Available online at www.sciencedirect.com
SCIENCE DIRECT®
Vision Research 45 (2005) 855–863
Vision Research
www.elsevier.com/locate/visres

Impaired visual processing of multi-element arrays is associated with increased number of eye movements in dyslexic reading

Stefan Hawelka, Heinz Wimmer *

Department of Psychology and Center of Neurocognitive Research, University of Salzburg, Hellbrunnstr. 34, Salzburg, Austria

Received 20 July 2004; received in revised form 5 October 2004

Abstract

For assessing simultaneous visual processing in dyslexic and normal readers a multi-element processing task was used which required the report of a single digit of briefly presented multi-digit arrays. Dyslexic readers exhibited higher recognition thresholds on 4- and 6-digit, but not on 2-digit arrays. Individual recognition thresholds on the multi-digit arrays were associated with number of eye movements during reading. The dyslexic multi-element processing deficit was not accompanied by deficient coherent motion detection or deficient visual precedence detection and was independent from deficits in phonological awareness and rapid naming. However, only about half of the dyslexic readers exhibited a multi-element processing deficit.
© 2004 Elsevier Ltd. All rights reserved.

Keywords: Developmental dyslexia; Multi-element arrays; Reading rate

1. Introduction

Developmental dyslexia is a learning disorder which hampers the development of age-appropriate reading despite conventional instruction, adequate intelligence and the absence of gross neurological pathology. It is assumed to be genetically mediated and affects between 5% and 10% of the population (Shaywitz, 1998). The dominant cognitive explanation links the difficulties in learning to read to preceding difficulties in language acquisition and specifically to a phonological deficit (e.g., Vellutino, Fletcher, Snowling, & Scanlon, 2004). The standard version of this explanation postulates deficient awareness for the phonemic segments of spoken words which limits the mapping of letters onto phonemes and, thereby, hinders the self-reliant decoding of new words and the efficient storage of the letter patterns of frequently encountered words. However, recently visual and visual-attentional deficits of dyslexic children were put forward as alternative explanation (Hari & Renvall, 2001; Stein & Walsh, 1997). These alternative accounts are of particular interest for explaining reading difficulties in regular orthographies such as Italian or German, where the mapping of letters onto phonemes is easier than in English, and where the acquisition of decoding is less of a hurdle. In such orthographies the problem of dyslexic readers does not become manifest as a sheer inability to read a new word or as gross misreadings, but as very slow, effortful, non-automatic reading (e.g., Landerl, Wimmer, & Frith, 1997; Wimmer, 1993). A recent demonstration of this reading problem was provided by Ziegler, Perry, Ma-Wyatt, Ladner, and Schulte-Körne (2003) who found for dyslexic German children (11-year-olds) a reading onset latency increase of more than 300 ms per additional letter for both short words and pseudowords (3–6 letters long), whereas the reading time of normal readers increased only 30–50 ms per additional letter. Ziegler et al. (2003) interpreted this finding as a limitation to serial grapheme–phoneme conversion.

* Corresponding author.
E-mail addresses: stefan.hawelka@sbg.ac.at (S. Hawelka), heinz.wimmer@sbg.ac.at (H. Wimmer).

0042-6989/$ - see front matter © 2004 Elsevier Ltd. All rights reserved.
doi:10.1016/j.visres.2004.10.007

The most direct demonstration of the serial reading strategy of developmental dyslexic children in regular orthographies comes from a series of eye movement studies of an Italian research group (De Luca, Borelli, Judica, Spinelli, & Zoccolotti, 2002; De Luca, Di Pace, Judica, Spinelli, & Zoccolotti, 1999; Zoccolotti et al., 1999). These studies documented for dyslexic children a substantially higher number of fixations during reading compared to normal readers. The high number of fixations is primarily caused by short eye movements in the reading direction since the proportion of regressions made by the dyslexic readers was low. A similar pattern was found for German dyslexic children (Hutzler & Wimmer, 2004).

These reading difficulties of dyslexic children in consistent orthographies resemble the difficulties shown by cases of an acquired disorder known as letter-by-letter reading (e.g., Behrmann, Shomstein, Black, & Barton, 2001). After brain insult, formerly normal readers lose their ability to process words as a whole and are forced to rely on a slow and laborious serial letter-by-letter decoding strategy during reading. This reading strategy leads to a massive word length effect on reading time and is dominantly interpreted as reflecting a general difficulty to perceive multiple visual forms simultaneously (Farah & Wallace, 1991). The demonstration of the difficulty with the simultaneous perception of multiple visual forms in letter-by-letter readers typically relied on variants of the partial report method of Averbach and Sperling (1968) which requires reporting only a single element of briefly represented multi-element arrays in response to a post-stimulus cue. In a study with letter-by-letter readers, Kinsbourne and Warrington (1962) showed that the tachistoscopic recognition thresholds were normal when a single form had to be identified, but dramatically impaired when identification of more than one form was required. This result was also found for non-nameable visual forms (Friedman & Alexander, 1984). This and several other findings led to the conclusion that the locus of impairment in cases of letter-by-letter readers is in the early stages of visual processing (for review see Farah & Wallace, 1991).

