Perhaps correlational but not causal: No effect of dyslexic readers' magnocellular system on their eye movements during reading

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Abstract

During reading, dyslexic readers exhibit more and longer fixations and a higher percentage of regressions than normal readers. It is still a matter of debate, whether these divergent eye movement patterns of dyslexic readers reflect an underlying problem in word processing or whether they are – as the proponents of the magnocellular deficit hypothesis claim – associated with deficient visual perception that is causal for dyslexia. To overcome problems in the empirical linkage of the magnocellular theory with reading, a string processing task is presented that poses similar demands on visual perception (in terms of letter identification) and oculomotor control as reading does. Two experiments revealed no differences in the eye movement patterns of dyslexic and control readers performing this task. Furthermore, no relationship between the functionality of the participants' magnocellular system assessed by the coherent motion task and string processing were found. The perceptual and oculomotor demands required during string processing were functionally equivalent to those during reading and the presented consonant strings had similar visual characteristics as reading material. Thus, a strong inference can be drawn: Dyslexic readers do not seem to have difficulties with the accurate perception of letters and the control of their eye movements during reading – their reading difficulties therefore cannot be explained in terms of oculomotor and visuo-perceptual problems.
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Keywords: Dyslexia; Magnocellular deficit; Eye movements; String processing; Visual search

It is a well-documented (and undisputed fact) that eye movements of dyslexic readers differ from those of normal readers. During reading, dyslexic readers exhibit more and longer fixations, shorter saccades and a higher percentage of regressions than normal readers (for review, see Rayner, 1998). However, whether these specific eye movement patterns of dyslexic readers are causal for dyslexia or whether they reflect an underlying problem in the processing of written words is still a matter of debate – a dispute mentioned in Tinker's (1958) review on eye movements during reading. Since then, several theoretical positions were built upon visual perceptual and/or oculomotor deficits as

a causative factor for reading difficulties. In the present paper, a short overview will be given about the magnocellular deficit hypothesis of dyslexia, a quite recent theoretical position claiming that oculomotor and visual perceptual deficits are causal for dyslexic readers' difficulties during the processing of written words and their divergent eye movement patterns during reading. For this theory, possible problems in the linkage of the theoretical framework towards reading are discussed and subsequently an alternative task will be presented that poses similar demands on visual perception and oculomotoric control as reading does. This so called string-processing task is the logical consequence of the discussed problems in the theoretical linkage and closes the gap between the theoretical framework of the magnocellular deficit hypothesis and reading.

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1. The magnocellular deficit hypothesis of dyslexia

By proposing that the development of the visual transient system in dyslexics is mildly impaired, Lovegrove (1991; Lovergrove, Bowling, Badcock, & Blackwood, 1980) gave rise to the magnocellular deficit hypothesis; oculomotor and visual perceptual deficits were proposed as an underlying deficit of dyslexia. The theoretical framework of the magnocellular deficit hypothesis builds upon the existence of two distinct systems – magnocellular and parvocellular – in visual perception. Whereas the fast acting magnocellular system is responsible for the processing of stimuli with high temporal but low spatial frequencies, the parvocellular system serves stimuli with high spatial and low temporal frequencies. According to the proponents of the magnocellular deficit hypothesis (Stein & Walsh, 1997; Stein & Talcott, 1999; Stein, Talcott & Walsh, 2000; Stein, 2003), dyslexic readers suffer from an impairment of the magnocellular system, possibly caused by a disorganized magnocellular layer and smaller magnocells in the Lateral Geniculate Nucleus (a kind of a relay station of the visual projection pathways from the eye to the visual cortex, see Livingstone & Hubel, 1988). In fact, Livingstone, Rosen, Drislane and Galaburda (1991) provided evidence from a post mortem dissection showing that magnocells in the lateral geniculate nucleus of dyslexic readers were 30% smaller and more disorganized than those of controls. According to Stein and Walsh (1997), these slight impairments in the performance or organization of the magnocellular laminae of the lateral geniculate nucleus might result in greater deficits in the functioning of the posterior parietal cortex (for a more detailed review, see Stein, 2003).

The magnocellular deficit hypothesis of developmental dyslexia is supported by differences between dyslexic and control readers in behavioral tasks testing the sensitivity of the magnocellular system, as well as by group differences in evoked potential and functional imaging studies in response to these tasks. A task that is most often used to measure the functionality of the magnocellular system is the coherent motion task. During that task (described in more detail in Sections 5.1 and 9.1) participants are instructed to detect whether a certain percentage of dots within a cloud of randomly moving dots moves in the same direction. Several studies provide evidence for differences in sensitivity between dyslexic and control readers in detecting such a coherent movement (Cornelissen, Richardson, Mason, Fowler & Stein, 1995; Hansen, Stein, Orde, Winter & Talcott, 2001; Talcott, Hansen & Stein, 1998; Talcott, Hansen, Elikem & Stein, 2000 – but see Kronbichler, Hutzler & Wimmer, 2002). Furthermore, correlational relations between coherent motion sensitivity and tasks that require positional letter encoding were reported (Cornelissen et al., 1998), as well as between coherent motion sensitivity and single word reading (Cornelissen, Hansen, Hutton, Evangelinou & Stein, 1998). On the electrophysiological level, Schulte-Körne, Bartling, Demel and Remschmidt (2004a and 2004b) reported differences in

visual evoked potentials between dyslexic and control children in response to coherently moving dots. In a functional imaging study, Eden et al. (1996) provided evidence that during the viewing of randomly moving dots, V5 (a region that responds strongly to visual motion located in the prestriate cortex at the junction of the occipital and the temporal lobe) was less activated in dyslexic readers than in normal readers.

