intrinsic difficulty in reading, one of the main characteristics of developmental dyslexia is an enduring and pervasive difficulty in phonological processing (for recent reviews, see Shaywitz & Shaywitz, 2005; Vellutino, Fletcher, Snowling, & Scanlon, 2004). Thus, developmental dyslexia is typically viewed as resulting from a core phonological disorder (Ramus, 2001; 2003; Snowling, 2001; Stanovich, 1988). Unfortunately, the emphasis on phonological deficit in dyslexia has overshadowed the fact that reading is a visual task. Relatively little attention has been paid to the visual side of reading acquisition. However, recent research emphasizes the need for better understanding the relationship between visual processing and the extraction of orthographic information from print.

Visual Processing and Word Recognition Acquisition

Some recent studies point out that limits set by pre-lexical visual processes may constrain visual word recognition and its development. In a series of experiments, Hawelka and Wimmer (Hawelka, Huber, & Wimmer, 2006; Hawelka & Wimmer, 2005) showed that simultaneous perception of visual forms is impaired in dyslexic individuals. They used a thresholding procedure to determine the minimal presentation time required for the dyslexic participants to accurately report one cued digit amongst 2-, 4- or 6-digit strings in a partial report task (Averbach & Coriell, 1961; Averbach, & Sperling, 1968). Dyslexic and control children thresholds estimates differed significantly for the longest strings (4 and 6 digits), but not for the shortest ones (2 digits). Moreover, thresholds for the longest strings predicted a unique amount of variance (16%) in the number of eye movements recorded when reading lists of words and pseudo-words, independently of the participants phonological processing and rapid naming skills (Hawelka & Wimmer, 2005). Similar results were obtained in large groups of French and English dyslexic children (Bosse, Tainturier, & Valdois, 2006; Valdois, Bosse, & Tainturier, 2004) as well as in case studies (Valdois et al., 2003). Studying high educational achieving dyslexic young adults further demonstrated the persistence of this deficit (Hawelka, Huber, & Wimmer, 2006).

Also, Pammer and collaborators (Pammer, Lavis, Hansen, & Cornelissen, 2004) found that dyslexic children exhibited a reduced sensibility to relative position in strings. In order to avoid differences induced by reading experience, position encoding was assessed in a two Alternative-Forced-Choice task with letter-like symbol-strings. Dyslexic children showed lower sensitivity (*d*-prime) scores than control subjects when having to choose a target symbol-string among very similar strings which only differed in symbol order. Related findings further suggest that individual variation in symbol-strings sensitivity is linked to reading performance in both children and adult normal readers, independently of phonological skills (Pammer, Lavis, Cooper, Hansen, & Cornelissen, 2005; Pammer, Lavis, Hansen, & Cornelissen, 2004). While the exact relationship between visual processing and the development of an efficient reading system remains speculative, these findings suggest that pre-orthographical visual processing contributes to reading acquisition, independently of phonological skills, so that a deficit in visual processing may prevent becoming a proficient reader.

Whitney and Cornelissen (2005) recently proposed a theoretical account of the development of orthographic information extraction from print. They applied the SERIOL model of proficient orthographic processing (Whitney, 2001) to reading acquisition and dyslexia. This model specifies how an abstract letter-position coding scheme is extracted from print and further used to activate lexical information. A key assumption of the model is the serial encoding of letter order by means of a left-to-right activation gradient input on letter nodes. In this framework, becoming a proficient reader requires the acquisition of this left-to-right gradient. Whitney and Cornelissen (2005) hypothesized different visual strategies, depending on the acquisition of linkages between graphemes and groups of phonetic features (what they called *graphonemes*) and optimisation of visual information extraction. At the earliest stage of reading acquisition, the reader fixates each letter and applies conversion rules. With the progressive automation of grapho-phonemic conversions, all letters will progressively fire in quick succession when fixating the first letter of the word. However, due to decreasing visual acuity, fixating the first letter limits the visibility of letters at the end of the word. Therefore, following these authors, the pre-proficient reader has to learn to fixate near the centre of the word and invoke a locational gradient (first by attentional control, then progressively becoming a bottom-up activation gradient) in order to maintain the sequential order of the letters. Moreover, Whitney and Cornelissen (2005) point out difficulties in acquiring this complex position encoding mechanism as a potential source of developmental dyslexia.

The Viewing Position Effect as a Tool for Studying Visual Processing in Visual word Recognition

Visual constraints during word recognition have been largely studied in skilled readers by means of the fixation-contingent display paradigm (O'Regan, Lévy-Schoen, Pynte, & Brugaillère, 1984). By a systematic manipulation of where the eyes fixate in the word, a variation of word recognition performance is elicited. This variation is known as the viewing position effect (hereafter VPE). With only one fixation in the word, there is a position where recognition is optimal. In languages read from left to right, this optimal viewing position (OVP) is located slightly left from the word centre. Performance decreases when the eyes deviate from this optimal position, thus, producing an inverted U-shaped function (i.e. the VPE function). However, performance varies with fixation position in an asymmetrical way: words are better processed when fixating their initial than final letters. The VPE is a robust phenomenon which has been reported for a variety of dependent measures: naming (accuracy and latency) (Brysbaert, Vitu, & Schroyens, 1996; Nazir, Heller, & Sussmann, 1992; Nazir, Jacobs, & O'Regan, 1998; O'Regan & Jacobs, 1992; O'Regan, & Lévy-Schoen, 1987; O'Regan, Lévy-Schoen, Pynte, & Brugaillère, 1984), lexical decision (accuracy and reaction times) (Nazir, O'Regan, & Jacobs, 1991; O'Regan & Jacobs, 1992) and probability to refixate (e.g. McConkie, Kerr, Reddix, Zola, & Jacobs, 1989).

Although various alternative explanations of the asymmetric VPE function have been proposed (e.g. hemispheric specialisation, asymmetry of the perceptual span and reading direction, perceptual learning; for a recent review, see Brysbaert & Nazir, 2005), computational models suggest that a combination of (1) letter legibility and (2) lexical constraints is sufficient to capture the characteristic profile of the VPE function (Kajii & Osaka, 2000; Stevens & Grainger, 2003). The drop of letter perceptibility outside fixation location was first emphasised as a major determinant of the VPE (Nazir, Heller, & Sussmann, 1992; Nazir, Jacobs, & O'Regan, 1998; Nazir, O'Regan, & Jacobs, 1991). Relative position also affects letter legibility: recognition of internal letters is more difficult than for outer letters (i.e. the lateral inhibition phenomenon: see Bouma, 1970). Moreover, empirical measurements demonstrate that the drop-off rate of letter legibility is asymmetric: at the same eccentricity, letters are better identified in the left than in the right visual field (Nazir, Heller, & Sussmann, 1992; Nazir, Jacobs, & O'Regan, 1998; Nazir, O'Regan, & Jacobs, 1991; but see Stevens & Grainger, 2003; see also the SERIOL model for a theoretical account: Whitney, 2001). Fixating slightly on the left of the word centre (the optimal viewing position) thus maximises visual information. However, perceptibility of letters on its own is not sufficient to account for the VPE. Indeed, all of the letters do not carry the same amount of information for word recognition (Clark & O'Regan, 1999). So, computational models failed to simulate VPE curves on the sole basis of letter perceptibility. A lexical access process was further postulated to account for the probability of recognizing words on the basis of incomplete information (Kajii & Osaka, 2000; Stevens & Grainger, 2003). In line with this view, behavioural data showed slight variations of the OVP as a function of lexical/morphological constraints. In their seminal work, O'Regan *et al.* (1984) compared long words with a unique beginning and long words with a unique end. They found an advantage of fixating the eyes to the informative part of the word. Similar findings were reported for shorter (5-letter) words (Brysbaert, Vitu, & Schroyens, 1996), and for prefixed and suffixed words (in Arabic Farid & Grainger, 1996; and in Hebrew Deutsch & Rayner, 1999). These findings suggest that lexical ambiguity does influence the VPE curve shape. The optimal viewing position thus emerges as the landing site maximizing letter perceptibility and minimizing lexical ambiguity.

If extraction of visual information is a key component of the VPE, then variations in the way visual information is extracted from the input would lead to different VPE curves. Following this point of view, Aghababian and Nazir (2000) investigated reading development using the VPE paradigm. They expected different VPE curves depending on reading strategies. Unexpectedly, results showed that typical inverted U-shaped curves were obtained after only a few months of reading acquisition, suggesting that beginning readers extract visual information as skilled readers do. However, contrary to skilled readers, beginning readers' performance was affected by word length. This length effect progressively vanishes with reading acquisition and is not observed in skilled readers. Aghababian and Nazir (2000) also pointed out that a closer analysis of the VPE function might help identify deviant reading behaviours. Accordingly, various non classical VPE curves are reported in pathological cases: a flat curve in a deaf beginning reader (Aghababian, Nazir, Lançon, & Tardy, 2001) and a reverted asymmetry in a pure alexic patient (Montant, Nazir, & Poncet, 1998). Also, Aghababian and Nazir (2000) reported no VPE in a German dyslexic children group and inverted V-shaped curves in poor beginning readers. Interestingly, the authors interpreted the inverted V-shaped curves as reflecting a limitation in multi-elements processing. The variety of VPE shapes reported in the reading disabled highlights the need for a better understanding of their visual processing of printed words. However, there is, to our knowledge, no well-described in-depth investigation of VPE abnormalities in developmental dyslexia. The present paper is a first step in this direction.

We report here the case study of MT, a French dyslexic boy, who did not suffer from any obvious phonological deficit. We first examined MT's reading skills together with providing in-depth analyses of his phonological awareness and verbal short-term memory abilities. Visual constraints on word recognition were then studied in two experiments. In Exp. 1, we estimated the VPE for words of various lengths, while letter visibility was measured in Exp. 2. Finally, we provide a model that takes the letter-recognition data from Exp. 2 as an input and produces VPE profiles as an output. The resulting predicted curves will be used as a reference to which MT's actual VPE curves were compared.

Statistical analysis

Throughout the article, we assessed the difference between MT and the control group mean performance using a method based on the *t* distribution proposed by Crawford, Howell and Garthwaite (1998), which is more robust than traditional testing based on *z*-scores (Crawford & Garthwaite, 2006b; Crawford & Garthwaite, 2006a; Crawford, Garthwaite, Azzalini, Howell, & Laws, 2006). Also, dissociations between two tasks were quantified by comparing the amplitude of the difference between the patient's scores on the two tasks with the mean difference between these tests in the control sample, using either raw data or Standardised scores (respectively Unstardised Difference Test -- hereafter t_{UDT} -- and Revised Standardised Difference Test – hereafter t_{RSDT} --, Crawford & Garthwaite, 2005b). Finally, in agreement with Crawford's operational proposals (Crawford & Garthwaite, 2005b; Crawford, Garthwaite, & Gray, 2003), significance was assessed through one-tailed tests for deficits (unless otherwise stated) and bi-lateral tests for dissociations.

Case Report

Case History

MT is a right-handed native French speaker, who was 13 years 8 months (164 months) old at the time of testing. His relatives reported neither a history of neurological disorder nor problems in speech and language development. Vision was corrected to normal. He received conventional instruction when attending primary school. There had been concerns about his progress in reading and spelling since early primary school. He repeated Grade 2 due to difficulties in learning to read and received extra assistance during one year. When he was in Grade 4, MT was diagnosed as dyslexic, on the basis of a 3 year 8 month difference between his chronological and reading age (evaluated by means of the Alouette test Lefavrais, 1963; Lefavrais, 1965) and was given remedial reading instruction for two years. He was in 7th Grade at the time of testing. Intellectual assessment conducted at the age of 11 revealed superior intellectual skills (Full scale IQ: 126; verbal scale IQ: 119; performance scale IQ: 126; WISC III: Wechsler, 1996).

Tests of Reading Ability

Reading Level

MT's general reading level was estimated with the French-Standardised LUM test (Khomsi, 1998). This test requires reading lists of words in limited time so that the final score reflects both accuracy and reading speed. With a total of 57 words accurately read in one minute, MT's score differed significantly from that of school level matched control subjects (M=86.1, SD = 13.8; $t(87) = -2.53$, $p < .007$).

