Available online at www.sciencedirect.com
SCIENCE DIRECT®
Vision Research 46 (2006) 718–723
Vision Research
www.elsevier.com/locate/visres

Impaired visual processing of letter and digit strings in adult dyslexic readers

Stefan Hawelka, Christine Huber, Heinz Wimmer *

Department of Psychology, Center of Neurocognitive Research, University of Salzburg, Austria

Received 7 March 2005; received in revised form 12 September 2005

Abstract

The slow word reading of developmental dyslexics may stem from a string processing impairment which in turn reflects visual attentional deficits. We indeed found substantially enhanced recognition time thresholds in the dyslexic adult readers. However, their position profiles were hard to reconcile with any of the discussed visual attentional deficit hypotheses and with the prediction that dyslexic readers suffer from an absent string processing system as they exhibited similar M-shaped position profiles for digit and letter strings as the normal reading controls.

Keywords: Developmental dyslexia; Reading fluency; Visual attention

1. Introduction

Adolescent and adult persons who suffer from developmental dyslexia typically have to rely on slow serial decoding of words which are immediately and automatically recognized by non impaired readers (Shaywitz & Shaywitz, 2005). The serial decoding strategy of dyslexic readers becomes most evident in their eye movement behavior. Whereas normal readers most of the time recognize short words with a single fixation, dyslexic readers require a substantially higher number of fixations (De Luca, Di Pace, Judica, Spinelli, & Zoccolotti, 1999; Hawelka & Wimmer, 2005; Hutzler & Wimmer, 2004). In English with its complex and rather inconsistent grapheme–phoneme relations, the slow word decoding is often accompanied by a higher number of misreadings, especially in younger readers. This is not the case in more regular orthographies such as German (Landerl, Wimmer, & Frith, 1997; Ziegler, Perry, Ma-Wyatt, Ladner, & Schulte-Körne, 2003). A straightforward interpretation of the slow serial decoding of dyslexic readers in regular orthographies is offered by the dual-route conception of visual word recognition which distinguishes between a slow phonological reading route and a fast visual orthographic route (Coltheart, Rastle, Perry, Langdon, & Ziegler, 2001). In this conception, dyslexic readers in regular orthographies lack orthographic recognition units for frequently encountered words and, therefore, have to rely on serial decoding. However, we found that even children with spelling performance in the normal range adhered to slow serial reading (Wimmer & Mayringer, 2002).

This latter finding suggests that the slow serial reading of at least some dyslexic readers may have to do with perceptual or attentional problems in processing letter strings and not with orthographic word recognition. Evidence for a string processing deficit was obtained in a recent study from our laboratory which required participants to name a single element in response to a position cue when digit strings were briefly presented and then masked (Hawelka & Wimmer, 2005). The critical measure was the string presentation time required for reliable performance estimated by an adaptive staircase procedure. For 2-digit strings the dyslexic readers exhibited about the same low presentation time thresholds as fluent readers of about 20 ms only. However, for 4- and 6-digit strings they exhibited much higher

* Corresponding author. Tel.: +43 662 8044 5151.
E-mail address: heinz.wimmer@sbg.ac.at (H. Wimmer).

0042-6989/$ - see front matter © 2005 Elsevier Ltd. All rights reserved.
doi:10.1016/j.visres.2005.09.017

thresholds than the fluent readers (e.g., 80 vs. 40 ms for 4-digit strings). Furthermore, presentation time thresholds for the longer strings were reliably associated with the number of fixations during word and pseudoword reading.