In the field of developmental dyslexia, this visual interpretation has received little attention. An early study by Morrison, Giordani, and Nagy (1977) presented eight elements—letters, geometric and abstract forms—in a circular array for 150 ms and cued the position of the to-be-reported element at varying time intervals (0–2000 ms). A dyslexic deficit was found, but only when the cue was delayed for about 750 ms and not when the cue was presented after 300 ms or less. This evidence for unimpaired multi-element processing when the cue followed shortly after array presentation can be questioned since no mask was used. A systematic study by Enns, Bryson, and Roes (1995) avoided this interpretational problem, but nevertheless arrived at a similar conclusion. In this study the stimulus arrays—strings of 1–5 letters in length—were masked after being presented for 150 ms. When the cue—a probe letter—was presented simultaneously with the array and participants had to indicate whether the probe was present in the array (identification task), disabled readers (15-year-olds) did not differ from age controls. However, when participants had to indicate the position of the probe letter (location task) then the dyslexic readers showed impaired performance for the longer 4- and 5-letter stimuli. This finding is relevant, as in reading both the identities and the position of the letters of a word are of crucial importance. Recently, a deficit of dyslexic readers with position encoding was shown by Pammer, Lavis, Hansen, and Cornelissen (2004).

1.1. The present study

The studies by Morrison et al. (1977) and Enns et al. (1995) were done with English dyslexic readers. We reasoned that a visual deficit with multi-element processing may become more readily apparent for German dyslexic readers who—different from their English counterparts—are diagnosed via slow reading speed and not by a high error rate. We attempted to provide direct evidence for a serial reading strategy of our dyslexic participants by examining their eye movements during word and pseudoword reading. The main question was, whether slow serial reading is associated with a general visual perceptual deficit for multi-element arrays. Multi-element processing was measured in a stringent and sensitive manner. In correspondence with the original partial report method (Averbach & Sperling, 1968), one position of multi-element arrays was cued for report, so that correct performance depends on both identity and position encoding. The cue was presented immediately after array presentation to avoid memory problems. However, masking of the stimulus prevented that correct performance could be based on processing the after-image of the stimulus. We chose digits instead of letters as elements of the arrays as one could reason that dyslexic readers are less frequently exposed to letter string processing than normal readers. The main new feature of the present task is that, instead of a fixed presentation time, an adaptive staircase procedure was applied to determine individual presentation time thresholds for reliable performance. Thresholds were estimated for arrays of varying lengths (2-, 4-, and 6-digit arrays). If dyslexic readers suffer from deficient multi-element processing then—corresponding to the findings with letter-by-letter readers—the increased number of elements should have a stronger effect on presentation time thresholds for dyslexic readers than controls.

Although the focus of the present study is on multi-element processing, we also report the findings of a visual precedence detection task, which presented two horizontally arranged bars (one to the left and one to the right of a centered fixation cross) one after the other with varying inter-stimulus intervals (ISIs). Participants had to detect which bar preceded. Again a threshold was applied to estimate the critical ISI independently for the right and left visual hemifield. The task serves as a control for a dyslexic deficit in the rapid employment of visual attention. Such a deficit was proposed by Hari and Renvall (2001) and was interpreted as resulting from a dysfunction of the right parietal lobe. The behavioral symptom of the deficit would be a left mini-neglect, that is, a disadvantage of visual stimuli in the left visual hemifield. In our version of the precedence detection task, this would result in higher thresholds for detecting the precedence of stimuli presented to the left side of the fixation cross. One could speculate that a problem with visual spatial attention would affect performance on the multi-element processing task.

Furthermore, since our participants were recruited from a longitudinal study, we were able to explore how a potential deficit in multi-element processing of dyslexic readers is related to results of preceding assessments which included phonological awareness measures, rapid naming and coherent motion detection. The results of the preceding assessments for the present participants were reported in Kronbichler, Hutzler, and Wimmer (2002). As already noted, a deficit in phonological awareness is postulated by the phonological deficit explanation of dyslexia (e.g., Vellutino et al., 2004) and a recent extension of the phonological explanation postulated an additional deficit in rapid naming (Wolf & Bowers, 1999). The coherent motion detection task serves as an assessment of a potential dyslexic deficit in the sensitivity of the magnocellular visual pathway which was proposed as an alternative account of the causation of developmental dyslexia (e.g., Stein & Walsh, 1997).

2. Material and methods

2.1. Subjects

The dyslexic readers and controls (15 in each group) of the present study were recruited from a longitudinal study with altogether 530 boys who were first tested at the age of six, shortly after they started school (Wimmer, Mayringer, & Landerl, 2000). At the time of the present study they were in Grade 9. All participants were native German-speakers with normal or corrected to normal vision. Participants and their parents gave written informed consent.