Single-Grapheme Processing

MT was able to name single letters (26/26) and to sound out all French graphemes (37/37).

Regular Word, Irregular Word and Pseudo-Word Reading with Time Constraints

MT was asked to read aloud two lists of 40 regular and 40 highly irregular words (from the ODEDYS test: Jacquier-Roux, Valdois, & Zorman, 2002) matched on frequency, word length and grammatical class. Pseudo-word reading was assessed using a list of 90 pseudo-words. The pseudo-words were constructed by substituting the vowels in a list of 90 regular 4-to-8 letters words (for details, see Valdois et al., 2003). The list of source words was also given to read in order to allow direct comparison between strictly matched lists. In the absence of normative data for 13 year-olds, MT's performance was compared to a school-level matched control group (N = 24; Grade 7; mean CA = 152 months, SD = 3.7, range = 145-158. Control subjects were described in Valdois et al., 2003). Participants were instructed to read aloud the lists as quickly and accurately as possible. Children from the control group were exposed to the same lists of regular and irregular words but to a reduced list of only 40 pseudo-words having the same characteristics as the extended list given to MT. Results were therefore expressed as percentages. Processing time (in sec per item) was taken into account for the pseudo-words and matched word lists. Following the multitrace memory model framework

(Ans, Carbonnel & Valdois, 1998), performance on irregular words and pseudo-words was interpreted as providing information on the efficiency of the global and analytic reading procedures respectively.

Results - Results are displayed in Table 1. MT's performance on irregular words was significantly lower than for the controls ($p < .01$). He also read regular words less accurately ($p = .056$) but his performance on these items tended to be better preserved than for irregular words, $t_{UDT}(23) = 1.469$, $p = .077$ (one-tailed). All MT's reading errors on irregular words were regularisations, reflecting the application of grapheme to phoneme correspondence rules and a predominant use of the analytic procedure. MT's regular word reading errors, however, were more visual in nature. MT's pseudo-word and matched word reading accuracy did not differ from control subjects, but his reading was significantly slower [1.6 and 2.2 sec/item for matched words and pseudo-words respectively; controls: 0.57 (*SD*: 0.09) and 0.9 (*SD*: 0.18), both $p < .001$]. This finding suggests that the analytic procedure of reading may not be fully functional in MT. However, strategies could also partially account for these results. Indeed, at a qualitative level, while control subjects read the lists as quickly as possible, MT seemed to favour the accuracy criterion. This potentially might have reduced differences on reading scores and inflated differences in processing times. A further test without time constraints was thus proposed.

(Insert table 1 about here)

Irregular Word and Pseudo-Word Reading Without Time Constraints

MT was asked to read aloud a mixed list of 40 highly irregular words and 40 pseudo-words (subtest from de Partz, 1994) matched on word length. No time pressure was made on answers. MT was compared to a chronological age-matched control group ($N = 16$, mean CA = 165.9, $SD = 3.575$, range = 160-171).

Results – MT's deficit on irregular words was confirmed ($p < .001$) (see Table 1) as well as his difficulties in pseudo-word reading ($p < .05$). Both the analytic and global reading procedures were thus impaired in MT. However, MT's irregular word reading was significantly more impaired than his pseudo-word reading, $t_{UDT}(15) = 2.367$, $p = .032$. This dissociation suggests that the analytic route of reading is more reliable and preferentially used. This assumption is supported by the nature of the errors. For irregular word reading, all MT's errors but one (89%) were regularisations.

Visual Lexical Decision

A visual lexical decision task was used to assess MT's orthographical knowledge (subtest from de Partz, 1994). The items were the 40 irregular words and 40 pseudo-words previously used in reading without time constraints, to which were added 20 regular words and 20 pseudo-homophones. Items were presented randomly one at a time in the centre of a white screen, for unlimited exposure duration. They were displayed in the standard Times New Roman font (black colour, 24 point size). Participants were informed that some items were pseudo-homophones. They were asked to decide whether or not the displayed items were well written real words. The same chronological age-matched control group was used for comparison.

Results – As shown in Table 1, the overall visual lexical decision score was lower in MT than in the control group ($p < .001$). He erroneously rejected a number of real words, most of which were irregular (84.21%: 16/19). Most pseudo-words accepted as real words were pseudo-homophones (91.67%: 11/12).

Tests of Metaphonological Awareness and Phonological Short-Term Memory

Phonological deficit is widely 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. MT was diagnosed as dyslexic in our clinical centre three years before the current study. A phonological processing assessment was carried out at this time. It was thus possible to explore whether his current reading deficit was related to earlier measures of phonological processing, prior to any specific phonological training. When he was in Grade 4, MT was exposed to a Standardised phonological test battery including:

- Forward and backward *digit spans* (from WISC-III: Wechsler, 1996);
- A *pseudo-word repetition task* (from the BELEC standard French test battery: Mousty & Leybaert, 1999; Mousty, Leybaert, Alegria, Content, & Morais, 1994): two lists of tape-recorded pseudo-words were presented. The two lists differed in syllable complexity (Consonant Vowel (CV) and CCV syllables). Each list was divided into four series of pseudo-words of increasing length (1 to 5 syllables). Spans, as well as number of accurately repeated pseudo-words, were computed for each list;
- A *task of acronyms* (from the BELEC: Mousty & Leybaert, 1999; Mousty, Leybaert, Alegria, Content, & Morais, 1994): the task required extracting the first phonemes from two auditorily presented words and blending them (e .g. gant/gã/ – épais/ep_/ -> /ge/).

A few months later, when MT was in Grade 5, phonological awareness was further assessed, by means of research-made tests (see Valdois et al., 2003):

- *A sound categorisation task*: in which an odd word had to be retrieved among four words presented orally (e.g. *ruse* /*ryz*/ – bulle /byl/ – butte /byt/ – buche /byʃ/) on the basis of a phonological difference;

- *A phoneme deletion task*: the participants were asked to delete the first sound of a word and produce the resulting pseudo-word (e.g. placard /plakaR/ -> /lakaR/);
- *A phoneme segmentation task*: a set of 20 words were presented auditorily to the participants who had to sound out each of the word constitutive phonemes (e.g. sandale /sãdal/ -> /s/ /ã/ /d/ /a/ /l/).

In the absence of data from age-matched control group in the research-made test battery, MT's performance was compared to that of older control subjects (MT: 140 months, control group: $N = 24$; Grade 7; mean CA = 152, $SD = 3.7$, range = 145-158).

Results – As shown in Table 2, MT's verbal short-term memory was well within the norm of older controls. MT further demonstrated very good phonological skills. His phoneme awareness was normal or above average on all of the tasks, even in comparison with older control subjects.

(Insert Table 2 about here)

Summary

MT showed significant deficits in irregular word reading. His overall pattern of errors was characterised by a large number of regularisations. In lexical decision, most words rejected by MT as non-words were irregular and most pseudo-words accepted as real words were pseudo-homophones. All of these features suggest a deficit of lexical orthographic knowledge, and point to a failure of developing an efficient global reading procedure, as typically reported in the context of surface dyslexia. In contrast, analytic processing was relatively preserved, as shown by his significantly better performance in regular word and pseudo-word reading. However, it is clear that MT's reading impairment did not represent a 'pure' case of surface dyslexia. Indeed, pseudo-word reading was very slow as typically reported following an analytic procedure disorder in more transparent languages than English (De Luca, Borrelli, Judica, Spinelli, & Zoccolotti, 2002; Wimmer, 1993; Wimmer, 1996; Zoccolotti, De Luca, Di Pace, Judica, & Orlandi, 1999). MT performed similarly in pseudo-word reading with or without time constraints in contrast to control readers who favoured speed over accuracy when reading time was recorded. MT seemed to favour accuracy in any case, a strategy that might have reduced differences in reading scores but inflated differences in processing times. It is noteworthy, however, that his performance remained slightly lower than that of the controls in condition without time constraint, again suggesting poorer sublexical processing skills in MT.

Despite his poor reading performance, MT showed preserved phonological processing skills as ascertained by his good phoneme awareness, good pseudo-word repetition and verbal short term memory skills. The predominance of regularisation errors in reading and MT's trend to accept pseudo-homophones as real words in lexical decision further support reliance on phonological processing, as reported in previous cases of developmental surface dyslexia (see e.g. Castles & Coltheart, 1996).

The absence of phonological deficit, in conjunction with the production of visual errors in reading, leads us to explore in greater detail MT's pre-orthographical processing in single word recognition.

Experiment 1. The Viewing Position Effect

The fixation-contingent display was used to investigate MT's printed word recognition.

The source of variation in word recognition performance as eye fixation position varies is at least twofold. Firstly, due to variations in letter legibility, the amount of visual information available for processing depends on the relative position of the eyes' fixation within the word. Secondly, the available visual information differentially constrains word recognition, depending on the probability for the stimulus to be recognized on the basis of the perceived letters. It has been acknowledged that the way visual information is extracted affects the shape of the VPE curve (Aghababian & Nazir, 2000; Aghababian, Nazir, Lançon, & Tardy, 2001; Montant, Nazir, & Poncet, 1998). The classical, asymmetric, inverted U-shaped VPE curve reflects a reading system maximising visual information extraction and using some orthographical knowledge. Besides, because the analytic reading procedure involves a serial left-to-right translation procedure starting with the left-most orthographic unit of the letter string to be read (Ans, Carbonnel, & Valdois, 1998; Coltheart, Curtis, Atkins, & Haller, 1993; Valdois et al., 2006), we inferred that if MT strictly applied a left-to-right scan while reading then better performance would be expected when fixating at the beginning of the word. This behaviour would result in a negative linear VPE function. On the other hand, if words were primarily recognized on their visual appearance (such as word shape or salient features), the curve would be affected by the position of the distinctive visual features used by the subject. Averaged over different lists of words, no systematic viewing position effect should be expected, resulting in a flat curve. This profile was already described in a deaf beginning reader (Aghababian, Nazir, Lançon, & Tardy, 2001) and a dyslexic group (Aghababian & Nazir, 2000). Moreover, Aghababian and Nazir (2000) reported an inverted V-shaped curve for some beginning readers. Based on a mathematical model, the authors interpreted this curve shape as reflecting a reduction of the size of the word identification span, which is the region around fixation from which letters are processed for word recognition. This inverted V-shape was more pronounced when word length increased. A length effect also affected the height of VPE curves in beginning readers (Aghababian & Nazir, 2000). Thus, the shape of the curve and possible interaction with length could provide insights on the way MT processes printed words.

Methods

Participants

Sixteen healthy 7th Grade participants (ten females, six males) from a secondary school in Brussels (Belgium) served as controls. They were matched to MT for chronological age (mean CA = 160, *SD* = 4.4, range = 152-167). All participants in the control group were native French-speakers and had normal or corrected-to-normal vision. The children were judged by their teachers as “average” or “good” readers. The experiments were undertaken with the understanding and written consent of both the children and their parents.

Material

The experimental stimuli were 80 five- and 112 seven-letter French words. Five- and seven-letter words were respectively 2 and 3 syllables long. Only nouns and adjectives were used. Words of different lengths were matched as closely as possible for frequency. Due to the absence of French lexical database for adolescents, matching was done using frequencies estimated on both adult literature (*Brulex*: Content, Mousty, & Radeau, 1990) and children’s books corpuses (*NovLex*: Lambert & Chesnet, 2001). Following *Brulex*, occurrence frequencies ranged from .04 to 321.5 (median: 13.33) and .04 to 481.6 per million (median: 13.23), for 5- and s7-letter words respectively (following *Novlex*: 5-letter words range: 2.38-147.6, median: 7.14; 7-letter words range: 2.38-154.7, median: 7.14). As word orthographic neighbourhood (Coltheart, Davelaar, Jonasson, & Besner, 1977) is found to affect the VPE function (Grainger, O'Regan, Jacobs, & Segui, 1992), only words without orthographic neighbours were selected. Stimuli were displayed at the centre of the LCD screen of a DELL Lattitude C500 laptop, refreshed at 60 Hz. They were presented in lowercase letters, light grey against a black background, in the Courier New-Bold font. Each letter was defined in a matrix of 30*55 pixels, corresponding to a width of 0.8° of arc visual angle at a viewing distance of about 60 cm. The stimulus presentation, driven by the E-Prime software (version 1.1 SP3: Schneider, Eschman, & Zuccolotto, 2002), was locked to the refresh rate of the computer monitor.