In the Hawelka and Wimmer (2005) study, presentation time thresholds were estimated for whole strings and, therefore, no information was available for position dependent performance. In the present extension we used only strings of five elements (both digits and letters), but estimated presentation time thresholds for each position separately. The resulting position profiles are of relevance for accounts of visual attentional deficits in dyslexic readers. One such account postulates that dyslexic readers suffer from a narrowed visual attentional window and Valdois, Bosse, and Tainturier (2004) have recently reviewed the supportive evidence for this account. If a single attentional window is centered around fixation in the middle of our five-element strings then there should be little or no difference between dyslexic and normal readers for the fixated middle letter (and possibly immediately adjacent letters) and an increased group difference for the outer letters. A similar but more specific prediction follows from Whitney (2001) complex account of letter position encoding which assumes that the spatial left-to-right letter order is preserved in activation differences of neuronal letter nodes. Whitney and Cornelissen (2005) point out potential difficulties in acquiring this complex position encoding mechanism. In the extreme case *string specific processing is not learned* [and] *words are processed like other visual objects* (p. 295). From such a difficulty one would expect that our dyslexic readers fail to exhibit the advantage of the first and the final position of letter strings observed for competent readers (e.g., Mason, 1982). They may actually exhibit the opposite, that is, a U-shaped profile with a disadvantage for the first and final position. Such a profile reflects the reduced visual acuity of the outer positions and was repeatedly observed for strings of symbols which—different from letters and digits—commonly do not occur in string format (e.g., Mason, 1982). A further expectation of interest is suggested by the hypothesis that dyslexic readers suffer from left mini-neglect due to a right parietal lobe dysfunction (Facoetti & Molteni, 2001; Hari, Renvall, & Tanskanen, 2001). This would imply that letter positions left of fixation receive less attention than positions right of fixation and this would exaggerate the disadvantage of the left compared to the right visual field which is commonly observed in orthographies which are read from left to right (e.g., Ellis, 2004). There is a direct linkage between the left mini-neglect hypothesis and the string processing account of Whitney and Cornelissen (2005) who propose that a left mini-neglect would be specifically damaging for the set-up of the string processing mechanism.

2. Method

2.1. Participants

The dyslexic readers of the present study (all German speaking adults) were recruited via posters asking for persons who had experienced reading and spelling difficulties during their school career. All of the 12 participants (8 males, 4 females) were either university students or had mastered the exam for university admission. Selecting high achieving dyslexics minimizes the risk of including individuals with another comorbid disorder such as ADHD. Inclusion of dyslexic participant with comorbid ADHD would be problematic as our task requires high vigilance and sustained attention. Inclusion criterion for the dyslexic reading group was a low performance (corresponding to a percentile of below 16) on a standardized sentence reading test for adults for which norms are currently sampled. This test requires the marking of 51 sentences of simple content as correct or incorrect within a time limit of 1 min. Two parallel versions of the test were administered and the measure for inclusion was the mean number of correctly marked sentences. Furthermore, six subtests of the German Version (Tewes, 1991) of the Wechsler Adult Intelligence Scale (WAIS-R) were administered (Vocabulary, Similarities, Digit Span, Digit Symbol, Block Design, and Object Assembly). All participants had normal or corrected to normal vision and with the exception of one all showed clear right hand preference by performing at least 8 of 9 pantomimic activities (e.g., teeth brushing) with the right hand. Fourteen normal readers (9 males, 5 females) in the age range of the dyslexic readers served as controls.

As evident from Table 1 the dyslexic group exhibited much lower scores on the sentence reading test than the fluent readers. The lower scores are caused by slow reading since the average number of wrong markings was below 0.2 sentences for both groups. The mean sentence reading score of the poor readers corresponds to percentile 12 compared to the preliminary norm sample of 300 students, whereas the mean of the fluent readers corresponds to percentile 75. The bottom section of Table 1 gives the mean Scale scores on the six subtests of the WAIS-R which have to be related to the norm average of 10 and a standard deviation of 3. Obviously, the dyslexic readers exhibited means above or at

Table 1
Means and standard deviations of the normal and dyslexic readers of the defining and descriptive measures

	Normal readers[a] $M(SD)$	Dyslexic readers[b] $M(SD)$	$t(24)$
Age (years) sentence reading (N/min)	25.32 (3.09)	15.46 (2.15)	−9.26**
WAIS-R			
Vocabulary	14.71 (2.49)	13.17 (1.75)	−1.80
Similarities	13.29 (1.86)	13.67 (1.61)	0.55
Digit span	12.50 (2.77)	8.67 (3.03)	−3.37*
Object assembly	13.71 (3.00)	12.08 (2.47)	−1.50
Block design	13.50 (2.50)	11.75 (3.44)	−1.50
Digit-symbol	13.14 (2.48)	10.92 (3.48)	−1.90

[a] $n = 14$.
[b] $n = 12$.
* $p < .01$.
** $p < .001$.

the norm average on all subtests with the exception of the Digit Span subtest which is known to lead to low performance in dyslexic persons (e.g., Paulesu et al., 2001).