The selection of the present participants is based on an assessment in Grade 7, two years before the present one by Kronbichler et al. (2002). At that time, for being included in the dyslexic group, participants had to score below percentile 10 on both a standardized reading speed test (Auer, Gruber, Mayringer, & Wimmer, in press) and on a standardized but unpublished spelling test developed in our laboratory. The control group consists of boys who had reading and spelling scores above percentile 20. The reading speed test required the participants to mark sentences of simple content as correct or incorrect and the measure was the number of correctly marked sentences within a time limit of 3 min. The spelling test required the participants to write 29 complex words to dictation. Exclusion criteria were left-handedness and low non-verbal intelligence (<85). The non-verbal IQ was assessed at the end of Grade 1 and is based on three scales (spatial sequences, spatial integration, and spatial concepts) of the Primary Test of Cognitive Skills (Huttenlocher & Cohen-Levine, 1990).

Table 1 gives the means and standard deviation of the dyslexic and control readers on the descriptive and defining measures and the *t*-values for the group comparisons. As evident from Table 1, the means of the dyslexic group for number of correctly judged sentences and for percentage of correct spellings were much lower than those of the controls, and both measures correspond to the fifth percentile compared to the norm sample which consisted of 200 students of the same grade. The means of the controls correspond to percentiles around 60. The low dyslexic performance on the sentence reading test is due to slow reading as the mean of wrong judgements of the dyslexic group was only 0.5 sentences.

To further characterize the reading rate deficit of the dyslexic group, Table 1 also gives current reading rate measures for lists of words and pseudowords (items read per minute). These measures were derived from the reading aloud tasks used for the eye movement recording (see below). The means show that the reading rate of the dyslexic readers for both word and pseudoword reading was only about half the rate of the controls. The error rates were low even for the dyslexic readers with 4% and 8% for word and pseudoword reading, respectively. It is also evident from Table 1 that the

Table 1
Means and standard deviations of the dyslexic and control group for defining and descriptive measures

	Dyslexics[a]	Controls[a]	t[b]
	M (SD)	*M* (SD)	
Sentence reading (*N*/3 min)	25.1 (4.9)	44.1 (6.4)	-9.10^{***}
Spelling (% correct)	31.7 (14.9)	84.6 (8.0)	-12.08^{***}
Age (years:months)	15:11 (0:9)	15:3 (0:6)	2.72^{*}
Non-verbal IQ	104.4 (12.1)	106.2 (13.5)	−0.37
Reading aloud (items/min)			
Words	49.7 (16.5)	92.3 (11.0)	-8.31^{***}
Pseudowords	36.0 (12.0)	67.3 (6.8)	-8.77^{***}

[a] $n = 15$; [b] df = 28; * $p < .05$; *** $p < .001$.

dyslexic participants did not differ in non-verbal IQ, but were slightly older than the controls.

2.2. Eye movement recording

Eye movements were recorded during a word and a pseudoword reading task. The reading material was presented on a 17 in. CRT-Computer monitor, interfaced with a Windows PC. An additional Windows PC was connected with an infrared video-based EYELINK eye-tracker manufactured by SR Research (Canada). A sampling rate of 250 Hz was used. Calibration was conducted prior to the reading tasks and required the participants to track the position of a dot which was presented at nine different locations on the computer screen. For eye movement recording we used the eye for which calibration was more accurate. After calibration, lists of words and pseudowords (three screens each) were presented after a short instruction trial for both the word and pseudoword lists, respectively. Participants were instructed to read each screen aloud as quickly and accurately as possible. A screen consisted of six or seven lines with six items per line. The words were all bisyllabic and varied in length between 5 and 7 letters. The pseudowords were created by interchanging the syllables of the words from the word lists (e.g., the pseudoword *Parbiet* was created from the words *Partei* and *Gebiet*). For determining the number of saccades per screen, the first and the last item of each line were disregarded to exclude effects of the line sweep. This left 80 word and pseudoword items for analysis. The algorithm implemented in the system defines saccades via velocity and acceleration of eye movements and detects saccades from 0.30 degrees of visual angle upwards. Only horizontal saccades were used of analysis. From a viewing distance of 75 cm, a single letter of the reading material extended horizontally approximately over 0.35°, thus, the longest 7-letter words had a width of approximately 2.45°. Additionally to the eye movement recording, reading rate measures for words and pseudowords were derived from the time measurements for each screen and are expressed in items read per minute. Furthermore, reading errors were noted by the experimenter.

2.3. Multi-element processing

Participants sat at 75 cm distance in front of the same monitor (refresh rate: 100 Hz) as used for the eye movement recording. The experiment was driven by the Presentation® software Version 0.71 of Neurobehavioral Systems. The software locks stimulus presentation to the refresh rate of the computer screen. The setup of the task is schematically shown in Fig. 1.