Design

Each letter was set out as a potential initial fixation position. Consequently, the 5- and 7-letter stimuli were respectively divided in five and seven lists of 16 words each. All lists were matched as closely as possible for frequency. The attribution of a particular fixation position to a particular word group was done randomly so that, taken over all subjects, each word was seen from all fixation positions. Stimuli were presented in blocks of the same word length. Testing was divided into sessions of 30–45 min. Each word length corresponded to one session. All participants completed the blocks of the experiment in the same sequence, beginning with the 5-letter words. The stimuli within each block were presented in random order. Each experimental session began with 20 or 21 warm-up stimuli, respectively for 5- and 7-letter words. In order to obtain robust VPE curves, MT testing was repeated twice, over different experimental sessions. The same stimulus lists were used, but the initial fixation position in a given word varied between the repeated sessions.

Before the experimental sessions, specific exposure durations were estimated for each subject in order to avoid ceiling and floor effects. Exposure durations were adjusted separately for the two word lengths during repeated sessions of practice trials. For each word length, exposure duration was initially set to 1 refresh cycle (16.67 ms) and progressively increased, until the percentage of correct responses was at least 50%. Each step corresponded to a refresh cycle. Only exposure durations below saccadic latency (< 200 ms) were allowed to prevent useful refixations. Two lists of 20 five- and of 21 seven-letter words served for practice; they differed from the experimental items. Practice and experimental stimuli were selected using the same criteria and matched for frequency.

Procedure

Each trial began with a fixation cross (+) appearing at the centre of the computer screen. After 1 second, the fixation cross was replaced by the target word. To force fixation on a certain letter position, horizontal eccentricity of the stimulus was varied relative to the fixation cross, such that the eyes were fixating one of the letters composing the word. After an individually adjusted presentation time, the stimulus was masked by a series of seven Xs. The participant was asked either to pronounce the whole word, or, if the word was not recognized, to spell aloud the letters he had identified. The experimenter registered each response and triggered the next trial by a key press. No feedback was provided. After the subject's response, the screen was cleared, and a new trial began following a 500-msec delay. No time pressure was imposed. Responses were considered as correct when the participants reported the target word. Eye movements were not recorded. However, the requirement of central fixation was strongly emphasized and repeated at regular intervals during the experiment.

Results

No significant difference was obtained between MT's two sessions ($p > .05$). MT's results were thus collapsed.

Average Performance and Exposure Duration

Table 3 gives the average proportion of correct word identification and the corresponding exposure duration for both control subjects and MT. Control subjects' performance was in the expected range (at least 50%, see above), avoiding ceiling and floor effects. Despite a wide inter-individual variation, mean exposure durations for both lengths (respectively, 71.6 and 74.7) were similar and did not reach significance ($t(15) = 1.86$, $p = .08$).

(Insert table 3 about here)

Contrary to the control subjects, MT's practice session performance only reached the minimum average level for 5-letter words (55%), but not for 7-letter words (28.6%), despite significantly longer exposure durations (respectively 166 and 199 ms; both $p < .001$). Like some control subjects, MT's performance decreased in the experimental sessions, as compared to the practice session. Recognition performance was lower for MT than for the controls for both 5-letter words (48.13%, $p = .042$) and 7-letter words (16.07%, $p = .002$). Moreover, performance was significantly more affected by word length in MT than in the controls for both accuracy, $t_{RSDT}(15) = 2.26$, $p = .039$, and exposure duration, $t_{RSDT}(15) = 2.03$, $p = .06$.

As can be seen in Table 3, MT's performance on the experimental 7-letter words approached floor effect. As a consequence, no direct comparison will be done between MT's and control subjects' curves shapes for 7-letter words.

Word Recognition Performance

Figure 1 shows the variation of word recognition probability depending on where the eyes fixated within words, for MT and the control subjects. Word identification accuracy (percent correct) is plotted as a function of viewing position, relative to the centre of the word. For control subjects, word recognition performance was optimal when fixating slightly left of the centre of the word and decreased when fixation deviates from this optimal viewing position. The probability of accurate word recognition for both lengths demonstrated a clear inverted-U shape, with a highly significant quadratic trend [$F(1,15) = 35.77$, $p < .001$ and $F(1,15) = 159.93$, $p < .001$, for 5- and 7-letter words respectively]. Also, as typically found, both functions were clearly asymmetrical, with highly significant linear trends[1] [$F(1,15) = 73.02$, $p < .001$ and $F(1,15) = 792.37$, $p < .001$, for 5- and 7-letter words]. Like proficient readers, the shape of MT's 5-letter words VPE function was characterised by the expected quadratic trend [$F(1,2) = 45.64$, $p = .02$]. However, his VPE function for 5-letter words did not show the typical asymmetry found in control subjects, with no sign of linear trend [$F(1,2) = 0.72$, $p = .48$]. His VPE curve seemed symmetrically inverse V-shaped. Furthermore, his poor overall performance on 7-letter words strongly affected MT's VPE curve. No significant linear or quadratic trend was obtained for MT's 7-letter words [$F(1,3) = 7.42$, $p = .07$ and $F(1,3) = 3.19$, $p = .17$, respectively]. This absence of clear trend might be mainly due to a floor effect on average accuracy. Therefore and contrary to controls, his profiles of performance drastically differed as a function of word length.

(Insert Figure 1 about here)

Parametrization of word recognition performance

In a further attempt to characterise MT's VPE profiles and their variation according to word length, identification probability was parameterised as a function of fixation position. This allows direct comparison between MT and control subjects on curve parameters. Brysbaert *et al*. (1996) showed that the shape of the VPE function is well described by a Gaussian distribution with the mode shifted to the left of the centre of the word. Each individual word recognition profile was fitted with non-centred Gaussian functions (using a modification of the quasi-Newton algorithm allowing box constraints: Byrd, Lu, Nocedal, & Zhu, 1995) with the R statistical software (Ihaka & Gentleman, 1996; R Development Core Team, 2005) according to:

$$P(x) = A \exp\left[-((x - OVP)/\sigma)^2\right],$$

P(x) being the probability of correct word recognition at viewing position *x*, *A* the peak amplitude of the Gaussian (i.e. the probability of correct word identification at the OVP), *OVP* the deviation from the centre of the word where recognition is maximal and σ the standard deviation of the Gaussian distribution[2]. Results of the fits are shown in Table 4 and Figure 2.

The curve fits accounted for 78–99% of the variance of the individual data[3], except for three control subjects on 5-letter words (R^2: 0.34-0.58), whose performance was removed from this second analysis[4] (see Fig. 2).

(Insert Table 4 about here)

(Insert Figure 2 about here)

As can be seen on Figure 2, VPE profiles are well captured by the Gaussian function for both the controls and MT. Surprisingly, MT's pattern for 7-letter words is also well fitted ($R^2 = 0.98$ for both lengths), despite his poor average performance.

Control subjects performed significantly better when they fixated about one character on the left of the centre of the word whatever its length, (OVP parameter, $M = -0.8$ and $M = -1.08$ character, respectively for 5- and 7-letter words), $t(12) = -7.65$, $p < .001$, and $t(12) = -12.39$, $p < .001$, thus further demonstrating the asymmetry of the function[5]. Furthermore, as previously reported by Brysbaert *et al*. (1996), the length only affected the OVP position, $t(12) = 2.04$, $p < .05$, but not the general shape of the curve (indexed by the two other parameters, A and σ), $t(12) = -0.84$, $p = .42$, and $t(12) = -0.16$, $p = .87$, respectively. The optimal viewing position shifted towards the word beginning when words became longer. The OVP deviation for 5-letter words was significantly reduced in MT, $t(12) = 1.8$, $p < .05$ as compared to controls and did not differ from zero, $t = -1.501$, $p = .27$. The height of the curve was significantly reduced for 5-letter words (see Table 4). The height and width (σ) of the 7-letter words curve were also reduced, probably as a result of MT's poor performance level due to exposure duration constraints.

Letter Recognition Performance

To further investigate MT's visual information extraction, his performance was analysed at the letter level. In order to control for the potential influence of lexical inference and level of performance, only responses scored as incorrect at the word level were analysed. Percentages of accurately reported letters were computed. Following Montant *et al.* (1998), the scoring was done independently of report order. In cases where the same letter occurred twice in a word, report of a single letter was scored as correct for both letters.

Table 3 shows that MT reported about 55% of the displayed letters on average when words were not recognized. His performance was similar to that of the controls ($p > .05$). Overall, MT incorrectly reported 270 items out of 384 (70%). In most cases (71.85%), errors followed from partial extraction of information from the input string (all reported letters belonged to the target word and were reported in the correct order). The remaining errors were visual[6] in nature. No regularisation error was observed. For the controls, letter recognition scores were computed on 1137 erroneous responses [out of 3072 items: 37%; ranging from 38 (19.8%) to

112 (58.3%) per subject]. Also, control subjects majoritarily reported parts of stimuli or made visual errors (79.14%). As for MT, no regularisation error was described.

(Insert Figure 3 about here)

MT's reading strategy during the VPE task might potentially be inferred from systematic variations in the amount of letters accurately reported according to their position in the string. If MT strictly applied a serial left-to-right scan of the input string (see e.g. Valdois et al., 2006; Vidyasagar, 1999; Vidyasagar, 2005; Whitney & Cornelissen, 2005), then correct letter identification probability would be inversely related to letter position within words. Accordingly, initial letters would be more accurately reported than final letters. Figure 3 plots letter recognition probabilities as a function of relative letter position within words (from the first letter of the word --position 1-- to the last letter --position 5 or 7), separately for 5- and 7-letter words. As shown on Figure 3, the amount of accurate letter recognition does not seem to systematically vary with letter position. Linear regressions were run to quantify this effect and assess its statistical significance. They were fitted to predict letter recognition probability on the basis of letter position, separately for each word length. Congruently, fitted models displayed in Table 5 show that the slopes did not differ from zero, neither for MT nor for the control group. These results do not support an interpretation of MT's letter identification scores as reflecting a word reading serial procedure.

(Insert table 5 about here)

(Insert Figure 4 about here)

The same letter identification data are plotted in Figure 4 as a function of visual eccentricity. Data for each word length are presented into different panels. Performance for control subjects and for MT is respectively plotted in the left and right panels. In each panel, fixation is marked by a vertical dotted line. Thus, probabilities for letters viewed in the left visual field are given in the left half of each panel; conversely, the right half shows scores for letters that fell into the right visual field. In each panel, different curves correspond to words seen at different viewing positions. Averaged data across viewing positions are displayed in the two lower panels. As can be seen from these two panels, MT's letter identification performance was dramatically affected by eccentricity. Letters around fixation were well identified, but letter recognition probability dropped rapidly with increasing eccentricity. This drop was far less pronounced in control subjects. Averaged letter identification scores were computed for the three positions around fixation (-1 to 1) and the largest three eccentricities in each visual field. For both lengths, MT accurately identified fewer letters than the controls when displayed far from fixation while his performance was similar near fixation (see statistical tests in Table 6). Moreover, the difference between around fixation positions and outer positions was typically higher in MT than in the controls for both 5-letter words, $t_{RSDT}(15) = 2.58$, $p = .02$ and $t_{RSDT}(15) = 1.3$, $p = .21$, and 7-letter words, $t_{RSDT}(15) = 2.41$, $p = .03$, and $t_{RSDT}(15) = 2.8$, $p = .013$, for left-to-centre and centre-to-right comparisons respectively. Thus, the present analysis confirms that MT's letter identification was more narrowed around fixation. This is particularly clear when looking at the probability for the first letter of words to be accurately identified. As can be seen from upper panels of Figure 4, control subjects well reported the first letter of words (i.e. the far left point of each line), whatever their eccentricity. This corresponds to the so-called "end-effect", well known in vision research (e.g. Bouma, 1970). Contrary to normal readers, first letter recognition was far more affected by visual eccentricity in MT.