2.2. String processing

The string processing task was conducted in a windowless room dimly illuminated by a single ceiling light. Participants sat at 75 cm distance in front of a 17 in. CRT-Computer monitor (refresh rate: 100 Hz), interfaced with a Windows PC. The task was driven by the Presentation software (Version 0.81) of Neurobehavioral Systems. The stimulus presentation was locked to the refresh rate of the computer monitor providing stimulus timing with milliseconds accuracy.

The setup of the string processing task is schematically shown in Fig. 1. Five equally spaced gray boxes, which indicated the positions of the forthcoming stimulus elements, were permanently presented at the center of the monitor. Before stimulus presentation a red fixation cross was displayed for 300 ms centered above the position boxes and participants were repeatedly prompted to keep their eyes on it. Stimulus strings—either five digits or five consonant letters—were presented 100 ms after the offset of the fixation cross. Immediately after presentation, the string was masked and one of the gray boxes turned into blue to cue the to-be-reported element. Digits ranged from 1 to 5 and were typed in Times New Roman. For the letter condition, visually dissimilar letters (r, v, s, n, and z)—typed in Courier New—were chosen. An element could only occur once in a string. The digit and letter strings were equal in width which corresponded to 2.5° of visual angle. We used lower case letters as they are more frequently encountered in reading. Thus, the letter strings and the digit strings slightly differed in height which was 0.3° and 0.23° of visual angle for digit and letter strings, respectively. The digit and letter strings were presented block-wise in counterbalanced order and within each block the stimuli were randomized for each participant. The string positions were randomly cued, but a position was never cued more than twice in immediate succession.

Threshold estimation used a 1-step up/1-step down staircase procedure, that is, the presentation time of the strings was adaptively varied dependent on the participant's response on the previous trial. The initial presentation time of the digit and the letter strings was 1000 ms. After a correct response the presentation time of the next stimulus string was decreased by 10% and after an incorrect response it was increased by 10%. The staircase procedure was applied to each single string position separately, that is, the correct or incorrect response to a position cue altered only the presentation time of a string with the same position cue. Thus, for each string position an individual threshold could be estimated. The staircase for a specific position was terminated after the 10th reversal and the arithmetic mean of the final 8 reversals was taken as threshold. This value was also used for further string presentations which cued a position for which the staircase procedure was already completed. To prevent that participants recognize that correct responses result in shorter presentation times, trials with fixed presentation times of 750 or 250 ms were included. The frequency of such trials was one in six. Two rest periods interrupted the lengthy threshold estimation procedure. On average, 217 letter strings and 227 digit strings had to be presented. Participants were familiarized with the procedure by 30 letter and 30 digit