Visual perception is proposed to be affected by an impaired magnocellular system in several ways. The magnocellular system is necessary to control eye movements, to suppress the flow of visual information during the saccadic movement of the eyes (a mechanism called saccadic suppression) and to keep binocular vergence while fixating a word (Stein & Walsh, 1999). A deficient magnocellular system is claimed to lead to erroneous visual perceptions due to destabilized binocular vergence during the fixation of a word (Stein & Walsh, 1999). Furthermore, the magnocellular system is responsible for the control of visually guided eye movements which are necessary for subsequent fixations on a stimulus after a first fixation (Stein & Walsh, 1999) – a failure in correctly guiding these eye movements during targeting the next location of a fixation would lead to a corrective saccade, resulting in an overall higher number of fixations on a word. The consequences of a deficient magnocellular system for visual perception are – according to the proponents of the magnocellular deficit hypothesis – quite drastic: Dyslexic readers might perceive that "[...] letters seem to move around on the page [...] in and out of the plane of the paper [...] merge and cross over each other [...]." (Stein & Talcott, 1999). Furthermore erroneous perceptions might occur, suggesting that "[...] letters would jumble up, thoroughly confusing the reader." (Lovegrove, 1991) – or in other words: "[...] letters might then appear to move around and cause visual confusion." (Stein & Walsh, 1997).

According to the proponents of the magnocellular deficit hypothesis, magnocellular impairments are quite common among dyslexic readers. For example, it was suggested that two thirds of the dyslexic readers do have visual problems (Stein, 2001), 75% do have low coherent motion sensitivity (Stein, 1999) – or as Stein, Talcott & Walsh (2000) noted: "[...] the idea that many, if not most, developmental dyslexics have mildly impaired development of the visual magnocellular system has taken firm root" (Stein, Talcott & Walsh, 2000). In consequence, criterions commonly used by the proponents of the magnocellular deficit hypothesis for the selection of dyslexic participants are IQ, reading, and spelling abilities (e.g., Talcott et al., 1998, 1999; Witton et al., 1998).

To summarize, there are two major implications of a deficient magnocellular system in dyslexic readers. First of all (taking into account the drastic perceptual consequences mentioned like moving and merging letters), it is proposed that dyslexic readers suffer from a visual perceptual deficit that hinders them from accurately perceiving a letter string they have to read. Secondly – although not directly mentioned

– it is implicitly suggested that the divergent eye movement patterns of dyslexic children during reading can be explained in terms of magnocellular deficits: A statement like "letters seem to move around and merge" (Stein & Talcott, 1999) implies that dyslexic readers would have to make a greater effort to perceive an unknown letter string and therefore would need to make more and longer fixations during reading.

Besides these drastic depictions of possible consequences for the visual perception of dyslexic readers it is important to take into account how the theoretical framework of the magnocellular deficit is empirically linked with reading research. Numerous studies report differences between dyslexic and control readers in the functionality of their magnocellular system (assessed for example by the coherent motion task) and electrophysiological correlates of these differences. However, Frith and Frith (1996) pointed out that it is very unlikely that magnocellular deficits are a direct cause of the dyslexics' reading difficulties. Rather, it could be the case that a possible dysfunction of the magnocellular pathway is a marker of a genetic deviation – manifesting itself in several ways that are not related to the cognitive level. Thus, even if dyslexic readers do have reduced magnocellular sensitivity – this deficit does not necessarily have consequences for visual perception and oculomotor control during reading.

Therefore – apart from theorizing in which way a possible magnocellular deficit might influence visual perception and oculomotor control – it is necessary to provide a direct link between the well elaborated magnocellular framework and the behavior during a task which demands the similar visual perceptual and oculomotor requirements as reading does. This link is of theoretical importance because the tasks (e.g., the coherent motion task) that are used to assess the functionality of the magnocellular system are only of indirect relevance to reading.

2. Immediate and indirect relevance of nonreading tasks

Concerning the issue whether it is legitimate to conclude from a given task the interpretation of oculomotor control during reading, Pavlidis (1981) argued that if erratic eye movements were causal for developmental dyslexia, the differences between dyslexic and normal readers should be obvious in a simple oculomotor task (for a review concerning subsequent studies that failed to replicate (Pavlidis, 1981), findings, see Rayner, 1985). This line of arguments can also be extended to the issue of deficient visual perception: If problems in visual perception underlie dyslexia, then dyslexic readers should also do worse than controls in a perceptual task. However, it is of importance that the visual and oculomotor demands of such a task match those required for reading. Therefore, Radach, Heller, and Huestegge (2002) suggested the distinction between tasks of immediate rele-

vance and tasks of indirect relevance for reading. Immediate relevance for reading would be demonstrated if it could be shown that the oculomotor and perceptual demands of a specific task are identical or functionally equivalent to those required for reading. For example, a task of immediate relevance could require the identification of letters or the examination of strings of symbols from left to right – therefore demanding processes and behavior that are close to those occuring during reading. Indirect relevance for reading would be demonstrated if processes or behavior are tested that are supposed to be symptomatically affected by a specific deficit which is the (or a) cause of dyslexia. For example, within the framework of the magnocellular deficit hypothesis, the coherent motion task can be considered as a task of indirect relevance for reading. Motion detection is not required during reading, but is assumed to be affected by an impaired magnocellular pathway – and therefore is supposed to be symptomatic for dyslexia (according to the proponents of the magnocellular deficit hypothesis of dyslexia). However, when a nonreading task is of indirect relevance, one has to be cautious with regard to inferences concerning the nature of visual perception or oculomotor control of dyslexic readers during reading.