The digit arrays varied in length and consisted of 2, 4 and 6 elements (height: 1.2°, width: 1.2°, 2.3°, and 3.5°,

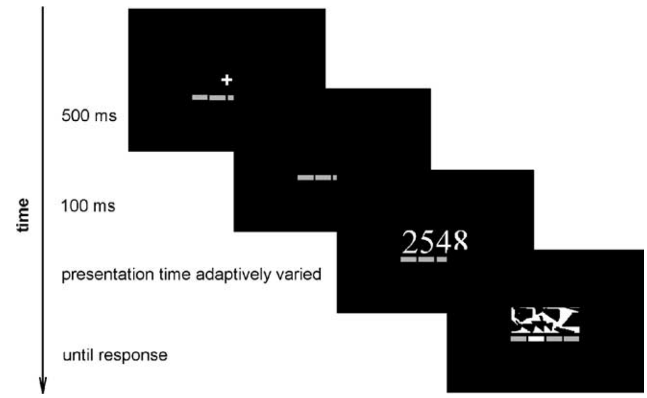

Fig. 1. Schematic illustration of the sequence of events of the multi-element processing task. In the original setup, the fixation cross was blue and the position cue was green. See text for details.

respectively). The items of the same length were presented block-wise, with the 2-digit arrays first and the 6-digit arrays last, because in a pilot study with this task, participants found it easier to start with the shorter arrays. During presentation of the items, the digit positions were continuously displayed on the screen as small grey boxes above which the digits appeared. Stimulus presentation was preceded by a blue fixation cross and a 4000 Hz warning tone. Digits between 0 and 9 were used and the sequence within an item was randomized, but the same digit could not appear in adjacent positions. Immediately after stimulus offset, the string was masked. Simultaneously with the mask, one position was cued by changing the color of the position box from grey to green. Participants had to respond by naming the cued digit. The response was typed into the keyboard and an auditory feedback was generated. Participants were prompted to guess when uncertain.

Presentation time thresholds were estimated by a simple 1-up/1-down staircase procedure. The first array of each length level was presented for 200 ms. For the first five trials, the presentation time was decreased by 30 ms after a correct and increased by only 10 ms after an incorrect response. This rule for the initial items has the effect that presentation time relevant for threshold estimation was quickly reached. Thereafter, the response-dependent shortening and prolongation of stimulus presentation time was 10 ms. The threshold for a string length condition was defined as the arithmetic mean of the last 8 from a total of 12 reversals. Since the probability of guessing the digit at the cued position is low (about 1 out of 10), the threshold corresponds to the mean presentation time at which the digits of a certain string length are reliably identified.

2.4. Precedence detection

The precedence detection task was modeled after Robertson, Mattingley, Rorden, and Driver (1998) and presented two white bars on a dark background symmetrically to the left and the right side of a centered fixation cross. One of the bars preceded the other at varying ISIs, and the participant had to indicate which bar appeared first by a button press on a Microsoft Sidewinder Game-pad with the corresponding index finger. Again, the ISIs were adaptively adjusted by a simple 1-up/1-down staircase procedure which was terminated after the 10th reversal and the arithmetic mean of the final eight reversals was taken as the threshold. For assessing differences in the sensitivity of the visual hemifields two independent thresholds were estimated for left and right precedence detection, respectively. In contrast to the threshold of the multi-element processing task, the threshold for this two-alternative forced-choice task indicates the mean presentation time at which performance is at chance level.

2.5. Previous assessments

For the assessment of a magnocellular deficit—carried out two years before the present one by Kronbichler et al. (2002)—the coherent motion detection task of Hansen, Stein, Orde, Winter, and Talcott (2001) was used. The task presented two panels of dot kinematograms on a computer screen which contained randomly arranged white dots on a dark background. A certain proportion of the dots of one panel moved coherently in the same direction, whereas the dots of the other panel moved randomly. Participants had to point to the panel with the coherently moving dots. The proportion of coherently moving dots was varied and a 1-up/1-down staircase procedure was used for determining the proportion at which performance was at chance level. The threshold was defined as the geometric mean of the last 8 of a total of 10 reversals. Two trials were conducted and the arithmetic mean of the two thresholds was used as measure. See Kronbichler et al. (2002) for detailed description.

The verbal-phonological assessment at school entrance included the following tasks: A pseudoword repetition task (15 items) required immediate repetition of orally presented pseudowords, which all consisted of three confusable syllables (e.g. /liruli/). The rhyme detection task (15 items) required matching a given word with the rhyming one of two alternative words which differed by one phoneme only (e.g. "What rhymes with cat: fit or fat?"). In the pluralization task (15 items) children had to say the irregular plural form of a singular noun (e.g. Experimenter: "One mouse."—Child: "Two mice."). The rapid naming task, modelled after Denckla and Rudel (1976), consisted of two trials which required rapid naming of sequences of five different object pictures, each presented four times in random order. Naming speed is expressed in syllables per minute. For a more detailed description of the tasks see Wimmer et al. (2000).