(Insert table 6 about here)

Discussion

The present data clearly show a viewing position effect in MT, even if the shape of his viewing position curve was atypical. Like normal readers, MT's word recognition performance was best when fixating near the word centre, i.e. at a position maximizing visual information. The viewing position curves undoubtedly demonstrate that MT does not attempt to shift either his eyes or attention to the initial letters of words to realise a left-to-right scan of the word string. Like normal readers, MT's performance was well characterised by a Gaussian curve. Congruently, his letter identification probability was not inversely related to the relative letter position within words. Data thus suggest that in this particular task, in which fixation was constrained and stimuli displayed for short exposure durations, reading strategies were similar in MT and control subjects. However, MT's processing of printed words was not efficient. Despite exposure durations more than two times longer than for the controls, MT failed to reach the average word recognition level exhibited by control subjects. Furthermore, his VPE curve lacks asymmetry, is clearly inverted V-shaped (at least for 5-letter words) and markedly affected by word length. Finally, a strong effect of viewing eccentricity was observed on MT's probability to report word letters.

As previously stated in the introduction, two main factors interplay to produce the viewing position effect: visibility of the individual letters and lexical constraints exerted by the perceived letters on word recognition. As a consequence, two different but non exclusive hypotheses might be put forward to explain MT's VPE curves. In the case report section, we have shown that MT suffered from a lexical orthographic knowledge deficit. This deficit might affect his ability to make inferences from partial letter information, resulting in a reduction of his word recognition performance and a strong length effect. In agreement with this hypothesis, a poor word recognition accuracy, interacting with word length, was obtained in the first modelling attempts of the VPE curve, when letter visibility was conceived as the only determinant factor of the VPE function (McConkie, Kerr, Reddix, Zola, & Jacobs, 1989; Nazir, O'Regan, & Jacobs, 1991; Nazir, Heller, & Sussmann, 1992). Also, a reduced letter visibility might potentially account for –at least-- some of the features of MT's VPE curves. Indeed, an increased lateral masking has sometimes been reported in dyslexic patients, yielding to a reduction of –internal-- letters visibility. Bouma and Legein (1977) showed a significant deficit in recognizing flanked letters in a group of dyslexic children, while they did not differ from matched controls for isolated letters. The influence of adjacent letters on the internal letter identification was dramatically increased in parafoveal presentation (Bouma & Legein, 1980; Pernet, Valdois, Celsis, & Demonet, 2006; Spinelli, De Luca, Judica, & Zoccolotti, 2002). Interestingly, MT's letter identification scores were markedly affected by visual eccentricity. A reduction of –internal-- letters visibility would also reduce MT's general level of performance in the VPE task. Moreover, if the severity of the deficit varies with visual eccentricity, then words fixated at end-letters will be more affected, yielding an inverted V-shaped VPE curve. Also, as longer words contain more letters, a main effect of length as well as an interaction with viewing position would be expected.

Experiment 2 was thus performed in an attempt to determine wether MT's VPE profile could be accounted for by a reduction of letter visibility.

Experiment 2. Spatial Profiles of the Visual Span

First introduced by O'Regan *et al*. (1983), the *visual span* is conceived as the region around fixation within which characters of a given size can be resolved. The boundaries of the visual span are jointly determined by decreasing letter acuity in peripheral vision, and lateral masking between adjacent letters (Bouma, 1970). Legge *et al.* (2001) also showed a temporal dependence of the size of the visual span. In adult normal readers, maximal letter identification performance is reached at fixation in 100 ms or less. However, the width of the visual span increases more slowly and requires longer exposure durations to reach asymptotic performance. The visual span thus corresponds to a sensory bottom-up limitation to letter recognition at particular exposure durations.

In order to measure spatial profiles of the visual span, we used a method developed by Legge, Mansfield and Chung (2001; see also Chung, Legge, & Cheung, 2004). Visual span profiles were estimated with trigrams (i.e., meaningless arrays of three letters) displayed at various horizontal eccentricities. With this paradigm, the middle letter of the trigram captured lateral masking. As stated by the authors, this method "(1) explicitly takes into account exposure time; (2) does not depend on eye-movement strategies; and (3) does not depend on lexical inference" (Legge, Mansfield, & Chung, 2001, pp. 730-731).

This second experiment aimed at assessing whether a reduction of letter visibility could account for MT's word recognition performance in Experiment 1. Our purpose was not to estimate whether MT suffered from a deficit in letter recognition *per se*. Consequently, display conditions were matched as closely as possible with those of Experiment 1. In particular, Experiment 2 was performed keeping the same exposure durations as in Experiment 1 for both MT and the controls. If MT's word recognition performance in Experiment 1 resulted from reduced letter visibility, then his visual span, measured in the same conditions, would also be reduced. More specifically, if an increased lateral masking was at the source of MT's VPE profile, then a stronger reduction of his visual span profile is expected for middle than outer letters of the trigrams.

Methods

Participants

Seven healthy 7th Grade participants (three females, four males) from the same secondary school in Brussels (Belgium) served as a control group. They were matched to MT for chronological age (mean CA = 163.4, *SD* = 3.4, range = 159-167). All participants in the control group were native French-speakers and had normal or corrected-to-normal vision. Children were judged by their teachers as “average” or “good” readers. None of them participated in Experiment 1. The experiments were undertaken with the understanding and written consent of both the children and their parents.

Materials

Stimuli were legal trigrams (e.g. zos, ifu, chm) randomly selected from a French trigram database taken from *Lexique* (version 2.61: New, Pallier, Brysbaert, & Ferrand, 2004). Viewing conditions and display characteristics were the same as in Experiment 1.

Design

Performance was measured for trigrams displayed at 15 different horizontal viewing eccentricities, corresponding to 7 different letter slots on each side of fixation. The central letter of the trigram could occur at one of the 15 different eccentricities, covering a viewing area of 12.8° of arc visual angle centred at fixation. As positions were specified in letter-size units, external letters of the trigram were displayed on adjacent letter slots. Thirty trigrams were displayed at each position, yielding a total of 450 items. Trigrams were randomly associated with a particular viewing position. They were grouped in five different blocks of 90 items. All the different positions were tested in each block. Subjects completed the different blocks in the same sequential order, but items were presented at random within each block. Testing was divided into two or three sessions of 20-30 min. In addition to the rest period between blocks, the participants were allowed to take a break when necessary. Each experimental session began with 15 unscored warm-up stimuli.

Procedure

Subjects were instructed to fixate a small fixation cross appearing at the start of each trial. Eye movements were not monitored, but the requirement of central fixation was strongly emphasized and repeated at regular intervals during the experiment. After 1000 ms, the fixation cross disappeared and was immediately followed by a trigram. Stimulus lasted for predetermined exposure duration on the screen. As visual span profiles vary with exposure time, retinal eccentricity, and even relative position within a text string (Legge, Mansfield, & Chung, 2001), exposure durations were adjusted to match those used in Experiment 1 (MT: 166 ms and controls: 66 ms, i.e. multiples of the refresh cycle roughly corresponding to the mean exposure durations for 5-letter words in Exp. 1). A series of five #s served as a mask and remained visible until the response. The participants were required to verbally report the three letters immediately after they disappeared.

Results

As in Experiment 1, letters were scored independently of report order. Letter recognition probability was then plotted against viewing eccentricity in order to construct spatial profiles of the visual span (e.g. Figures 5 and 6). In these figures, the lower panels display MT's data and the summary curves for the control group, while the seven small panels show individual control subjects data. For each plot, viewing eccentricity was expressed in character size units relative to the eye fixation position. Positive eccentricity values are for letters displayed in the right visual field, and negative ones for letters presented in the left visual field. That is, an eccentricity of 2 represents a letter viewed two characters widths right of fixation.

Averaged Letter Recognition Probability Across Relative Positions

In Figure 5, data were collapsed across relative letter position in the trigram. Except for two farthest eccentricities, each data point corresponds to the average performance of an individual subject on 90 letters. These points combine data across letters presented at a given position whatever their location in the trigram. For both MT and the controls, performance is better at fixation and decreases with increasing distance from fixation. As can be seen from the small individual panels, control subjects exhibited a wide inter-subjects variation.

(Insert Figure 5 about here)

No global difference was observed between MT (M = 72.89%) and the control participants (M = 65.48%, SD = 8.28), $t(6) = 0.84$, $p = .22$. In order to assess whether MT's visual span was differentially affected by visual eccentricity, we computed individual means of the three central letter positions (-1 to 1) and the three farthest letter positions in each hemifield (left: -8 to -6; right: 6 to 8). Computed means and t-tests are shown in the upper part of Table 7. No significant difference was observed between MT and the controls on these averaged letter positions. Moreover, the difference between MT's central and outer positions was comparable to the control ones $t_{RSDT}(6) = 0.31$, $p = .77$ (left-to-centre), and $t_{RSDT}(6) = 0.04$, $p = .97$ (centre-to-right).

(Insert table 7 about here)

As proposed by Legge *et al*. (2001), individual visual span profiles were fitted with split Gaussians (using the R statistical software: Ihaka & Gentleman, 1996; R Development Core Team, 2005) characterised by three parameters: the amplitude and the standard deviations of left and right visual hemifields, following:

$$P(x) = \begin{cases} A \exp(-x^2/2\sigma_L^2) & \mathit{if}\ x < 0 \\ A \exp(-x^2/2\sigma_R^2) & \mathit{if}\ x \geq 0 \end{cases}$$

where *P(x)* is the probability of correct letter identification at letter position x, *A* is the peak amplitude of the curve, and σ_L and σ_R are the standard deviations of the Gaussian to the left and right side of the peak.

All curves account for 80-96% of the variance[7]. They are displayed in Figure 5. As in Experiment 1, data were fitted separately for each subject (in each one of the small panels) and MT's best-fitted parameters were compared to the mean of the different individual parameters in the control group. The fitted curve for the control group average performance in the central panel of Figure 5 was only given as an illustration. Upper part of Table 7 gives best-fit estimates, along with modified t-tests. No significant difference was obtained.

Recognition Probability according to Letter Relative Position in the Trigram

In order to test whether MT's letter visibility was differentially affected by crowding, visual span profiles were constructed for each letter position in the trigram. *Inner* letters refer to the letter nearest the fixation, *middle* letters to the middle letter of the trigram and *outer* letters to the letter farthest from fixation. In cases of increased lateral masking, middle trigram letter visual span profile would be narrowed. Data are displayed in Figure 6. Small panels are for individual control subjects, while the two bigger panels provide MT's data, along with control group means. As previously, control subjects demonstrate wide inter-individual variability. As typically observed, a wider span was obtained for outer letters in each subject (Legge, Mansfield, & Chung, 2001). More interestingly, MT seems to perform as control subjects for the different relative positions in the trigram. As in the previous analysis, each individual profile was fitted with split Gaussians. Curves explained 61-96 % of the variance of individual control subjects' data (inner letters: 0.61-0.80; middle letters: 0.74-0.96; outer letters: 0.68-0.93) and 77-85% of MT's performance variance (inner: 0.77; middle: 0.84, outer: 0.85). Best-fitted curves are displayed in Figure 6. The lower part of Table 7 shows parameter estimates, along with statistical comparison between MT and control subjects. None of the comparisons was significant. MT identified individual letters with the same accuracy as the control participants did and his performance did not exhibit increased lateral masking, as compared to controls.

(Insert Figure 6 about here)

Discussion

MT's visual span did not differ significantly from control ones, either considering raw data or best-fit estimates. In addition, MT's individual letter recognition probability was not differentially affected by lateral masking, as demonstrated by normal visual span profiles for middle trigram letters. Although one can not infer from these findings that MT's visual span was normal since MT needed a longer exposure duration to achieve a performance similar to that of control subjects, the present findings nevertheless show that the pattern of results obtained in Experiment 1 can not be attributed to a reduction of MT's visual span.