3. The string-processing task

To directly examine possible perceptual and oculomotor impairments that affect dyslexic children during reading, a task of immediate relevance that has to be as close as possible to the perceptual and oculomotor demands of reading is necessary. Such a task can be constructed in accordance to a simple pseudoword reading task: During the reading of series of pseudowords like:

GUFT, MURS, HIMD, . . .

every letter of a pseudoword has to be perceived and processed – otherwise it would be impossible to generate the correct pronunciation for this novel stimulus. On the basis of these pseudowords, consonant strings of nearly the same visual characteristics can be created by replacing vowels by consonants:

GRFT, MHRS, HMMD, . . .

A perceptual task that can be performed on these consonant strings is the search for two adjacent identical letters. Again, it is necessary to perceive and process each letter of a consonant string to successfully carry out this task. Therefore, the string-processing task requires very similar visual and oculomotor demands as pseudoword reading does and can be described as having immediate relevance for reading. This immediate relevance becomes obvious in comparison to Stein & Talcott's (1999) reasoning that the unstable visual perception caused by a magnocellular deficit is particularly harmful in the phonological stage, during which a child has to perceive and identify each letter in order to learn the grapheme-phoneme conversion rules. Clearly, the processing of every letter in accordance to its specific

position is an integral constituent of the string-processing task.

4. The rationale

The aim of the present paper is to explore possible visual and oculomotor deficits in dyslexic children using a task of immediate relevance for reading: The string-processing task. During the string processing task, participants perceive and identify the letters of an item in order to discover whether any of the adjacent letters within the string are identical. To perform this task, psycholinguistic processes beyond letter identification (e.g., grapheme-phoneme conversion) are neither necessary nor helpful. In contrast, during pseudoword reading, the constituent letters of an item not only have to be identified, but also higher psycholinguistic processes like grapheme-phoneme conversion have to be carried out to establish a phonological representation of the item. Therefore, if dyslexic readers do have poor oculomotor control and visual perception (e.g., as a consequence of a magnocellular impairment), then they should perform worse than normal readers in both tasks, string processing and pseudoword reading. However, if dyslexic readers perform as well as unimpaired readers during string processing, but perform worse during pseudoword reading, then the source of the problems experienced by the dyslexic readers is not likely to be at the level of oculomotor control or visual perception, but beyond – presumably at a higher psycholinguistic level of processing like grapheme-phoneme conversion.

5. Experiment 1

5.1. Method

5.1.1. Participants

Dyslexic and control readers were selected from a large longitudinal sample of more than 500 boys. Inclusion criteria for the dyslexic readers was a reading rate lower than percentile 15 in Grade 3 and a present (i.e., Grade 7) reading score lower than percentile 10 on an individually administered, standardized sentence-reading test developed in our laboratory. This paper and pencil test measures reading speed

by presenting 70 sentences of very simple content with a time limit of 3 min and the instruction to mark each sentence as correct or incorrect and to do so as quickly as possible. A low nonverbal IQ (i.e., 85 or lower) based on three scales (spatial sequences, spatial integration, and spatial concepts) from the Primary Test of Cognitive Skills (Huttenlocher & Cohen-Levine, 1990) was an exclusion criterion. The normal reading children had to achieve a reading score above percentile 20. The low reading and spelling performance of the eleven dyslexic readers is shown in Table 1. The substantial group differences in reading speed between dyslexic and normal readers were also obvious in their eye movements during the reading of simple passages of text - for illustrative purposes we would like to refer to data that was reported in Hutzler and Wimmer (2004): The poor readers exhibited the typical eye movement patterns of dyslexic readers: During reading, they showed a higher number fixations than normal readers (M = 1.53; S.D. = 0.20 and M = 0.83; S.D. = 0.20, respectively, $t(20) = 7.00$; $p < 0.01$) and longer fixation durations than normal readers (M = 367; S.D. = 132 and M = 192; S.D. = 34, respectively, $t(11.33) = 4.27$; $p < 0.001$).

The means for the processed items in the sentence reading task correspond to percentiles 5 and 60, respectively. No reliable differences in nonverbal IQ and age were found. However, because the mean IQ of the dyslexic children was nine points lower than that of the controls, we checked upon the influence of IQ on sentence processing and found the correlation between IQ and the items processed in the sentence reading task to be small and unreliable, $r(22) = 0.23$; $p > 0.29$.