3. Results

Means and standard deviations for all measures are shown in Table 2. In addition, the magnitude of the group difference is given as z-score measure, which is computed by dividing the difference between the group means by the standard deviation of the control group. A negative z indicates lower performance of the dyslexic group with a z of -1.0 implying that the mean dyslexic performance is 1 SD worse than the control mean. The final column presents the results of the t-test group comparisons.

The first section of Table 2 shows that—as expected—dyslexic readers exhibited more eye movements per item than controls. Group differences of similar size were found for word and pseudoword reading. Whereas the controls exhibited only slightly more than a single eye movement per item, the dyslexic readers exhibited more than two. The large majority of the saccades of both groups were rightward moving as evident from the low percentages of regressions. The percentage of regressive saccades was significantly higher for dyslexic than normal readers, but still rather small. The group difference in the number of eye movements remained large and reliable, when regressive saccades were excluded, $t(28) = 4.69$, $p < .001$ and $t(28) = 4.09$, $p < .001$ for words and pseudowords, respectively.

Of main importance are the group differences in the multi-element processing task shown in the second section of Table 2. Individual scores of the participants and the group means are presented in Fig. 2. Obviously, there was no group difference for the 2-digit arrays, but as expected, the increase in presentation time threshold with increasing number of elements was larger for dyslexics than controls. To illustrate, for dyslexics the threshold for the 4-digit arrays was about four times the threshold for the 2-digit arrays, whereas for controls it was only doubled. This differential effect of array length for the two groups was reliable, $F(2,56) = 4.71$, $p < .05$, as were the main effects of group and length, $F(1,28) = 8.97$, $p < .01$ and $F(2,56) = 128.57$, $p < .001$, respectively. As shown by the t-values, the dyslexic deficit was limited to the 4- and 6-digit arrays. However, as evident from the individual scores in Fig. 2, there was a substantial overlap between the groups. To estimate the number of dyslexic readers with substantially impaired multi-element processing, we averaged the scores for the 4- and 6-digit arrays. Impaired performance was defined as thresholds 1 SD above the control mean. Nine of the 15 dyslexic participants scored above this cut-off.

In contrast to the lower performance on the longer arrays of the multi-element processing task, the dyslexic group did not differ reliably from controls on the precedence detection task. The thresholds of dyslexic readers for precedence detection in the left and the right visual

Table 2
Means and standard deviations of dyslexic and normal readers of the visual measures, and the school entrance measures

	Dyslexics[a]	Controls[a]	z	t[b]
	M (SD)	M (SD)		
Visual measures				
Eye movement measures				
Words				
Saccades (N per item)	2.3 (0.7)	1.1 (0.2)	−6.00	−6.08***
Regressions (%)	15.5 (8.2)	8.2 (4.8)	−1.52	−2.90**
Pseudowords				
Saccades (N per item)	2.5 (0.8)	1.4 (0.3)	−3.67	−5.23***
Regressions (%)	15.7 (7.8)	11.0 (4.0)	−1.18	−2.08*
Multi-element processing				
2-digit array (ms)	22.0 (5.7)	20.4 (7.3)	−0.22	−0.66
4-digit array (ms)	82.3 (35.9)	48.4 (31.5)	−1.08	−2.75**
6-digit array (ms)	152.5 (54.7)	102.8 (50.1)	−0.99	−2.59*
Precedence detection				
Left precedence (ms)	32.3 (23.4)	25.8 (19.5)	−0.33	−0.81
Right precedence (ms)	33.8 (21.9)	29.4 (18.5)	−0.24	−0.59
Coherent motion detection [c]	11.1 (6.6)	11.2 (5.4)	0.02	0.05
School entrance assessment				
Pseudoword repetition (% correct)	51.6 (21.3)	72.9 (14.8)	−1.44	−3.19**
Rhyme detection (% correct)	79.6 (17.9)	93.8 (5.3)	−2.68	−2.95**
Pluralization (% correct)	73.9 (16.9)	87.7 (10.4)	−1.33	−2.70*
Rapid naming (syl/min)	39.3 (6.9)	48.4 (11.1)	−0.82	−2.71**

[a] $n = 15$; [b] df = 28; [c] % of coherently moving dots; * $p < .05$; ** $p < .01$; *** $p < .001$.