However, one major impediment might be raised against these conclusions; namely that they rely on accepting the null hypothesis. This might be viewed as an important flaw, because no control was obtained on the probability of false negative results (i.e. the probability of not detecting true differences). The criticism is particularly relevant when comparing a single patient with a small-sized control group, where the power of the test is at best moderate and the probability of false negatives inflated (Crawford & Garthwaite, 2005a; Crawford & Garthwaite, 2006b). However, the notion of power relies on the different hypotheses tested. When hypotheses are directional, low power raises the possibility that some true differences *in the direction of the specified hypothesis* were not detected. In the present experiment, the hypothesis of a reduction of the size of the visual span predicted *lower* values for MT. Contrary to our hypothesis, his scores were always *above* the controls' means (with the exception of the σ_R best-fit estimate on averaged letter relative positions and the *A* estimated for outer letters).

In order to quantify the reliability of our conclusions in front of possible measurement errors, we further computed point estimates and 95% confidence intervals (CI) of the rarity of MT scores (Crawford & Garthwaite, 2002). Point estimates of the rarity of scores indicate the rate of control participants who scored lower than MT. They correspond to the one-tailed p-value of the test, expressed in percents. CI further capture variations introduced by sample size and error measurement. They could be conceived as an alternative to power analysis[8] (Cumming & Finch, 2001). As can be seen from Table 7, point estimates of the rarity were in the range 38% – 89%. Thus, 38% of the controls obtained scores below the poorest score of MT (i.e. all positions σ_R). One can further notice that confidence intervals, drawn around point estimates, are inversely proportional to the control sample size. They are thus quite wide (up to 50% of the distribution), due to the small size of the control group. However, none of these intervals includes values lower than our α criterion (lower bound of the lower confidence interval is

14.35% > α [= 5%]). There is thus no indication that MT might have lower scores than controls not detected as significant due to the small sample size.

Conjoint Analysis of Experiments 1 and 2

In Experiment 1, MT's VPE function for word recognition was characterised by a strong length effect and an atypical inverted V-shaped curve for 5-letter words. The hypothesis that a reduction of letter visibility might be at the source of this particular VPE function shape was discarded in Experiment 2 since MT's visual span was found to be highly similar to that of the controls. However, letter visibility is not the only factor known to affect VPE curves. Lexical constraints also affect the shape of the VPE curve (Brysbaert, Vitu, & Schroyens, 1996; Deutsch & Rayner, 1999; Farid & Grainger, 1996; O'Regan, & Lévy-Schoen, 1987; O'Regan, Lévy-Schoen, Pynte, & Brugaillère, 1984). MT's deficit of orthographical knowledge -- as revealed by his low performance in irregular word reading and in the lexical decision task – certainly affected his word recognition performance in Experiment 1. This raises the possibility that the differences in VPE functions between MT and the control participants just reflected differences in the lexical knowledge used to boost word recognition when unambiguous visual information is not available. However, unless the impact of impoverished orthographical knowledge on the VPE curves can be fully determined, there is no guarantee that this disorder is exclusively responsible for MT's abnormal VPE profile.

We propose to address this hypothesis in an ideal-observer's perspective. An ideal observer is an algorithm that yields the best possible performance in a specified task, given a set of constraints on the available input information. The ideal observer is not intended to be a realistic model of what happens in human subjects. However, it provides an index of the performance that can be achieved when all the available information is used in an optimal fashion. Following Legge, Klitz and Tjan (1997, p. 525), « comparison of human performance to ideal performance can establish whether human performance is limited by the information available in the stimulus or by information-processing limitations within the human ».

If MT's orthographical knowledge deficit were the only cause of his VPE curves profile, then the pattern of results he demonstrated in Experiment 1 should be mainly determined by letter visibility. The model was thus designed to rely only on letter visibility information to predict VPE performance, without resorting on any kind of lexical knowledge. Ideal performance of the model could thus be regarded as the level of performance reached when full available visual information is used. Thus, if MT's word recognition performance were only determined by visual factors, then the simulated VPE function would mimic MT's one and exhibit an inverted-V shape. On the other hand, if MT tried to infer the displayed word on the basis of partial visual information despite impoverished lexical knowledge, then his VPE function should exceed model's performance. Finally, a lower performance is expected for MT if available visual information were not optimally used.

Modelling VPE Functions

In order to simulate MT's performance, we used a simplified version of the model proposed by Legge *et al.* (2001) to link visual span profiles to reading speed. Some modifications were made to the model to produce VPE functions as output, instead of reading speed. We will compare the model's performance with MT's VPE function from Experiment 1. Due to floor effects on 7-letter words MT's VPE curve, only 5-letter words were simulated.

The model includes two different stages: (1) *letter recognition*: visual span profiles from Experiment 2 were used to model letter recognition for each viewing position, and (2) *word recognition*: the probability of word recognition was computed by the model.

Letter Recognition

The visual span profiles estimated in Experiment 2 capture the visual factors affecting letter recognition. They specify the probability of accurate letter recognition according to their relative position in the array (*inner*, *middle* or *outer*) and visual eccentricity. Consequently, the different words from Experiment 1 were ‘filtered’ through these visual spans. For a given fixation position, the probability of correct identification was derived for each letter of the target word from the appropriate visual span profile. Given that letter recognition probability is better for outer than internal letters (Bouma, 1970), visual-span profiles derived from outer trigram letters were used to model recognition performance for the first and last letters of the word. Profiles for middle trigram letters were used for the remaining letters. For each letter in the word, we thus selected the corresponding correct identification probability according to the letter relative position in the word string and to visual eccentricity relative to fixation. For modelling purposes, averaged visual span profiles were used for the control group. Obviously, MT’s visual span profiles served as model for his letter recognition probabilities performance. Thus, for a 5-letter word fixated on the first letter (i.e. viewing position -2, in letters relative to word center), the identification probability of the first letter corresponds to the probability at fixation from the outer trigrams letter profile. The other letters were displayed in the right visual hemifield at eccentricities 1 to 4 (expressed in letter slots). Consequently, the probability of recognizing correctly the last letter of the stimulus word is derived from the outer letter trigram visual span profile at eccentricity 4. Finally, the remaining probabilities are from the middle letter visual span profiles (at eccentricities 1 to 3). The same was done for the different viewing positions. Resulting letter probabilities are presented in Table 8.

(Insert Table 8 about here)

Word Recognition

Word identification probability was computed as the product of the independent letter identification probabilities. The model did not resort to any kind of lexical knowledge so that its output was only determined by individual letter visibility. As a consequence, the generated VPE function could be considered as a *purely visual reference VPE curve* against which MT's word recognition performance will be compared.

As a control condition, we also computed the predicted curve for the control group. We used averaged individual control subjects best-fit parameters to specify visual span profiles. As control subjects have an intact reading system, allowing lexical inferences, their mean VPE curve was expected to largely outperform the model's one.

(Insert Figure 7 about here)

Results

Simulated word recognition probabilities are displayed in the right column of Table 8 and in Figure 7. The left panel of Figure 7 shows MT's actual curve and his VPE predicted curve as established from his letter visibility data. At the optimal viewing position, MT's word recognition probability is slightly above the simulated performance. However, contrary to MT's data, the model predicts only moderate differences between viewing positions and does not capture MT's atypical inverted-V shaped curve. Moreover, MT's word recognition falls largely below (up to 23%) the model's performance for fixations at the extremities of words. This result, if significant, suggests that MT does not process all the available information on letter identity. Control data are presented in the right panel of Figure 7. As expected, control subjects largely outperform the model's predictions.

Bootstrap Analyses

Reliability of the difference between MT's and the simulated VPE curves was quantified by means of bootstrap analyses (for methodological aspects, see Appendix A). Two different bootstrap analyses were undertaken. The first one was designed to incorporate variability in letter identification and visual-span profiles curve fitting. The second analysis aims to test the reliability of the difference between MT's and the model's VPE curves, while controlling for the variability of both letter and word identification curves in MT.

(Insert Figure 8 about here)

Drawing confidence intervals.

MT's trigrams data were resampled 10,000 times. Each bootstrap sample was provided as input to the model. We then obtained 10,000 different simulated curves, reflecting prediction variability depending on the letter identification intra-individual measurement error. As illustration, Figure 8 shows the distribution of the bootstrap estimates of MT's predicted word recognition probabilities at viewing position -2. In this example, the bootstrap estimates distribution is close to the normal function, centered near the original model predicted value (0.517) with a standard deviation of 0.0434. Percentiles 95% confidence intervals bounds were computed, yielding to the interval [0.435;0.605] in the current example. Used in this way, the bootstrap method allows us to compare MT's word recognition probability in Experiment 1 with the predicted model's scores distribution. Bootstrap results are displayed in Table 9. All bootstrap estimates can be considered as normally distributed (Kolmogorov-Smirnov tests) and biases (difference between the original predicted score and the bootstrap mean) are very small (the biggest one is only 0.3%). Obtained confidence intervals are plotted around the model's predicted curve in Figure 7. For fixations at the beginning and end of the word, MT's word identification scores are below the *lower* bound of the confidence interval around the model's predictions. In other words, when fixating first/last letters of words, MT's word recognition probability is significantly lower than what would be expected if he used all of the information he could extract from the word's individual letters.

(Insert table 9 about here)

Testing the reliability of the difference

In the previous bootstrap analysis, letter identification measurement errors were incorporated in the computation of confidence intervals. However, MT's actual VPE curve is also subject to such measurement errors. A second analysis was thus designed to deal with both sources of measurement errors. In this analysis, two different bootstrap samples were drawn for each bootstrap run: one from MT's letter identification data (as in the previous analysis) and one from his word identification data (from Exp. 1). The letter bootstrap sample was provided as input to the model. The *difference* between the curve outputted by the model and the word identification bootstrap sample was then computed, resulting in a bootstrap distribution of the differences for each viewing position (see Appendix A for methodological aspects). Results are displayed in Table 10. As previously, all the bootstrap estimates were normally distributed (Kolmogorov-Smirnov tests) and biases were very small (max: 0.38%). As expected by introducing two different sources of variability, standard deviations were quite high (range: 8.7 - 10.5%). These bootstrap distributions were then used to test if the observed difference between MT's VPE curve and the model's predicted curve was significantly different from zero. For each viewing position, *p*-values were computed as the percentage of bootstrap estimates falling below zero. As can be seen from Table 10, performance differences in the -2 and +2 viewing positions remain highly significant ($p < .05$ and $p < .01$ respectively).

(Insert table 10 about here)

Discussion

The aim of this modelling section was to compare MT's inverted V-shaped VPE curve with a purely visual reference curve built from MT's letter visibility data. This comparison provides new insights on MT's viewing position effect. The main finding of this study is the marked difference between MT's VPE curve and the model's one. When provided with MT's own letter identification data as input, the model largely outperforms MT's performance for words fixated at end-letters. MT's curve is also more narrow than the model's one. As a consequence, MT's orthographical knowledge deficit is certainly not sufficient to account for his VPE pattern. As the model simply combines all the visual information about letter identities to compute word recognition probabilities, MT's lower performance suggests that he does not use the whole available visual information. Some bottleneck seems thus to further operate at a pre-orthographical level, which reduces the amount of letter identities information available to MT.

General Discussion

In this paper, we reported the case of a young surface dyslexic boy. Reading assessment suggests that MT suffers from a deficit in acquiring lexical knowledge. While relatively preserved in comparison to his irregular word reading perfomance MT's pseudo-word reading was very slow and not error-free. Difficulties in pseudo-word reading are typically interpreted as reflecting a failure in mastering grapheme-to-phoneme conversion rules, linked to an underlying phonological deficit. However, MT's phonological processing abilities were preserved, as ascertained by his good results in phoneme awareness, pseudo-word repetition and verbal short-term memory tasks, as typically found in surface dyslexic patients (see e.g., Castles & Coltheart, 1996). Moreover, MT's good achievement on these tasks could not be due to special phonological training or remedial program. Indeed, phonological assessment was carried out three years before the present study, and before MT attended to any reading remedial program. Similarly, Valdois *et al*. (2003) reported the case of Nicolas, a young French dyslexic boy who exhibited the reading pattern characteristic of surface dyslexia, in the absence of any sign of phonological deficit, but in association with a slow pseudo-word reading rate. These authors advocated that Nicolas' poor pseudo-word reading performance without poor performance in any other phonological tasks could result from a dysfunction at the level of the visual analysis system.