5.1.2. Apparatus and procedure

Participants sat in a distance of 120 cm from a Belinea 21 in. Computer monitor that was connected to a Pentium II (233 MHz) computer used for stimulus presentation. Uppercase letters of the reading material were 12 mm high and therefore corresponded to a visual angle of 0.6 degree per letter encountered during a natural reading situation with a letter size of 3 mm for uppercase letters at a distance of 30 cm. The stimulus material was presented in yellow color on a black background in a dimly illuminated room. The brightness of the monitor was adjusted to a comfortable level and was the same for all participants. In a natural binocular viewing situation, eye movements were recorded every 20 ms from the left eye by an ISCAN (Model RK-464)

Table 1
Descriptive characteristics for the 11 dyslexic and the 11 normal readers included in the analysis of eye movements

Measure	Dyslexic readers[a]		Normal readers[a]		Difference	t[b]
	M	S.D.	M	S.D.		
Sentence reading [N sentences]	24	5	42	7	−18	8.74[***]
IQ	100	13	109	13	−9	1.75
Age [months]	163	5	160	4	3	1.69
Spelling [% correct]	25	18	82	12	−57	6.80[***]

[a] $n = 11$; [b] d.f. = 20; [***] $p < 0.001$.

video-based eye tracking system. During recording, the forehead was stabilized with a headrest. Subsequent to the initial calibration of the system that took about two minutes, the pseudoword reading task and the string-processing task were presented. Both tasks were preceded by a short familiarization trial with two lines of the stimulus material.

5.1.3. Stimulus material

5.1.3.1. String-processing. The task was to search through lists of consonant strings (e.g., GDR, LBQD) for items with two adjacent identical letters (e.g., VPLL). Each list was presented on the monitor in five lines with six items per line. Six of the 30 items of each list were targets. Two lists with strings of consonant letters were presented. To avoid a rigid matrix-like visual arrangement on the screen, items of different length were used: half of the items was of three- and the other half was of four-letter length. The instruction was to search through the lists from left to right, line per line. Participants had to respond with "yes" to a target, and the experimenter checked whether a target was actually fixated. Eye movements to targets were not included in the analysis. For examples of the consonant strings (experimental and target stimuli) used in Experiment 1, see Appendix A.

5.1.3.2. Pseudoword reading. Similar to the string-processing task, the pseudowords were presented in two lists, each of which consisted of six lines with five items per line. Again, the instruction was to search through the lists from left to right, line per line; however, during pseudoword reading, participants had to silently read the stimulus material. Of the altogether 60 items, twenty were short (four letters long) and monosyllabic (e.g., DREV, GINZ). The remaining 40 items were 7–8 letters long and were not included in the analysis, because they were not comparable with respect to letter-length to the items used in the string processing task. For examples of the four-letter pseudowords included in the analysis, see Appendix A.

6. Results

6.1. String-processing task

In a first step, the eye movement patterns of dyslexic and normal readers exhibited during the string-processing task were analyzed. The relevant means for the three measures number of fixations per item, duration of the first fixation on an item and gaze duration (i.e., the total time spend on an item during first pass reading) are provided in Table 2. All three measures were submitted to separate 2×2 ANOVAs with length (three versus four letters) as within-subject factor and group (dyslexic versus normal readers) as between subject factor. In the case of a significant effect involving group in subject-based analyses (F_1), the generalizability over stimu-

Table 2
Number of fixations, first fixation duration and gaze duration of dyslexic and normal readers during the processing of three- and four-letter consonant strings (CS) and during the reading of four-letter pseudowords (PW)

Measure	Dyslexic readers[a]		Normal readers[a]	
	M	S.D.	M	S.D.
Number of fixations [N]				
3 Letter CS	1.20	0.18	1.07	0.16
4 Letter CS	1.35	0.32	1.20	0.25
4 Letter PW	1.65	0.45	1.15	0.19
First fixation duration [ms]				
3 Letter CS	372	86	347	85
4 Letter CS	389	105	367	109
4 Letter PW	707	280	417	107
Gaze duration [ms]				
3 Letter CS	527	145	417	121
4 Letter CS	534	138	463	141
4 Letter PW	1123	449	505	162

[a] $n = 11$.

lus material was examined with items as cases (F_2), whereby all factors were between-item factors.

6.2. Number of fixations

As can be seen in Table 2, no clear differences were observed between dyslexic and normal readers, $F_1 < 2.3$. However, there was a reliable main effect of length with a higher number of fixations on long than on short items, $F_1(1,20) = 12.11; MSE = 0.02; p < 0.002$ and $F_2(1,96) = 6.46; MSE = 0.08; p < 0.013$. The length by group interaction was not significant, $F_1 < 1$.

6.3. First fixation duration

For the duration of the first fixation, neither a main effect of group, nor a main effect of length was observed. The length by group interaction was also not significant, all $F_1 s < 1.21$.

6.4. Gaze duration

Also for gaze duration, there was no reliable main effect of group, $F_1 < 3$, no main effect of length, $F_1 < 1.04$, and no length by group interaction, $F_1 < 1$.