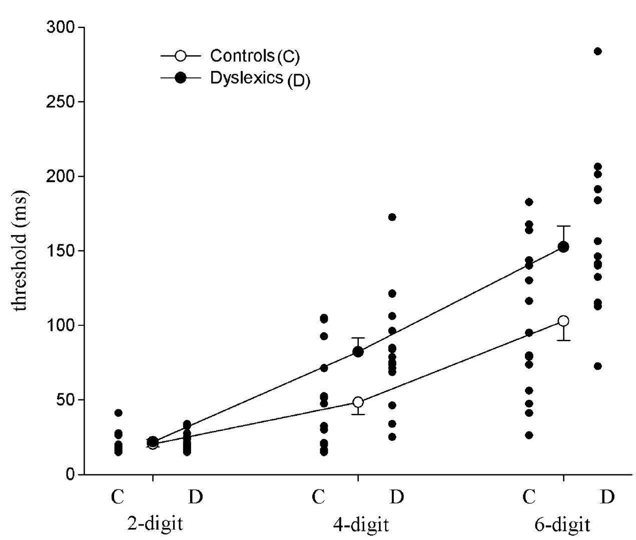

Fig. 2. Individual scores of normal (C) and dyslexic (D) readers on the 2-, 4-, and 6-digit arrays of the multi-element processing task. The imbedded graphs show group means and standard errors of the mean.

field were similar. There also was no dyslexic deficit on the coherent motion detection task where both groups performed equally. In contrast to the failure to find group differences in the visual precedence and coherent motion detection tasks, the bottom section of Table 2 shows that dyslexic readers exhibited substantially lower performance on all phonological tasks and on the rapid naming task administered at school entrance.

Table 3 shows the intercorrelations between the main measures. For reading we used the number of eye movements as this measure could be seen as being directly affected by impaired multi-element processing. As expected, the association between number of eye movements and reading rate (each measure combined for words and pseudowords) was tight, $r = .89$, $p < .01$, that is, a lower reading rate was highly related to a higher number of eye movements during reading. As the multi-element impairment of the dyslexic readers was limited to 4-digit and 6-digit arrays, averaged thresholds for these array-lengths were used. Also, averaged thresholds were computed for left and right precedence detection.

An important finding is the substantial correlation between number of eye movements and multi-element processing, that is, more eye movements were associated with higher thresholds for the multi-element arrays. In contrast, precedence detection and coherent motion detection were unrelated to both number of eye movements and to multi-element perception threshold. Number of eye movements was also related to rapid naming and pseudoword repetition and, additionally, rapid naming was associated with multi-element processing.

This pattern of correlational results led to two further analyses. An ANCOVA examined whether the dyslexic deficit in multi-element processing (averaged threshold of the 4-, and 6-digit arrays) would still be found when the deficits in pseudoword repetition and rapid naming

Table 3
Correlations between reading rate, eye movements, visual measures, rapid naming, and phonological measures

	(1)	(2)	(3)	(4)	(5)	(6)	(7)
(1) Eye movements[a]							
(2) Multi-element processing[b]	.50*						
(3) Precedence detection[c]	.04	.10					
(4) Coherent motion detection	−.16	.23	.30				
(5) Rapid naming	−.45*	−.37*	−.29	.02			
(6) Pseudoword repetition	−.42*	.08	−.36	−.07	.10		
(7) Rhyme detection	−.18	−.16	−.30	−.38*	.28	.45*	
(8) Pluralization	−.30	.11	−.11	.10	.11	.62**	.52**

[a] Word and pseudoword reading combined; [b] 4- and 6-element arrays combined; [c] Left and right precedence detection combined; * $p < .05$; ** $p < .01$.

were controlled for. This was indeed the case as the group difference in multi-element processing remained reliable, $F(1,27) = 4.93$, $p < .05$, and the size of group difference was hardly affected. The original averaged threshold means were 75.6 ms and 117.4 ms for control and dyslexic participants, respectively. Inclusion of the covariates led to adjusted means of 79.21 ms and 113.79 ms, respectively.

A further question was whether multi-element processing contributes to differences in the number of eye movements independently from pseudoword repetition and rapid naming. Therefore, we computed two hierarchical regression analyses. In both analyses, pseudoword repetition was entered in the first step and accounted for 18% of variance, $F(1,28) = 5.94$, $p < .05$. In the first model, the order of the further predictors, which were entered in the second and third step, was rapid naming and multi-element processing, respectively. Rapid naming accounted for additional 15% of variance, $F(1,27) = 6.30$, $p < .05$, and multi-element processing accounted for further 16% of variance, $F(1,26) = 8.33$, $p < .05$. In the second model, the order of entering rapid naming and multi-element processing was reversed. Therein, multi-element processing added 17% of explained variance, $F(1,27) = 13.44$, $p < .01$, whereas rapid naming did not explain a significant additional amount of variance, $F(1,26) = 2.26$, $p = .15$. In summary, these analyses show that multi-element processing differences contributed to number of eye movements independently from pseudoword repetition and rapid naming and, in relation to rapid naming, multi-element processing turned out to be the more potent predictor.

4. Discussion

The present German dyslexic readers exhibited the reading difficulties which were characterized as typical for dyslexic reading in regular orthographies, that is, they committed few errors, but suffered from a reading rate which was only about half the rate of the normal readers. This was the case for reading aloud lists of words and pseudowords, but also for silent reading of sentences for meaning. Of main importance is that the reading rate differences were highly associated with the number of eye movements during reading. The frequent eye movements of the dyslexic readers are indicative of reliance on a serial grapheme-phoneme conversion during word recognition.