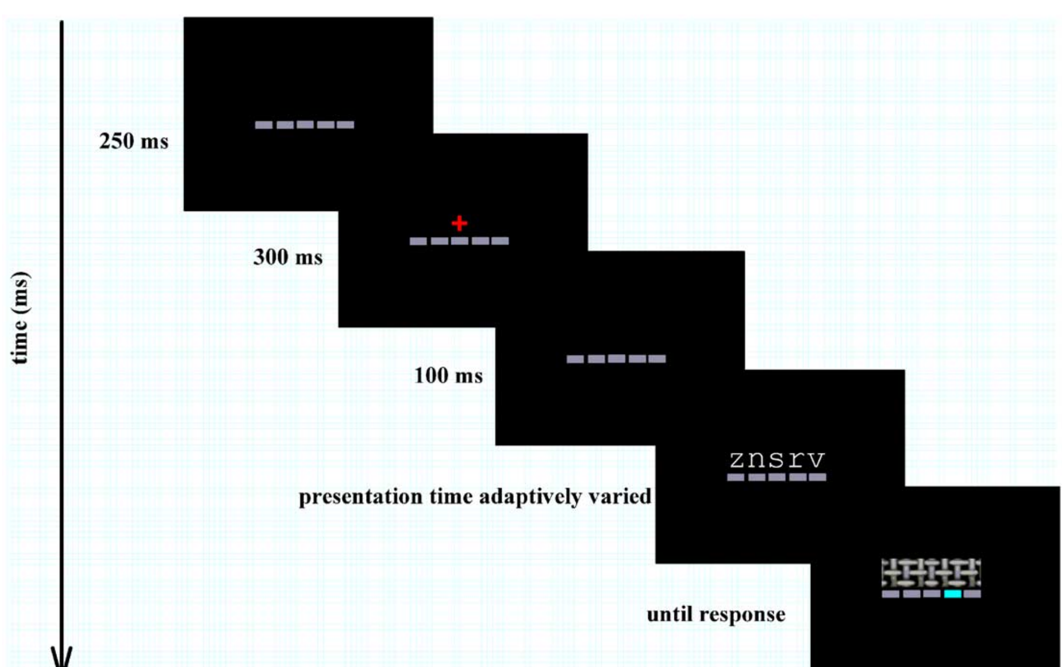

Fig. 1. Schematic illustration of the set-up of the string processing task.

strings for which presentation times ranged from 750 to 250 ms and for which auditory feedback was provided. In case of more than 50% errors the familiarization procedure was repeated.

3. Results

Two dyslexic participants had to be excluded as they did not exhibit an advantage for the mid-position which was marked by the preceding fixation cross, but very low threshold for at least one end position in the letter string condition. Apparently, these participants did not conform to instruction and fixated an end position rather than the middle position. Inclusion of these dyslexic readers would lead to an over-estimation of the ends-effect in the dyslexic reading group. One further participant in the dyslexic group also did not exhibit a clear mid position advantage in the letter condition, but similar thresholds for all positions. Fig. 2 (top section) shows the individual presentation time threshold profiles and the mid section shows the central tendency measures for each group.

As evident from the individual profiles in the top section of Fig. 2, a substantial number of dyslexic readers needed enormously long presentation times for at least some positions to achieve reliable recognition. Only three dyslexics exhibited low threshold profiles for the digit strings in the sense that for each position the threshold was within the range of the thresholds of the normal readers. For the letter strings, only two dyslexic readers performed within the range of the controls. Because of the large variance in the dyslexic reader group, a first analysis relied on the nonparametric Mann–Whitney U test and found the group difference reliable for each position of both the digit and the letter strings, all $Z\text{s} > 2.00$, all $p\text{s} < .05$, one-sided. Of main importance is that the majority of the dyslexic individuals exhibited similar profiles as the controls although at much higher levels. This profile similarity is also obvious form the group profiles in the mid section of Fig. 2: for the letter strings a clear M-shape is evident with lower thresholds for the first and final position (i.e., the ends-effect) and for the fixated middle position. For the digit strings there were markedly reduced thresholds for the first and the middle position.

Group differences in the size of the ends- and visual hemifield-effect were examined in separate ANOVAs for letter- and digit-strings. The within-subject factors were end vs. inner positions (i.e., 1 and 5 vs. 2 and 4) and left vs. right visual field (i.e., positions 1 and 2 vs. 4 and 5). For the digit strings neither the ends-effect, $F(1,22) = 2.72$, $p = .13$, nor the hemifield-effect, nor the interaction between these two factors was reliable, both $F\text{s} < 1$. Most importantly, neither the two-way nor the three-way interaction involving group was reliable, all $F\text{s} < 1$. For the letter strings—different from the digit strings—both the ends- and hemifield-effect were reliable, both $F\text{s}(1,22) > 14.75$, $p\text{s} < .01$, but the interaction between these factors was not, $F < 1$. Similar to the digit strings, none of the interactions with group was reliable, all $F\text{s}(1,22) < 2.45$, $p\text{s} > .13$. As evident from Fig. 2 (mid section) the size of the ends advantage tended to be larger for the dyslexic readers than for the controls with means of 224 and 122 ms, respectively. This is the opposite of the expectation—explicated in the Introduction—that dyslexic readers should exhibit an absent or diminished ends-effect. In correspondence with the expectation from the left mini-neglect hypothesis, the size of the left hemifield disadvantage was larger for the dyslexics than for the controls: means 170 and 72 ms, respectively. However, these tendencies towards larger ends- and hemifield-effect for the dyslexic readers have to be put into perspective as the dyslexic readers generally exhibited much higher thresholds and much larger variances. To remove the influence of the high individual dyslexic thresholds on the effects of interest we used a transformation procedure which was recommended by Faust, Balota, Spieler, and Ferraro (1999) and which in our case amounts to: individual z-scores for each position are obtained by taking the individual position threshold subtracting the mean threshold of all five positions and dividing by the standard deviation of the five position thresholds for each participant separately. This transformation abolishes the group difference and equalizes the standard deviations of the groups and, therefore, in our case allows an unbiased examination of group specific differences of the ends- and the hemifield-effect. As evident from the bottom section of Fig. 2, with the transformed thresholds the profiles of the two groups are close to identical for the letter strings. For the digit strings there is a tendency towards a more pronounced left hemifield disadvantage. However, separate ANOVAs using these transformed scores for digit and letter strings confirmed the original findings with the untransformed thresholds as none of interactions involving group was reliable, all $F\text{s} < 1$.