7. String-processing versus pseudoword reading

A further comparison of theoretical relevance is that of the eye movement patterns exhibited during the string-processing task and that exhibited during pseudoword reading. In the following analyses, eye movements elicited by four-letter pseudowords were compared to those elicited by four-letter consonant strings. The relevant means for number of fixations, duration of the first fixation and gaze duration are provided in Table 2. All three measures were submitted to separate 2×2 ANOVAs with task (string-processing versus

pseudoword reading) as within-subject factor and group (dyslexic versus normal readers) as between-subject factor.[1]

7.1. Number of fixations

For number of fixations, the task by group interaction approached significance in the subject based analysis, $F_1(1,20) = 3.41$; MSE = 0.10; $p = 0.08$ and was highly reliable in the item-based analysis, $F_2(1, 84) = 11.83$; MSE = 0.06; $p < 0.001$. The main effect of group was reliable, $F_1(1,20) = 11.98$; MSE = 0.10; $p < 0.002$ and $F_2(1,88) = 39.53$; MSE = 0.06; $p < 0.0001$. The main effect of task was not found to be reliable, $F_1 < 1.62$. As evident in Table 2, post-hoc tests revealed no difference between dyslexic and normal readers in number of fixations during string-processing, $F_1 < 1.48$. However, during pseudoword reading dyslexic readers exhibited a higher number of fixations than normal readers, $F_1(1,20) = 11.75$; MSE = 0.12; $p < 0.01$ and $F_2(1,38) = 39.90$; MSE = 0.06; $p < 0.001$.

7.2. First fixation duration

For this measure, a task by group interaction was reliable, $F_1(1,20) = 7.85$, MSE = 24,992, $p = 0.011$ and $F_2(1, 84) = 32.48$, MSE = 12,106, $p < 0.001$. Furthermore, a main effect of task, $F_1(1,20) = 14.90$; MSE = 24,993; $p < 0.001$ and $F_2(1,88) = 57.52$; MSE = 12,106; $p < 0.0001$ and main effect of group were found reliable, $F_1(1,20) = 8.55$; MSE = 31,388; $p < 0.008$ and $F_2(1,88) = 45.23$; MSE = 12,106; $p < 0.0001$. Subsequent analysis revealed no group difference during string-processing, $F_1 < 1$, whereas the first fixation duration of dyslexic readers during the reading of pseudowords was about 290 ms longer than that of the normal readers, $F_1(1,22) = 10.28$; MSE = 44,943; $p < 0.004$ and $F_2(1,38) = 48.76$; MSE = 17,567; $p < 0.0001$.

7.3. Gaze duration

For the measure gaze duration, a task by group interaction was reliable, $F_1(1,20) = 16.03$; MSE = 51,393; $p < 0.001$ and $F_2(1,84) = 68.60$; MSE = 22,902; $p < 0.001$. Furthermore, the main effect of group, $F_1(1,20) = 15.87$; MSE = 82,063; $p < 0.001$ and $F_2(1,88) = 110.77$; MSE = 22,902; $p < 0.0001$, and the main effect of task was reliable, $F_1(1,20) = 16.03$; MSE = 51,393; $p < 0.001$ and $F_2(1,88) = 85.26$; MSE = 22,902; $p < 0.0001$. Subsequent analysis revealed, that – as obvious in Table 2 – no group difference was observed during string-processing, $F_1 < 1.40$, whereas during pseudoword reading, the dyslexic readers' gaze duration was about 610 ms longer than that of the normal readers, $F_1(1,20) = 18.43$; MSE = 113,879; $p < 0.001$ and $F_2(1,38) = 106.42$; MSE = 34,889; $p < 0.0001$.

7.4. Correlation between reading speed and eye movement patterns during pseudoword reading

To check the reliability of eye movement recording, the relationship between number of items processed during the sentence reading test (i.e., reading speed) and the three eye movement measures during the reading of pseudowords was inspected by means of non-parametric correlations. Analysis revealed reliable correlations of reading speed with number of fixations, $r(22) = -0.49$; $p < 0.05$, first fixation duration, $r(22) = -0.62$; $p < 0.01$, and gaze duration, $r(22) = -0.75$; $p < 0.0001$.

8. Discussion

No differences were found between dyslexic and control readers' eye movement patterns during string-processing. Dyslexic readers exhibited about the same number of fixations and first fixation and gaze durations of equivalent length as normal readers did. This finding is of theoretical relevance because we claim that the string-processing task requires very similar perceptual and oculomotor demands as pseudoword reading does. Similar to pseudoword reading, during string-processing each letter of each stimulus has to be processed with respect to its specific location in the letter string. This notion of serial processing during the string-processing task is supported by the finding that a higher number of fixations was necessary to process the four-letter compared to the three-letter consonant strings. However, when the task was changed from string-processing to pseudoword reading – while perceptual and oculomotor demands were kept constant – drastic group differences emerged: during pseudoword reading, the dyslexic readers exhibited a higher number of fixations and a longer first fixation duration. The gaze duration (i.e., the overall time spent on an item during first pass reading) of dyslexic readers during pseudoword reading was about 600 ms longer than that of control readers.

Concerning the instruction to read pseudowords silently, the reliable high correlations between the participants' eye movement patterns during pseudoword reading and their sentence reading speed indicated the reliability of this task (for which no control of the participants' compliance was possible). Moreover, this correlation also indicated sufficient quality of recording. Furthermore, even though no differences between the eye movement patterns of dyslexic and control readers were found, it is possible that the interindividual (although not group) differences during string-processing could be related to the functioning of the participants' magnocellular visual system.