The guiding question of the present study was, whether the serial reading strategy of dyslexic readers—similar to that of letter-by-letter readers—is due to a deficit in processing multiple visual forms. The pattern of findings provides some support for this possibility. Unlike Morrison et al. (1977) and Enns et al. (1995), we found a dyslexic deficit in multi-element processing. This deficit was specific in the sense that it was only present for 4- and 6-digit arrays, but not for 2-digit arrays. The finding of unimpaired performance of the dyslexic participants on the 2-digit arrays speaks against the possibility that the multi-element processing deficit of dyslexic readers is caused by deficits in feature detection or single letter recognition which are considered as the first stages of visual word recognition (Whitney, 2001). Of main importance is that multi-element processing was substantially related to differences in the number of eye movements during reading. Furthermore, differences in multi-element processing contributed to differences in the number of eye movements independently from the phonological measures and from rapid naming which were also found to be associated with number of eye movements. This finding suggests that multi-element processing affects reading performance independently from verbal phonological factors.

The finding that the dyslexic deficit with the multi-digit arrays was not accompanied by a deficit in visual precedence detection rules out the possibility that the poor performance of the dyslexic readers for multi-element arrays is due to a visual attentional problem. Specifically, dyslexic readers exhibited no deficit, when the left bar preceded the right one which speaks against a right parietal lobe dysfunction which, according to Hari, Renvall, and Tanskanen (2001), would be apparent in a left mini-neglect which, in turn, would hinder fluent reading. It is of further interest that the present dyslexic readers on a previous assessment (Kronbichler et al.,

2002) showed no deficit for coherent motion detection which serves as an assessment of the visual magnocellular system (Hansen et al., 2001). A specific role of the magnocellular system for encoding the positions of letters was suggested by Cornelissen et al. (1998). Our finding that dyslexic readers showed impaired multi-element processing without a magnocellular deficit corresponds to the pattern of findings reported by Amitay, Ben-Yehudah, Banai, and Ahissar (2002). These authors found that in a substantial number of dyslexic readers a deficit on a variety of visual perceptual tasks was not accompanied by a deficit in tasks which selectively tap magnocellular processing.

We note that a purely visual interpretation of the multi-element processing deficit of the dyslexic readers can be criticized from a verbal deficit perspective. One could reason that the locus of the difficulty may not reside in the visual recognition of multiple objects, but in the access and short-term maintenance of the names of these multiple objects. Such an interpretation has plausibility, but it is hard to reconcile with the well supported position that the partial report method, different from the whole report method, measures primarily early stages of visual processing (Averbach & Sperling, 1968). It also does not fit with the finding that letter-by-letter readers exhibit the multi-element processing deficit not only for nameable objects, but also for abstract (non-nameable) visual forms (e.g., Friedman & Alexander, 1984). Corresponding with the latter finding, Pammer et al. (2004) found a deficit of developmental dyslexic children (10-year olds) in processing arrays of multiple geometric forms which were not nameable.

The association between multi-element processing and number of eye movements during reading is consistent with the idea that an impaired ability to process multiple visual forms simultaneously is responsible for the serial reading strategy of our dyslexic participants. However, this interpretation can be questioned as multi-element processing and eye movement control during reading was assessed at the same time. One could argue that the higher reading experience of normal compared to dyslexic readers is carried over to the multiple-element processing task. Although we tried to avoid this problem by using digits instead of letters, this interpretation cannot be ruled out entirely. Longitudinal studies, which assess multi-element processing with preschool children, would be needed to avoid this interpretational problem.

Even if the frequent eye movements and the resulting low reading rate of our dyslexic readers were due to a deficit in multi-element processing, it has to be noted that only about half of the dyslexic sample showed substantially impaired multi-element processing. This speaks against the possibility that deficient multi-element processing is the only impairment which in dyslexic readers may lead to slow serial reading. The regression analyses showed that early differences in pseudoword repetition and rapid naming independently from multi-element processing were associated with number of eye movement during reading. This finding is in correspondence with expectations from the phonological deficit explanation of dyslexia and with the recent extension of this account by Wolf and Bowers (1999).

A similar conclusion follows from Bosse and Valdois (2003) who differentiated between French dyslexic children who exhibited deficient multi-element processing and a further subgroup which exhibited phonological deficits. These authors interpreted their findings in relation to the multi-trace memory model of polysyllabic word reading of Ans, Carbonnel, and Valdois (1998) which distinguishes between a global reading mode, where all letters of a word are attended to, and an analytic reading mode which relies on smaller units (i.e., typically a syllable) during reading. In this perspective, deficient multi-element processing would affect reading in the global mode, whereas deficient phonological processing is related to the analytic reading mode.

Acknowledgments

The research reported here was supported by the Austrian Science Foundation (Grant No. P14494-SPR). We thank Kristina Moll, Martin Kronbichler, and Florian Hutzler for their help during planning and data acquisition. Thanks to John Stein and Joel Talcott for making available the coherent motion detection software. We gratefully acknowledge the helpful comments of two reviewers.