4. Discussion

Our approach to study string processing by using threshold estimation for each separate string position gave results similar to the target detection time method of Mason (1982). Similar to Mason, we found a clearly M-shaped position profile for strings consisting of five letters and a less pronounced M-profile for digit strings. The theorizing of Whitney (2001) provides a detailed account how the M-profile for letters comes about.

The present findings strengthen our previous finding (Hawelka & Wimmer, 2005) of a string processing deficit in German dyslexic readers. The present participants—different from our previous study—were adults with high educational achievement. Surprisingly, their string processing deficit seemed to be more serious than the one observed in the previous study. On the string processing task the adolescent dyslexic sample tested by Hawelka and Wimmer (2005) had a mean presentation time threshold of 153 ms for strings of 6 digits (controls: 103 ms). The present adult dyslexic sample exhibited a mean threshold of 235 ms for strings of only 5 digits

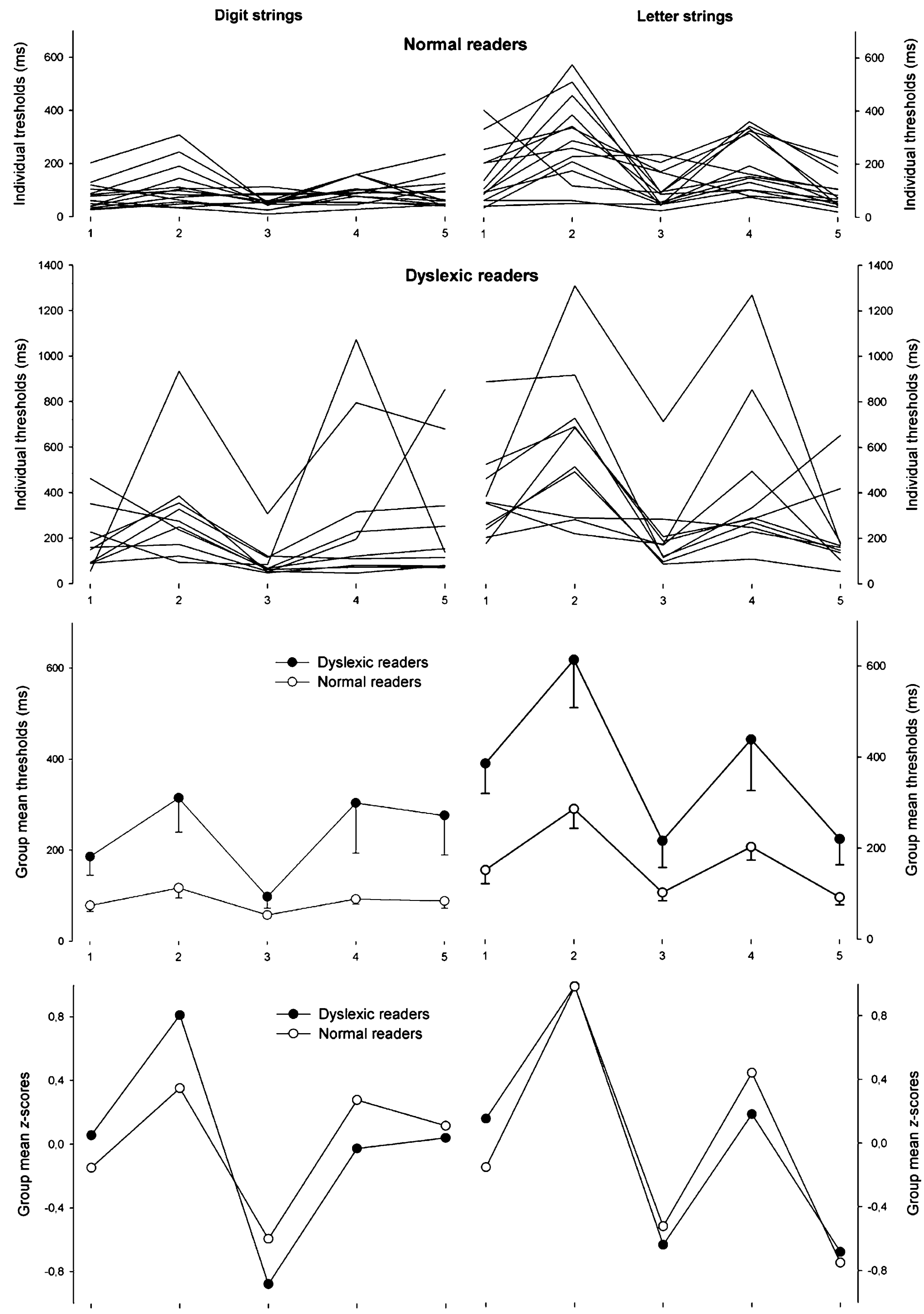

Fig. 2. Top section: individual threshold profiles of the normal and dyslexic readers over position 1–5 in the digit and letter string processing task. Mid section: mean group thresholds for digit and letter strings. Error bars show the standard error of the mean. Bottom section: mean z-scores of the groups. (See text for details.)

(controls: 109). This difference for digit strings was substantially enhanced for letter strings where the dyslexic exhibited a mean threshold of 375 ms (controls: 167 ms). This general and massive string processing deficit speaks against the hypothesis that the slow reading of the dyslexic participants solely results from a failure to store or to use visual orthographic recognition units for frequently encountered words.

The main new finding of the present study is that despite substantially enhanced presentation time thresholds our adult dyslexic readers exhibited position profiles which were rather similar to those of the normally reading controls. Specifically, for the letter strings the dyslexic readers—similar to the controls—exhibited a marked advantage for the first and final position and they also exhibited the same visual field asymmetry as the controls, that