Another critical issue is that the three and four-letter consonant strings could be most often perceived and processed by making a single fixation without the necessity for subsequent fixations on that stimulus. Because it is argued that the magnocellular system is responsible for the control of visually guided voluntary eye movements (and therefore

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[1] The eye movement patterns elicited by the four-letter pseudowords were reported in Hutzler and Wimmer (2004), in comparison with the eye movements on words.

is necessary to control subsequent saccades on a stimulus after the first fixation on that stimulus (Stein & Talcott, 1999)), the length of the consonant strings and therefore the low number of fixations exhibited on them could leave a possible effect of the sensitivity of the magnocellular system on eye movement patterns undetected – although the observed effect of consonant string length speaks against this argument.

9. Experiment 2

To inspect a possible influence of the functionality of the magnocellular system on oculomotor control and visual perception that is not related to reading skill, in Experiment 2 the eye movement patterns of the participants were analyzed with respect to the sensitivity of their magnocellular system. To increase the reliability of the pseudoword reading task, participants in Experiment 2 were instructed to read aloud. Finally, in order to examine a possible influence of a magnocellular deficit on visually guided eye movements, the length of the consonant strings used in the string-processing task was increased to elicit a higher number of fixations.

9.1. Method

9.1.1. Participants

Again, participants were selected from the same longitudinal sample as in Experiment 1, the participants of Experiment 2 were 2;1 (years; months) older than that in Experiment 1 and attended Grade 9. Inclusion criteria were a present reading score lower than percentile 15 for the dyslexic and above percentile 50 for the normal readers in another, age-appropriate reading task developed in our laboratory.

The low reading and spelling performance of the dyslexic readers is shown in Table 3, the means of the processed items in the sentence reading task correspond to percentiles 6 and 87, respectively. As obvious from Table 3, no substantial differences in nonverbal IQ and age were found.

9.1.2. Apparatus and procedure

Eye movements were recorded every 4 ms using a video-based Eyelink II System (SR Research) in a natural binocular viewing situation. An Eyelink II built in function was used to determine individually for every participant, for which eye the most reliable data was available during calibration. The corresponding eye was then used for data acquisition throughout the experiment. Stimuli were presented on a 17 in. Hyundai Computer monitor connected to a Pentium II (233 MHz) computer. The experimental settings were the same as described in Experiment 1, however this time the stimulus material was presented in black color on a white background. Again, short familiarization trials were presented prior to each of the tasks.

9.1.3. Stimulus material
9.1.3.1. String-processing. The same string-processing task as described in Experiment 1 was used. However, in Experiment 2 the consonant strings were five- and six-letters long (e.g., RHNBM, QDWKSX) and participants had to search for targets with three adjacent identical letters (e.g., LGNNN, TRRRBC). As mentioned in above, longer consonant strings were used in Experiment 2 in order to increase the number of fixations exhibited on an item. Because a pilot study revealed that searching for two adjacent identical letters in five or six letter consonant strings would result in a very difficult task, targets in Experiment 2 were made up of three – instead of two – adjacent identical letters.

The stimulus material was presented in two lists with seven lines and one list with six lines and six items per line. Filler items that were not included in analysis were placed at the beginning and the end of each line. By doing so, we tried to avoid effects of line sweep. In each line, one target was placed in a random position. Again, the instruction was to search through the lists from left to right, line per line and to respond with "yes" to a target. Eye movements to targets were not included in the analysis. For examples of the experimental stimuli and the target items, see Appendix B.

9.1.3.2. Pseudoword reading. In Experiment 2, pseudowords were six letters long and tri-syllabic (see Appendix B). The pseudowords were constructed by combining three high frequency two-letter German syllables and the resulting pseudoword must not violate orthographic and phonotactic rules. The 30 experimental (and 30 additional pseudowords that were not included in the analysis) were presented in two lists with seven lines and one list with six lines and five items per line. Again, filler items were placed in the beginning and the end of each line to avoid effects of line

Table 3
Descriptive characteristics for the 13 dyslexic and the 13 normal readers included in the analysis of eye movements

Measure	Dyslexic readers[a]		Normal readers[a]		Difference	t[b]
	M	S.D.	M	S.D.		
Sentence reading [N sentences]	11	2	21	3	−10	9.80[***]
IQ	104	11	105	13	−1	0.27
Age [months]	191	9	183	6	8	2.77[*]
Spelling [% correct]	29	14	71	20	-42	6.30[***]

[a] $n = 13$; [b] d.f. = 24; [*] $p < 0.05$; [***] $p < 0.001$.

sweep. Participants were instructed to read the pseudowords aloud.

10. Results

10.1. String-processing task

Again, eye movement patterns of dyslexic and normal readers exhibited during the string-processing task were analyzed. The relevant means for number of fixations, duration of the first fixation and gaze duration are provided in Table 4. All three measures were submitted to separate 2×2 ANOVAs with length (five versus six letters) as within-subject factor and group (dyslexic versus normal readers) as between subject factor.

10.1.1. Number of fixations

For the measure number of fixations, no main effect of group was observed, $F_1 < 1$. However, there was a reliable main effect of length, $F_1 = 12.47$; MSE $= 0.04$; $p < 0.002$ and $F_2(1,116) = 9.28$; MSE $= .14$; $p < 0.003$, indicating – see Table 4 – a higher number of fixations on long than short items. The length by group interaction was not reliable, $F_1 < 1$.