References

Amitay, S., Ben-Yehudah, G., Banai, K., & Ahissar, M. (2002). Disabled readers suffer from visual and auditory impairments but not from a specific magnocellular deficit. *Brain, 125*, 2272–2285.

Ans, B., Carbonnel, S., & Valdois, S. (1998). A connectionist multi-trace model of polysyllabic word reading. *Psychological Review, 105*, 678–723.

Auer, M., Gruber, G., Mayringer, H., Wimmer, H., in press. Salzburger Lesescreening 5–8. Bern: Huber.

Averbach, E., & Sperling, G. (1968). Short term storage of information in vision. In R. N. Haber (Ed.), *Contemporary theory and research in visual perception*. New York: Holt Rinehart & Winston.

Behrmann, M., Shomstein, S. S., Black, S. E., & Barton, J. J. S. (2001). The eye movements of pure alexic patients during reading and nonreading tasks. *Neuropsychologia, 39*, 983–1002.

Bosse, M. L., & Valdois, S. (2003). Patterns of developmental dyslexia according to a multi-trace memory model of reading. *Current Psychology Letters [online serial]*, 10.

Cornelissen, P. L., Hansen, P. C., Gilchrist, I., Cormack, F., Essex, J., & Frankish, C. (1998). Coherent motion detection and letter position encoding. *Vision Research, 38*, 2181–2191.

De Luca, M., Borelli, M., Judica, A., Spinelli, D., & Zoccolotti, P. (2002). Reading words and pseudowords: an eye movement study of developmental dyslexia. *Brain and Language, 80*, 617–626.

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.

Denckla, M. B., & Rudel, R. G. (1976). Rapid 'automatized' naming: Dyslexia differentiated from other learning disabilities. *Neuropsychologia, 14*, 471–479.

Enns, J. T., Bryson, S. E., & Roes, C. (1995). Search for letter identity and location by disabled readers. *Canadian Journal of Experimental Psychology, 49*, 357–367.

Farah, M. J., & Wallace, M. A. (1991). Pure alexia is a visual impairment: A reconsideration. *Cognitive Neuropsychology, 8*, 313–334.

Friedman, R. B., & Alexander, M. P. (1984). Pictures, images, and pure alexia: A case study. *Cognitive Neuropsychology, 1*, 9–23.

Hansen, P. C., Stein, J. F., Orde, S. R., Winter, J. L., & Talcott, J. B. (2001). Are dyslexics' visual deficits limited to measures of dorsal stream function. *Neuroreport, 12*, 1527–1530.

Hari, R., & Renvall, H. (2001). Impaired processing of rapid stimulus sequences in dyslexia. *Trends in Cognitive Sciences, 5*, 525–532.

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

Huttenlocher, J., & Cohen-Levine, S. (1990). *Primary Test of Cognitive Skills*. Monterey, CA: Macmillan/McGraw-Hill.

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

Kinsbourne, M., & Warrington, E. K. (1962). A disorder of simultaneous form perception. *Brain, 101*, 65–81.

Kronbichler, M., Hutzler, F., & Wimmer, H. (2002). Dyslexia: Verbal impairments in the absence of magnocellular impairments. *Neuroreport, 13*, 617–620.

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

Morrison, F. J., Giordani, B., & Nagy, J. (1977). Reading disability: An information-processing analysis. *Science, 196*, 77–79.

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

Robertson, I. H., Mattingley, J. B., Rorden, C., & Driver, J. (1998). Phasic alerting of neglect patients overcomes their spatial deficit in visual awareness. *Nature, 395*, 169–172.

Shaywitz, S. E. (1998). Dyslexia. *The New England Journal of Medicine, 338*, 307–312.

Stein, J., & Walsh, V. (1997). To see but not to read; the magnocellular theory of dyslexia. *Trends in Neuroscience, 20*, 147–152.

Vellutino, F. R., Fletcher, J. M., Snowling, M. J., & Scanlon, D. M. (2004). Specific reading disability (dyslexia): what have we learned in the past four decades? *Journal of Child Psychology and Psychiatry, 45*, 2–40.

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.

Wimmer, H. (1993). Characteristics of developmental dyslexia in a regular writing system. *Applied Psycholinguistics, 14*, 1–33.

Wimmer, H., Mayringer, H., & Landerl, K. (2000). The double deficit hypothesis and difficulties in learning to read a regular orthography. *Journal of Educational Psychology, 92*, 668–680.

Wolf, M., & Bowers, P. G. (1999). The 'double deficit hypothesis' for developmental dyslexias. *Journal of Educational Psychology, 91*, 1–24.

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.

Zoccolotti, P., De Luca, M., Di Pace, E., Judica, A., Orlandi, M., & Spinelli, D. (1999). Markers of developmental surface dyslexia in a language (Italian) with a high grapheme-phoneme correspondence. *Applied Psycholinguistics, 20*, 191–216.