is, a marked right visual field advantage. The advantage of the end positions speaks against the possibility that dyslexic readers suffer from a narrowed visual attentional window which may include only the fixated middle position and the adjacent positions. The end position advantage also speaks against the hypothesis of Whitney and Cornelissen (2005) that dyslexic readers lack the specific string processing system which in competent readers generates the end position advantage by overriding the visual acuity gradient. The similar size of the visual field asymmetry in both groups speaks against the hypothesis of a left mini-neglect in dyslexia. This finding is in correspondence with our previous study (Hawelka & Wimmer, 2005) where the dyslexic participants exhibited equal performance as the controls on a precedence detection task which required judging which of two bars—one presented in the left and one in the right visual field—preceded the other.

However, the present findings cannot be taken as the final verdict on the mentioned deficit hypotheses as they are limited by the specifics of the present study. Possibly, our adult dyslexic participants may indeed suffer from a narrowed visual attentional window, but the five elements of the present strings may still fall within its width. However, the massively enhanced presentation time thresholds of the dyslexic readers indicate that the present five element strings were not easy at all for our dyslexic participants. As noted by one of our reviewers (S. Valdois), the present negative conclusion hold only for a simple version of the narrowed visual attentional window hypothesis which assumes a single window. If more than one window is allowed, then attention could be directed to both the first and the final position of the string. However, in the theorizing of Valdois et al. (2004) the visual attentional window is recruited only in the analytic reading mode which becomes active when the global reading mode (i.e., whole word recognition) failed. In the analytic reading mode words are read by shifting the window from left to right over the word with small units (typically a syllable) being attended sequentially (Ans, Carbonnel, & Valdois, 1998). A split window which during analytic word decoding attends to the first and final letter does not fit in this conception.