10.1.2. First fixation duration

The length by group interaction was reliable, $F_1(1,24) = 5.25$; MSE $= 298$; $p < 0.05$ in subject based analysis, but not in item-based analysis, $F_2 < 1.82$. The main effect of group was not reliable, $F_1 < 1.58$, however there was significant main effect of length in subject-based analysis, $F_1(1,24) = 5.92$; MSE $= 298$; $p < 0.023$ that failed to reach significance in item-based analysis $F_2 < 2.06$. Subsequent analysis revealed an effect of borderline reliability: On the long items, the first fixation duration of normal readers tended to be about

30 ms longer than that of dyslexic readers, $F_1(1,24) = 3.61$; MSE $= 1681$; $p = 0.069$ and $F_2(1,58) = 9.06$; MSE $= 1547$; $p < 0.004$. However, no such a group difference was found for short items, $F_1 < 1$.

10.1.3. Gaze duration

Analysis for gaze duration revealed no main effect of group, $F_1 < 1$, but a reliable main effect of length, $F_1(1,24) = 9.42$; MSE $= 5388$; $p < 0.005$ and $F_2(1,116) = 8.73$; MSE $= 13,421$; $p < 0.004$, with long items being looked at about 60 ms longer than short items. The length by group interaction was not reliable, $F_1 < 1$.

10.2. String-processing versus pseudoword reading

In the following analysis, the eye movement patterns elicited by six-letter pseudowords were compared to those elicited by six-letter consonant strings. The relevant means for number of fixations, duration of the first fixation and gaze duration can be seen in Table 4, all three measures were submitted to separate 2×2 ANOVAs with task (string-processing versus pseudoword reading) as within-subject factor and group (dyslexic versus normal readers) as between-subject factor.

10.2.1. Number of fixations

For the measure number of fixations, a reliable task by group interaction was observed, $F_1(1,24) = 15.70$; MSE $= 1.153$; $p < 0.001$ and $F_2(1,116) = 187.28$; MSE $= .22$; $p < 0.0001$, as well as a main effect of task, $F_1(1,24) = 39.26$; MSE $= 1.15$; $p < 0.0001$ and $F_2(1,116) = 468.23$; MSE $= 0.22$; $p < 0.0001$ and a main effect of group, $F_1(1,24) = 15.70$; MSE $= 1.74$; $p < 0.001$ and $F_2(1,116) = 282.47$; MSE $= .22$; $p < 0.0001$. As evident from Table 4, subsequent analysis revealed no differences between dyslexic and normal readers during string-processing, $F_1 < 1$. In contrast, during pseudoword reading dyslexic readers exhibited 2.6 more fixations per item than normal readers, $F_1(1,24) = 24.24$; MSE $= 1.85$; $p < 0.0001$ and $F_2(1,58) = 346.11$; MSE $= 0.30$; $p < 0.0001$.

10.2.2. First fixation duration

Analysis revealed, that during pseudoword reading, for both groups the first fixation duration was about 180 ms (see Table 4) longer for pseudowords than for consonant strings, $F_1(1,24) = 47.93$; MSE $= 8442$; $p < 0.0001$ and $F_2(1,116) = 106.37$; MSE $= 8779$; $p < 0.0001$. No main effect of group, $F_1 < 1$, and no task by group interaction was observed, $F_1 < 1$.

10.2.3. Gaze duration

For gaze duration, a task by group interaction, $F_1(1,24) = 13.52$; MSE $= 364,122$; $p < 0.0012$ and $F_2(1,116) = 242.35$; MSE $= 46,898$; $p < 0.0001$, a main effect of task, $F_1(1,24) = 41.36$; MSE $= 364,122$; $p < 0.0001$ and $F_2(1,116) = 740.83$; MSE $= 46,898$; $p < 0.0001$, as well as a main effect of group was observed, $F_1(1,24) = 12.72$; MSE $= 368,373$; $p < 0.0016$

Table 4
Number of fixations, first fixation duration and gaze duration of dyslexic and normal readers during the processing of five- and six-letter consonant strings (CS) and during the reading of six-letter pseudowords (PW)

Measure	Dyslexic readers[a]		Normal readers[a]	
	M	S.D.	M	S.D.
Number of fixations [N]				
5 Letter CS	1.90	0.41	1.72	1.04
6 Letter CS	2.15	0.58	1.88	1.32
6 Letter PW	5.20	1.89	2.57	0.39
First fixation duration [ms]				
5 Letter CS	262	48	270	30
6 Letter CS	262	41	293	41
6 Letter PW	461	151	447	94
Gaze duration [ms]				
5 Letter CS	474	149	467	368
6 Letter CS	525	181	540	500
6 Letter PW	2217	1077	1001	148

[a] $n = 13$.

and $F_2(1,116) = 230.74$; MSE $= 46,898$; $p < 0.0001$. Subsequent analysis revealed, that – as evident from Table 4 – there were no differences between dyslexic and normal readers during the string-processing task, $F_1 < 1$, however during pseudoword reading dyslexic readers looked at an item 1200 ms longer than normal readers, $F_1(1,24) = 16.26$; MSE $= 590,979$; $p < 0.001$ and $F_2(1,58) = 277.02$; MSE $= 80,079$; $p < 0.0001$.