Visual word recognition was investigated by means of the fixation-contingent display paradigm (Experiment 1). A strong viewing position effect was elicited. However, MT's performance was clearly affected by length, yielding a floor effect for 7-letter words. More interestingly, his 5-letter words VPE function was markedly inverted V-shaped. In proficient readers, the VPE function is mainly determined by "(1) the perceptibility of the individual letters as a function of the fixation location, and (2) the extent to which the most visible letters isolate the target word from its competitors. " (Brysbaert & Nazir, 2005, p. 221).

Consequently, we investigated whether MT's atypical VPE profile could be due to (1) difficulties in perceiving letters (Experiment 2) and/or (2) MT's lexical knowledge deficit (modelling).

Letters Visibility, Low-Level Visual Factors and Visual Information Extraction

It is well established that some dyslexic people are more sensitive to low-level visual factors, potentially affecting letter visibility. For example, a dyslexic group studied by Bouma and Legein (1977) exhibited a particular sensibility to lateral masking (see also Bouma & Legein, 1980; Pernet, Valdois, Celsis, & Demonet, 2006; Spinelli, De Luca, Judica, & Zoccolotti, 2002). The dyslexic participants recognized significantly less flanked letters than matched controls, and the difference increased with visual eccentricity. Spinelli *et al*. (2002) further established that this lateral masking effect was also found for strings of symbols and took place at a pre-linguistic level. Interestingly, flanked letter identification has been linked to the magnocellular system (Omtzigt, Hendriks, & Kolk, 2002), particularly when no prior knowledge of letter location is provided (Omtzigt & Hendriks, 2004). Furthermore, it is often assumed that a magnocellular defect is responsible for problems in the allocation of attention in developmental dyslexics, which in turn results in reading problems (e.g. Stein & Walsh, 1997; Stein, 2001; Vidyasagar, 1999; Vidyasagar, 2004; Hari & Renvall, 2001; but see Amitay, Ben-Yehudah, Banai, & Ahissar, 2002; Skottun, 2000; Stuart, McAnally, & Castles, 2001 for a different point of view).

In line with the foregoing, evidence has indicated an asymmetry of the allocation of attention between the two visual fields in dyslexic patients, resulting in an asymmetrical processing of visual information. Hari, Renvall and Tanskanen (2001) have shown, by means of temporal order judgment and line motion illusion tasks, that a group of adult dyslexics processed stimuli more slowly in the left hemifield, indicating a left-side minineglect. Similar results were reported with different methodologies (e.g. Facoetti & Turatto, 2000; Facoetti & Molteni, 2001; Buchholz & Davies, 2005; Sireteanu, Goertz, Bachert, & Wandert, 2005). Moreover, this left-side deficit appears to be linked with a right-side enhancement, as suggested by an increased ability in dyslexics to report letters displayed in the right visual field in comparison to normal readers (Lorusso et al., 2004; Geiger & Lettvin, 1987; Geiger, Lettvin, & Zegarra-Moran, 1992). This would imply that letters left of fixation receive less attention than letters presented right of fixation.

In order to assess whether such low-level visual factors might explain MT's particular viewing position effect, we estimated spatial profiles of letter perceptibility by means of visual spans. The dynamic dimension of the visual span (Legge, Mansfield, & Chung, 2001) was also taken into account: different exposure durations were used for MT and the control group. Given a 100 ms presentation time difference, MT's and control subjects' visual span profiles were highly similar. The temporal difference between MT and the control subjects could be seen as potentially reflecting a general reduction in letter visibility in MT. It is in fact possible – and even very likely -- that the width of MT's visual span would be smaller than for skilled readers if similar exposure durations were used. However, the aim of Experiment 2 was not the investigation of MT's letter visibility *per se*. The strict matching of the display conditions (including exposure durations) between the estimation of the viewing position effect and the visual span profile allows a direct comparison of MT's performance in both tasks. When processing words, MT's VPE performance differed dramatically from the control group, suggesting a possible reduction of letter visibility. However, when letter visibility was assessed within the same viewing conditions, there was no indication of such a deficit. Furthermore, neither an increased lateral masking, nor inter-visual field variations for letter processing, were observed. Consequently, MT's visual span profiles speak against a role of such low-level factors in accounting for his VPE curve. MT exhibits a clear viewing position effect (despite a more narrowed curve). His optimal viewing position is located near the word centre, like well-achieving readers. The absence of a serial left-to-right word letters scan is further supported by the relative letter position analysis of Experiment 1's data. MT's recognition of letters was not inversely related to the relative letter position in the word. When he has to recognize words in a single fixation, MT's visual strategy is in fact similar to that of skilled readers.

Lexical Knowledge and VPE Modelling

We used an ideal-observer model perspective to establish a reference VPE curve to which MT's word recognition probability was compared. The model, adapted from Legge *et al.* (2001), takes MT's letter visibility data as input and produces VPE curves. To simulate MT's lexical deficit, no lexical knowledge was implemented. In this framework, our model outputted the word recognition probability that the patient would have obtained if he simply combined the whole available visual information to recognize words, without any attempt to guess. It thus represents the bottom-up stimulus information available for word recognition and is comparable to the first letter recognition stage implemented in current adult VPE models (Kajii & Osaka, 2000; Stevens & Grainger, 2003). When compared to MT's VPE profile, the model's reference curve did not capture his inverted V-shaped curve. Thus, while lexical knowledge is known to play a role in determining the VPE function shape, the present findings clearly speak against viewing MT's VPE profile as *uniquely* reflecting his lexical impairment.

A key assumption of this model is that letters are the basic units of word identification. Letters are processed separately, recognized independently, and then combined to trigger word recognition. Since the first model of the VPE function proposed by McConkie *et al.* (1989), the same assumption underlies most modelling attempts (see, e.g. Kajii & Osaka, 2000; Nazir, O'Regan, & Jacobs, 1991; Stevens & Grainger, 2003). Pelli, Farell and Moore (2003) recently provided strong support for letter identity as the basic perceptual unit of visual word recognition. By comparing visual identification thresholds for words of various lengths to ideal observer models, Pelli *et al.* (2003) demonstrated that human's word identification accuracy never exceeds the performance obtained by strictly letter-based models.

Our model's performance relies crucially on the way letter visibility was estimated. Different studies attempted to predict the VPE curves by combining letter visibility data and some measure of lexical constraints (Kajii & Osaka, 2000; Nazir, Heller, & Sussmann, 1992; Montant, Nazir, & Poncet, 1998; Stevens & Grainger, 2003; see also Legge, Mansfield, & Chung, 2001). In these studies, the way letter identification scores were collected varied in terms of string length, fixation position and letter-in-string position. Nazir *et al*. (1991; see also Nazir, Heller, & Sussmann, 1992; Nazir, Jacobs, & O'Regan, 1998 for similar procedures) reported visibility of a target letter embedded in an array of nine *k*s. The target was displayed at any one of the nine possible positions in the string, and fixation was either on the first or the last letter of the array. Contrarily, Kajii and Hosaka (2000) measured identification of only one letter surrounded by two digits and presented at various visual eccentricities. Both studies included only embedded letters and failed empirical estimates of the visibility of the end letters of words (those adjacent to a space), known to boost recognition accuracy relative to internal letters. Kajii and Osaka (2000) further demonstrated that the end-letter superiority effect must be considered in order to capture the shape of the VPE curves. The only –to our knowledge- study providing complete measurements of letter visibility was realised by Stevens and Grainger (2003). These authors measured letter recognition across all combinations of fixation position and letter-in-string position for one letter embedded in strings of either five or seven *X*s. Interestingly, they observed the typical end-letters effect (i.e. end-letters of strings were better recognized than internal letters), but no difference was found between the different string internal letters. The same pattern of results was observed for both five and seven letter strings. Congruently, Pelli *et al*. (2004) reported that the contrast threshold needed to recognize flanked letters increased when the number of flankers was increased from 1 to 2, but then remained constant despite further elevation of the number of flankers (at least up to 4, the maximal number of flankers used in this study). Consequently, despite differences in length, trigrams were sufficient to capture all the visual factors affecting letter visibility in five letter words. The effect of visual acuity was taken into account by varying visual eccentricity. Visual span profiles derived from outer letters of the trigram captured the end-letter superiority effect. Moreover, as lateral masking is maximal when a letter is surrounded by two flankers, visual span profiles obtained from the middle letter of trigrams validly simulate internal letters of the word. Further support for providing an ideal observer model with trigrams as input comes from the work of Legge *et al.* (2001). These authors successfully simulated reading speed in central vision by inputing a parameter-free model containing a simple lexical-matching rule (similar to the one we used) with letter trigrams.

Alternative Hypotheses

The main result of this paper is that a purely visual model, provided with MT's letter visibility data, outperforms the patient's VPE curve. That MT's word identification probability felt significantly below the ideal-observer's reference curve –when fixating end letters- indicates that MT's impoverished lexical knowledge is not sufficient to account for his inverted V-shaped VPE curve. It further points to a deficit at a pre-orthographical level. However, this deficit is not caused by an underlying perceptual impairment, or by general factors affecting the imbalance of letter processing between visual fields. Furthermore, the difference between MT's and the model's performance strongly suggests that MT does not use the whole available visual information on letter identities to recognize words. However, these results can be accounted for by a reduction of the number of letters MT simultaneously processed.

If the number of letters processed simultaneously is uncommonly reduced, say to only three or four characters at a time, MT will behave quite normally when facing short words or trigrams, but will have difficulties with longer words. Indeed, when the number of letters increases, only partial information will be used. In accordance with this hypothesis, comparison of MT's performance with the simulated data clearly demonstrated that MT does not use all the visual information available on letter identities to recognize words.
Congruently, analysing MT's word identification data at the letter level revealed a marked effect of visual eccentricity on letter identification. MT recognized letters in words as well as control subjects when the letters were displayed near fixation, but his identification scores drastically decreased for letters away from fixation. This eccentricity effect cannot be accounted for by sensory limitations, as MT well recognized letter trigrams displayed in the same viewing conditions at the same eccentricities. Thus, when MT has to identify longer words, the more extreme letters will be ignored. As a consequence, performance will be more or less normal when fixating near the word's centre, but will fall dramatically when the eyes fixation deviates towards word ends, resulting in an inverted V-shaped curve. Also, a strong length effect, interacting with the shape of the curve, is expected, as observed in MT.

To our knowledge, there is only one other report of such inverted V-shaped VPE curves in the literature. Aghababian and Nazir (2000) reported similar VPE patterns in "poor" beginning readers: these children exhibited typical inverted U-shaped curves for short four-letter words but for six-letter words curves became inverted V-shaped. The authors interpreted these results as reflecting a reduction of the *word identification span*, a sub-region of the *perceptual span*. Operationally, the word identification span is defined as the area around fixation from which useful identification is *effectively* extracted in order to identify words during a single fixation, while the perceptual span includes also detection of other elements such as spaces and words (for a review, see Rayner, 1998). This interpretation is similar to the one we propose. In support to their hypothesis, authors reported simulation results. As ours, their model combines individual letter recognition probabilities and does not incorporate any lexical knowledge. They simulated a narrow word identification span by reducing the input from more eccentric letters to an arbitrary value. Simulated curves well captured the effect of word length on the shape of VPE curves and obtained inverted V-shaped curves only for longer (6-letters) words. We approached the problem in another, complementary way. Contrary to Aghababian and Nazir (2000), we used real letter visibility data as input. This allowed direct comparison between MT's performance and the model's curve, in an ideal-observer perspective. Our data thus extend their initial observations.