The present findings obviously apply only to nameable visual stimuli, while the left mini-neglect hypothesis applies to visual stimuli more generally. It certainly would be interesting to examine dyslexic deficits for strings consisting of nameable vs. non-nameable stimuli. A deficit in processing strings of non-nameable symbols of dyslexic children was recently found by Pammer, Lavis, Hansen, and Cornelissen (2004). The phonological deficit explanation of dyslexia would have predicted that the dyslexic deficit should be limited to nameable stimuli. A further limitation of our study is that the present string processing task led to unexpectedly high position thresholds in some of the dyslexic readers, which may have allowed dyslexic readers to execute eye movements during string presentation. This may mask existing visual attentional deficits.

Acknowledgments

We gratefully acknowledge the helpful comments of Carol Whitney and Sylviane Valdois. The research reported here was supported by the Austrian Science Foundation (Grant No. P14494-SPR).

References

Ans, B., Carbonnel, S., & Valdois, S. (1998). A connectionist multi-trace memory model of polysyllabic word reading. *Psychological Review, 105*, 413–425.

Coltheart, M., Rastle, K., Perry, C., Langdon, R., & Ziegler, J. (2001). DRC: A dual route cascaded model of visual word recognition and reading aloud. *Psychological Review, 108*(1), 204–256.

De Luca, M., Di Pace, E., Judica, A., Spinelli, D., & Zoccolotti, P. (1999). Eye movement patterns in linguistic and non-linguistic tasks in developmental surface dyslexia. *Neuropsychologia, 37*, 1407–1420.

Ellis, A. W. (2004). Length, formats, neighbours, hemispheres, ant the processing of words presented laterally or at fixation. *Brain and Language, 88*, 355–366.

Facoetti, A., & Molteni, M. (2001). The gradient of visual attention in developmental dyselxia. *Neuropsychologia, 39*, 352–357.

Faust, M. E., Balota, D. A., Spieler, D. H., & Ferraro, F. R. (1999). Individual differences in information-processing rate and amount: Implications for group differences in response latency. *Psychological Bulletin, 125*, 777–799.

Hari, R., Renvall, H., & Tanskanen, T. (2001). Left minineglect in dyslexic adults. *Brain, 124*, 1373–1380.

Hawelka, S., & Wimmer, H. (2005). Impaired visual processing of multi-element arrays is associated with increased number of eye movements in dyslexic reading. *Vision Research, 45*, 855–863.

Hutzler, F., & Wimmer, H. (2004). Eye movements of dyslexic children when reading in a regular orthography. *Brain and Language, 89*, 235–242.

Landerl, K., Wimmer, H., & Frith, U. (1997). The impact of orthographic consistency on dyslexia: A German-English comparison. *Cognition, 63*, 315–334.

Mason, M. (1982). Recognition time for letters and nonletters: Effects of serial position, array size, and processing order. *Journal of Experimental Psychology: Human Perception and Performance, 8*, 724–738.

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

Paulesu, E., Demonet, J. F., Fazio, F., McCrory, E., Chanoine, V., Brunswick, N., Cappa, S. F., Cossu, G., Habib, M., Frith, C. D., & Frith, U. (2001). Dyslexia: Cultural diversity and biological unity. *Science, 291*, 2165–2167.

Shaywitz, S. E., & Shaywitz, B. A. (2005). Dyslexia (Specific reading disability). *Biological Psychiatry*, 1301–1309.

Tewes, U. (1991). *Hamburger-Wechsler Intelligenztest für Erwachsene Revision* (2nd ed.). Bern: Huber.

Valdois, S., Bosse, M. L., & Tainturier, M. J. (2004). The cognitive deficits responsible for developmental dyslexia: Review of evidence for a selective visual attentional disorder. *Dyslexia, 10*, 339–363.

Wimmer, H., & Mayringer, H. (2002). Dysfluent reading in the absence of spelling difficulties: A specific disability in regular orthographies. *Journal of Educational Psychology, 94*, 272–277.

Whitney, C. (2001). How the brain encodes the order of letters in a printed word. The SERIOL model and selective literature review. *Psychonomic Bulletin & Review, 8*, 221–243.

Whitney, C., & Cornelissen, P. L. (2005). Letter-position encoding and dyslexia. *Journal of Research in Reading, 28*, 274–301.

Ziegler, J. C., Perry, C., Ma-Wyatt, A., Ladner, D., & Schulte-Körne, G. (2003). Developmental dyslexia in different languages: Language-specific or universal? *Journal of Experimental Child Psychology, 86*, 169–193.