Other results are in close agreement with a reduction of the number of letters processed simultaneously in reading. By using the moving window technique, Rayner *et al.* (1989) found that the perceptual span was smaller for dyslexic readers than for well-achieving readers. In line with this, surface dyslexic readers showed more frequent and smaller rightward saccades when reading text (De Luca, Di Pace, Judica, Spinelli, & Zoccolotti, 1999); numerous fixations were needed to read single-words and their eye movement patterns were similar for words and pseudo-words (De Luca, Borrelli, Judica, Spinelli, & Zoccolotti, 2002). However, contrary to the visual span, which is entirely determined by sensory limitations, the size of the perceptual span (and its sub-region dedicated to word recognition, the word identification span) depends on factors in addition to letter recognition. As the size of the perceptual span is not constant but varies in function of the text difficulty (for a review, see Rayner, 1998), the reduced size of the perceptual span in dyslexic readers was typically interpreted as a consequence of their reading deficit, rather than reflecting a less effective processing of parafoveal information.

However, a more general difficulty in processing multi-element strings has recently been observed in dyslexic patients with simple multiple-elements string processing tasks that do not require word – or even letter - recognition (Hawelka, Huber, & Wimmer, 2006; Hawelka & Wimmer, 2005; Valdois et al., 2003; Valdois, Bosse, & Tainturier, 2004). In these studies, multi-element processing was directly measured in a stringent and sensitive manner, by means of report tasks of multi-elements strings (Averbach & Coriell, 1961; Averbach, & Sperling, 1968). Results consistently demonstrated that the simultaneous perception of visual forms was impaired in dyslexics. A number of data suggest that this deficit is not specific to letters. Hawelka and Wimmer (2005) indeed showed that individual recognition thresholds on multi-digit arrays were associated with dyslexic and normal-readers' number of eye movements in reading. Moreover, Hawelka and Wimmer (2006)'s findings suggest that the multiple-elements string deficit persists in adulthood. Some studies further suggest that the disorder affecting multi-element array processing is only found in some subtypes of dyslexic children (Bosse, Tainturier, & Valdois, 2006; Valdois et al., 2003; Valdois, Bosse, & Tainturier, 2004). Valdois *et al.* (2003) contrasted the case studies of two French dyslexic teenagers, matched for chronological age and general reading level. Laurent, the first dyslexic boy, conformed to the pattern of phonological dyslexia, while Nicolas exhibited a reading profile characteristic of surface dyslexia. In multi-elements string processing tasks, Laurent's number of correct responses was within the range of normal readers. In sharp contrast, Nicolas demonstrated severe difficulties on these tasks. Interestingly, MT's general reading profile was highly comparable to that of Nicolas. Also similarly, they both exhibit completely preserved phonological processing abilities. These findings suggest that the slow serial reading of at least some dyslexic readers may have to do with visual information extraction and/or attentional problems in processing letter strings and not with orthographic word recognition per se. Following Valdois *et al.* (2004), these difficulties might reflect a deficit in the allocation of attention across letters or symbols strings, causally limiting the number of elements that can be processed in parallel during reading. Such a deficit was called by Bosse *et al*. (2006) the visual attention span hypothesis of developmental dyslexia.

Conclusion

In this article, our aim was to study visual word recognition in MT, a French-speaking young dyslexic boy. The present study reports converging evidence from experimental investigation, combined with modelling and computer intensive statistical analyses, that MT's visual word recognition is constrained by a limitation in the number of letters he can simultaneously process. These findings also strongly suggest that, independently of phonological deficits, pre-orthographical factors limiting the number of letters simultaneously processed contributes to, and possibly causes, some developmental dyslexic children's reading difficulties. Future research is needed to investigate the precise nature of such a deficit and whether it is causally related to reading acquisition disorders. This approach also represents a new way to explore visual word recognition and its constraints.

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Notes

1. In our study, linear trends analyses were performed to assess the symmetry of the viewing position effect function (for a similar use, see Stevens & Grainger, 2003).

2. Instead of Gaussians, a quadratic model has also been proposed for the VPE function (McConkie, Kerr, Reddix, Zola, & Jacobs, 1989; Nazir, Heller, & Sussmann, 1992). We do not use this model for both theoretical and practical reasons. Mathematically, this quadratic function predicts negative values when x tends to infinity. Applied to word identification accuracy, these negative values don't make sense. That Gaussians tend to zero makes the interpretation more plausible. Moreover, the quadratic function predicts negative values for some viewing positions under particular experimental conditions. This can occur for patients (when the peak amplitude is low and falls drastically when fixation deviates from the OVP) fixating outer letters on long words. Indeed, this was the case for MT seven-letter word performance.

3. Numerous formulas are given for the R^2 computation, leading to different results and interpretations in the case of non-linear models. Following Kvalseth (1985), R^2 was computed as $1-\sum(y-\hat{y})^2/\sum(y-\bar{y})^2$, where y is the dependant variable, $\hat{y}$ the vector of predicted values, and $\bar{y}$ the mean of the dependant variable. Computed in such a way, the statistic could be interpreted as the proportion of the total variation of y that is accounted for by the non-linear fitted model.

4. These low R^2 values indicate that the model did not really capture the VPE profile of these three subjects. The reason for the inadequacy of the gaussian model in these subjects was further investigated. At first visual inspection, effect of the viewing position seems to be absent in these control subjects (see the three rightward upper panels from Fig. 2). We thus fitted the data with straight lines instead of splitted-Gaussian curves. These two different

models were compared by means of the Akaike Information Criterion (AIC: Akaike, 1973), which provides a measure of generalisability of the model independent of model complexity. The lower the AIC, the greater the likelihood with which the model in consideration generated the data (for the use of AIC and related measures, see e.g. Pitt & Myung, 2002; Glover & Dixon, 2004). Inference from the first visual inspection was confirmed. Contrary to the other control subjects, VPE profiles were better explained by straight lines than by Gaussians in these three subjects. Moreover, the slopes of individual regression lines did not significantly differ from zero, indicating a potential absence of the viewing position effect. It follows that the parameter estimates obtained with the split-Gaussian curve model cannot be considered as reliably characterising the shape of these subjects' VPE curve. They were thus removed from the analysis.

5. In a shifted Gaussian, the only parameter capturing an asymmetry is the OVP.

6. Following Morton and Patterson (1980), we considered errors as visual if the stimulus and the response shared at least 50% of the target letters, and if the relative order of the letters was globally preserved.

7. Only positions combining first, middle and last letters of trigrams were used to fit, resulting to the fitted letter position interval -6 to 6. This solution yields the more reliable parameter estimates. However, as control conditions, we also fitted intervals -7 to 7 and -8 to 8. While small variations in the best-fit estimates were observed, results yielded to similar conclusions. MT never significantly differed from control subjects.

8. Confidence Intervals around the abnormality of a patient score (Crawford & Garthwaite, 2002) and CI around the effect size (expressed as Cohen's *d*, see Cumming & Finch, 2001) are algebraically equivalent. In both cases, a CI is computed around a Standardised effect size. In our case, this effect size is computed as $\delta = \left(X_p - \overline{X}\right)/S$, in which δ is the effect size, X_p is the patient's score, $\overline{X}$ and S are respectively the control group's mean and standard deviation.

The “real” effect size will fall within the CI with 95% confidence. Crawford and Garthwaite then simply compute the rarity of the bounds of this CI as the unilateral p-value under a normal distribution (Crawford & Garthwaite, 2002).

Following Cumming and Finch (2001, p. 564), « CI width reflects a number of aspects of the precision of a study, including (…) the sample size and thus sampling error, and the amount of error in the dependent variable. Statistical power is also influenced by all these factors but is defined relative to an effect size that is set by the value of the population parameter specified by the alternative hypothesis. ». CI computation could thus be seen as an –interesting-- alternative of power computation (for a discussion of the advantages of CI about power analysis, see Cumming & Finch, 2001; and for a discussion of problems linked to power analysis in the case of accepting the null hypothesis, see e.g. Frick, 1995).

Appendix

Bootstrap analysis

First introduced by Efron (Efron, 1979; Efron, & Tibshirani, 1993), the bootstrap is a data-based simulation method for statistical inference.

The bootstrapping method relies on a resampling procedure in a computer-intensive way. It consists of creating many resamples of the same size as the original sample by repeatedly sampling *with replacement* from the original data. This way, any single obervation could be drawn a random number of times from the original sample. If a statistic (such as the mean or the more complex prediction from our model) is computed from each of the numerous different bootstrap samples, a bootstrap probability distribution of that statistic is obtained. The standard deviation of the bootstrap distribution is an estimator of the variability of the sampling distribution of that statistic. When resampling is done from a single subject's data, the bootstrap distribution represents the variability introduced by the measurement error related to each intra-individual measurement. It is particularly useful when investigating deficits at a single case level, where demonstrating that a given test's result did not occur by chance is crucial (for similar use of bootstrap analysis in single case studies, see e.g. Habekost & Bundesen, 2003; Habekost & Rostrup, 2006).

For both bootstrap analyses, MT's data was resampled 10,000 times. Resampling was made with replacement. Moreover, as the bootstrap samples were provided as input to the model, resampling was done in such a way that the same number of items was obtained for each viewing condition in a given bootstrap sample. This constraint was putted to ascertain that sufficient data was drawn from each condition to obtain robust curves estimates.

Drawing confidence intervals

In the first analysis, we sampled MT's letter identification data, consisting of 450 items. Thus, each bootstrap sample included also 450*3 letters data points. Each bootstrap data set was provided as input to the model. This way, 10,000 predicted curves were obtained (each curve consisting of one probability of correct word recognition for each of the five different viewing positions). We were thus given with five different distributions of the predicted values, one for each of the five viewing positions. Percentiles 95% bootstrap confidence intervals were finally derived from these distributions by taking the empirical 0.025 and 0.975 quantiles of the bootstrap estimates distribution.

p-value of the difference

In the second analysis, we would like to incorporate measurements errors from both MT's letter identification data and word identification experiment. Moreover, we are interested in the *difference* between MT's actual VPE curve and the model's predicted one. Consequently, in each bootstrap run, two different samples were drawn, one from MT's letter identification data (as in the previous analysis) and one from his word identification data (from Exp. 1). The letter bootstrap sample was provided as input to the model. The *difference* between the curve outputted by the model and the word identification bootstrap sample was then computed for each viewing position. This way, 10,000 difference values were obtained for each viewing position, yielding to five different distributions of this difference. Finally, unilateral *p*-values were computed as the percentage of bootstrap estimates falling below zero (that is, the absence of difference).

Tables

Table 1

Tests of reading ability

		Controls			
	MT	**M (SD)**	**range**	**t**	**p**
Reading with time constraints[a]					
Regular words (/40)	38	39.21 (0.72)	38 - 40	-1.647	.056
Irregular words (/40)	34	37.58 (1.41)	34 - 40	-2.488	.01 **
Pseudo-words					
Accuracy (%)	87.78	85.31 (2.59)	75 - 100	1.078	.85
Speed (sec/item)	2.2	0.9 (0.18)	0.6 - 1.38	7.076	<.001 ***
Matched words					
Accuracy (%)	100	98.02 (1.8)	95 - 100	0.934	.82
Speed (sec/item)	1.6	0.57 (0.09)	0.45 - 0.8	11.213	<.001 ***
Reading without time constraints[b]					
Irregular words (/40)	31	38.31 (1.62)	35 - 40	-4.378	<.001 ***
Pseudo-words (/40)	34	38.19 (1.9)	34 - 40	-2.139	.025 *
Visual Lexical Decision[b]					
Correct responses (/120)	89	110.31 (5.2)	99 - 117	-3.976	<.001 ***
Words (/60)	41	53.62 (2.58)	50 - 57	-4.749	<.001 ***
Pseudo-words (/60)	48	56.68 (3.84)	49 - 60	-2.194	.022 *

Note. MT is compared to: (a) a school-level (n = 24) or (b) an chronological age-matched (n = 16) control group.

*p < .05, one-tailed; **p < .01, one-tailed ; ***p <.001, one-tailed.

Table 2

Tests of phonological short-term memory and phonological awareness

		Norms	
	MT	**M (SD)**	**range**
Grade 4			
Chronological age (month)	131		
Verbal Short Term Memory			
Digit Span [a]			
Forward	7	5.51 (1.02)	3-9
Backward	4	3.9 (0.9)	2-6
Pseudo-word repetition [b]			
CV (span)	5	4.94 (0.28)	3-5
CV (performance)	19/20	16.08 (3.53)	0-20
CCV (span)	4	3.42 (0.83)	1-5
CCV (performance)	12/20	10.22 (2.74)	3-18
Phoneme awareness [b]			
Acronyms	16/16	13.72 (2.03)	5-16
Grade 5			
Chronological age (months)	140	152 (3.7)	145-158
Phonological Awareness [c]			
Sound categorisation	14/20	16.4 (2.6)	11-20
Phoneme deletion	18/20	18.7 (1.9)	13-20
Phoneme segmentation	20/20	16.4 (2.6)	11-20

Note. Spans were computed as the longest sequence accurately reported. Normative data are from: a) chronological-age matched controls for WISC-III; b) school-level matched controls for BELEC (n = 217) and c) an older control group (n = 24) from Valdois et al. (2003).

Table 3

Average performance across viewing positions

	Controls (N = 16)				
	MT	**M (SD)**	**range**	**t**	**p**
Practice session (%)					
5-letter words	55	61.33 (12.88)	50 - 85		
7-letter words	28.57	71.61 (12.33)	52.4 - 90.5		
Word identification (%)					
5-letter words	48.13	68.98 (10.97)	52.5 - 86.25	-1.844	.042*
7-letter words	16.07	61.72 (12.92)	34.8 - 82.25	-3.428	.002**
Exposure durations (ms)					
5-letter words	166	71.59 (20.76)	49.8 - 116.25	4.412	< .001***
7-letter words	199	74.71 (24.28)	49.8 - 133	4.966	< .001***
Letter identification (%)					
5-letter words	55.66	58.12 (8.36)	40.91 - 69.41	-0.285	.39
7-letter words	54.64	59.76 (7.42)	47.32 - 71.81	-0.67	.25

Note. Letter identification performance was computed on erroneously identified words (see text for details).

*p < .05, one-tailed; **p < .01, one-tailed ; ***p < .001, one-tailed.

Table 4

Viewing position functions – averaged individual model parameters

	Controls (N = 15)				
	MT	**M (SD)**	**Range**	**t**	**p**
5-letter words					
A	72.69	87.74 (7.7)	71.4 - 98.9	-1.883	.04*
OVP	-0.085	-0.80 (0.38)	-1.67 - -0.2	1.831	.046*
SD	2.01	3.14 (1.04)	1.77 - 5.742	-1.045	.16
7-letter words					
A	45.88	90.04 (9.98)	71.3 - 100	-4.036	< .001***
OVP	-1.3	-1.08 (0.31)	-1.84 - -0.67	-0.689	.25
SD	1.31	3.2 (0.79)	1.9 - 4.81	-2.307	.02*

Note. Three control subjects were removed for the analysis (see text for more details)

*p < .05, one-tailed; **p < .01, one-tailed ; *** p <.001, one-tailed.

Table 5

Output of regression models on MT's letter identification scores

	Coeff	SE	t	p
MT				
5-letter words				
(Intercept)	0.556	0.05	9.88	< .001***
Letter position	-0.004	0.04	-0.09	.93
7-letter words				
(Intercept)	0.546	0.05	10.15	< .001***
Letter position	0.029	0.027	1.07	.29
Control group				
5-letter words				
(Intercept)	0.73	0.09	7.805	0.004**
Letter position	-0.049	0.028	-1.757	0.18
7-letter words				
(Intercept)	0.61	0.103	5.982	.002**
Letter position	-0.004	0.023	-0.176	0.87

*p < .05, one-tailed; **p < .01, one-tailed ; *** p <.001, one-tailed.

Table 6

Averaged letter identification performance for left, central and right eccentricities

	Controls (N = 13)				
	MT	**M (SD)**	**range**	**t**	**p**
5-letter words					
Outer left	29.12	57.14 (9.04)	44.34 - 72.01	-3.01	.004**
Fixation	73.81	62.62 (12.1)	34.45 - 74.63	0.89	.81
Outer right	44.61	50.83 (18.42)	8.33 - 73.81	-0.33	.37
7-letter words					
Outer left	26.31	53.8 (11.4)	32.79 - 72.52	-2.34	.016*
Fixation	79.94	70.57 (10.27)	55.27 - 87.69	0.89	.81
Outer right	33.34	61.14 (10.11)	37.6 - 80.56	-2.67	.009**

Note. Outer eccentricities correspond respectively to positions -4 to -2 and 2 to 4 for five-letter words, and to positions -6 to -4 and 4 to 6 for seven-letter words.

*p < .05, one-tailed; **p < .01, one-tailed ; *** p <.001, one-tailed.

Table 7

Visual span profiles

	Controls (N = 7)					Rarity	
	MT	M (SD)	range	t	p	estimate	95% CI
All letters							
Averaged positions							
Outer left	45.56	37.04 (16.48)	17.04 - 59.63	0.48	.67	67.71	38.39 - 90.2
Fixation	92.96	89.68 (3.77)	85.18 - 95.93	0.81	.77	77.64	48.48 - 95.8
Outer right	58.52	45.93 (15.28)	25.56 - 67.41	0.77	.79	79.49	47.23 - 95.25
Best fit parameters							
A	93.46	89.31 (3.11)	85.88 - 94.03	1.25	.87	87.1	60.43 - 99.07
σ_L	5.45	4.45 (1.05)	3.37 - 6.29	0.9	.79	79.8	50.94 - 96.75
σ_R	5.89	6.33 (1.39)	4.86 - 8.59	-0.3	.38	38.88	14.35 - 67.63
By relative position							
Inner letters							

A	91.08	85.86 (3.95)	78.28 - 89.72	1.24	.87	86.89	60.13 - 99.03
σ_L	4.41	3.34 (1.03)	2.38 - 5.29	0.97	.82	81.52	52.98 - 97.43
σ_R	5.94	5.53 (0.97)	4.29 - 7.275	0.4	.65	64.95	35.82 - 88.36
Middle letters							
A	93.66	91.4 (4.9)	83.58 - 97.71	0.43	.66	65.96	36.75 - 89.0.4
σ_L	5.13	3.84 (0.86)	3.06 - 5.19	1.4	.89	89.39	64.04 - 99.5
σ_R	5.27	5.26 (0.94)	4.21 - 6.743	0.0009	.5	50.34	23.22 - 77.34
Outer letters							
A	95.98	96.98 (5.97)	89.6 - 1.07	-0.16	.44	44.05	18.23 - 72.12
σ_L	6.45	6.26 (1.77)	4.34 - 8.33	0.1	.54	53.93	26.18 - 80.2
σ_R	7.89	6.99 (2.07)	4.87 - 10.3	0.41	.65	65.1	35.96 - 88.46

Note. Outer eccentricities correspond respectively to positions -4 to -2 and 2 to 4 for five-letter words, and to positions -6 to -4 and 4 to 6 for seven-letter words. (See text for details on the estimation of the rarity of the score)

*p < .05, one-tailed; **p < .01, one-tailed ; *** p <.001, one-tailed.

Table 8

Computed word recognition probabilities for 5-letter words

Viewing position	**Letter eccentricity** -4	**-3**	**-2**	**-1**	**0**	**1**	**2**	**3**	**4**	**Word probability**
MT										
-2					**0.96**	0.92	0.871	0.796	**0.844**	0.517
-1				**0.948**	0.937	0.92	0.871	**0.893**		0.636
0			**0.915**	0.919	0.937	0.92	**0.929**			0.673
1		**0.862**	0.868	0.919	0.937	**0.952**				0.613
2	**0.792**	0.79	0.868	0.919	**0.96**					0.479
Controls										
-2					**0.97**	0.898	0.85	0.777	**0.823**	0.473
-1				**0.957**	0.914	0.898	0.85	**0.884**		0.591
0			**0.922**	0.884	0.914	0.898	**0.931**			0.622
1		**0.865**	0.798	0.884	0.914	**0.96**				0.535
2	**0.791**	0.674	0.798	0.884	**0.97**					0.365

Note. Bold font corresponds to letter correct recognition probabilities derived from outer letter visual span profiles.

Table 9

Bootstrap confidence intervals

			Bootstrap (N = 10,000)		
Viewing position	**MT**	**model**	**bias**	**SD**	**95% CI**
-2	0.3125	0.517	0.0013	0.043	0.435 – 0.605
-1	0.5625	0.636	0.0025	0.056	0.532 – 0.749
0	0.75	0.673	0.003	0.062	0.557 – 0.799
1	0.53125	0.613	0.0024	0.055	0.509 – 0.724
2	0.25	0.479	0.0012	0.042	0.399 – 0.564

Table 10

Differences between MT and the model. Bootstrap hypothesis testing.

				Bootstrap (N = 10,000)		
Viewing position	**MT**	**model**	**Difference**	**bias**	**SD**	**p**
-2	0.3125	0.517	0.2045	0.0016	0.0935	.015*
-1	0.5625	0.636	0.0735	0.0038	0.103	.23
0	0.75	0.673	-0.077	0.0033	0.097	.77
1	0.53125	0.613	0.08175	0.00054	0.105	.22
2	0.25	0.479	0.229	0.001	0.0875	.006**

*p < .05, one-tailed; **p < .01, one-tailed ; *** p <.001, one-tailed.

Figures Captions

Figure 1. Viewing position effect. Word recognition probability from Exp. 1 is shown for five- and seven-letter words (solid squares and open triangles respectively) as a function of viewing position within the word relative to word centre, for MT (left panel) and control subjects (right panel). Small bars are for standard errors of the mean.

Figure 2. Viewing position effect parametrisation. Word recognition probability from Exp. 1 is shown for five- and seven-letter words (squares and triangles respectively) as a function of viewing position within the word, together with the best fitting Gaussian curves. Data are shown separately for each control subject (in the small panels), for MT and for the control group average. Three control subjects were excluded from the analysis (see text and note 2 for details). These subjects were represented in the three upper panels on the right column. Curves with very poor fit were displayed in bold.

Figure 3. Relative letter position effect. Letter recognition probability from Exp. 1 is shown as a function of the relative letter position, separately for five- and seven-letter words. Open squares are for MT data, and solid circles for control subjects. Small bars are for standard errors of the mean.

Figure 4. Eccentricity effect. Letter recognition probability from Exp. 1 is plotted for MT (right panels) and control subjects (left panels) as a function of viewing eccentricity. Data for different lengths are presented in the four upper different panels. The four upper panels plot letter recognition probability for the different viewing conditions (one line per condition). The lower two panels show letter recognition probability averaged over viewing conditions.

Figure 5. Visual span profiles. Letter recognition probability from Exp. 2 is shown as a function of viewing eccentricity for the seven control subjects (small panels), for MT and for the control group average (ALL). Data have been fitted with split Gaussians (see text).

Figure 6. Effect of letter position within the trigram. Separate visual span profiles from Exp. 2 are displayed for *inner*, *middle* and *outer* letters of trigrams (respectively open circles, open triangles and solid circles). Small panels are for the seven control subjects. The two lower panels present MT data (left panel) and the control group average (right panel).

Figure 7. Comparing predictions of the model to MT’s (left panel) and control group’s (right panel) viewing position effect curves. Word recognition probability was plotted as a function of viewing position within the word, relative to word centre. Bootstrap 95% percentile confidence intervals around the model’s prediction were displayed in grey. Small bars represent standard error of the mean.

Figure 8. Distribution of 10,000 bootstrap estimates of the model’s predicted word recognition probability at a representative viewing position (-2), together with a normal density curve. MT’s letter visibility data is used as input.