10.2.4. Correlation between reading speed and eye movement patterns during pseudoword reading

Again the reliability of the eye movement recording was inspected by non-parametric correlations between the number of items processed during the sentence reading test (i.e., reading speed) and the three eye movement measures assessed during the reading of pseudowords. High correlations with reading speed were found for number of fixations, $r(26) = -0.83$; $p < 0.0001$, and for gaze duration, $r(26) = -0.87$; $p < 0.0001$. However, no correlation was found for reading speed and first fixation duration, $r = -0.02$.

10.3. Reanalysis of Experiment 2

To examine a possible relationship between the participants' eye movement patterns and the functioning of their magnocellular system, the eye movement data of Experiment 2 were reanalyzed with respect to the participants' coherent motion sensitivity, the most commonly used indicator for the functional sensitivity of the mangocellular system. The data of the coherent motion task entered in the subsequent analysis stems from a subset of participants whose results were reported in Kronbichler, Hutzler and Wimmer (2002).

To carry out the computerized coherent motion task, participants were presented with two panels of random dot kinematograms on a Belina computer monitor (17 in., 70 Hz) in a viewing distance of 60 cm in a windowless room. Each of the two panels contained 300 randomly arranged white dots on a black background. During the experimental trials (of 2300 ms duration), in one panel, a specific percentage of the dots moved in the same direction whereas in the other panel the dots moved randomly, the participants were instructed to identify the panel with the coherently moving dots. For details on stimulus generation, staircase procedure and individual staircases, see Hansen et al. (2001); for details on the testing procedure and the algorithm for the determination of the threshold level, see Kronbichler et al. (2002). For statistical analysis, a combined threshold level was calculated on the basis of the two runs of the coherent motion task the participants were presented with.

For the combined threshold level, no reliable group difference was observed, $t(24) = 0.53$; $p > 0.05$, with a mean threshold level of M $= 10.36$; S.D. $= 6.60$ and M $= 11.64$; S.D. $= 5.69$ for the dyslexic and the control group, respectively. Because no differences for the coherent motion threshold were found between dyslexic and control readers, it is likely that the group differences observed in the eye movement patterns during pseudoword reading can not be explained in terms of coherent motion sensitivity. However, to explore a possible relationship between the functioning of the magnocellular system on the one hand and visual perception and oculomotor control on the other, the combined threshold of the coherent motion task was compared to the measures number of fixations, first fixation duration and gaze duration (collapsed for the processing of five- and six-letter consonant strings) by means of non-parametric correlations. No reliable relationship was found between the combined threshold and number of fixations, $r(26) = -0.15$; $p = 0.46$, first fixation duration, $r(26) = 0.30$; $p = 0.13$, and gaze duration, $r(26) = -0.06$; $p = 0.77$.[2]

11. Discussion

Experiment 2 did not reveal any impairment in the dyslexic readers' eye movements during string processing. In comparison to Experiment 1, the increased length of the consonant strings in Experiment 2 resulted in a higher overall number of fixations during string-processing. However, even though a higher number of fixations (and therefore visually guided fixations subsequent to the first fixation on a stimulus) was exhibited, no differences in number of fixations could be observed between dyslexic and control readers. Despite the missing group differences during string-processing, again large differences between dyslexic and control readers were observed during pseudoword reading. Surprisingly, the substantial group differences found for gaze duration (dyslexic readers looked at a pseudoword 1200 ms longer than normal readers) were based upon a higher number of fixations exhibited by the dyslexic readers – whereas the first fixation duration of both groups was of comparable length. This lack of group differences in first fixation duration stands in contrast to the findings of Experiment 1 and also to the results reported in the literature (for review, see Rayner, 1998). However, this finding can possibly be explained by the developmental course of number of fixations and fixation duration in normal readers. In his seminal review article, Rayner (1998) reports the developmental course of fixation duration and number of fixations from Grade 1 to 6 and in adults from five studies. Children in first grade exhibit a 103% higher number of fixations, but only a 52% longer fixation duration than adults. In sixth grade, children's number of fixations is 13% higher than that of adults, whereas their fixation duration is only 7% longer. It seems likely that children's fixation duration approximates that of adults faster and is not as strongly linked to reading skill as number of fixations. Given the fact that the participants of Experiment 2 attended grade 7 it is

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[2] Since a slight trend towards a correlation was found between the combined threshold and first fixation duration, we examined whether a possible relationship could be hidden by the more conservative non-parametric correlation that was used throughout the paper. However, also the Pearson correlation did not reveal a reliable correlation, $r(26) = 0.24$; $p = 0.24$.

possible that the dyslexic readers – when confronted with pseudowords that were composed of simple and very high frequency CV-syllables as in Experiment 2 – already reached the level of the control readers with regard to the faster developing measure first fixation duration, but not with regard to number of fixations. This ceiling effect account for first fixation duration in response to pseudowords of very simple structure is also supported by the correlational analysis that did not reveal any relationship between reading speed and first fixation duration – but substantial correlations between reading speed and number of fixations as well as gaze duration.

To examine the possible influence of the functionality of the magnocellular system on visual perception and oculomotor control during string-processing and pseudoword reading, the participants' eye movement patterns were reanalysed with regard to their coherent motion sensitivity. In accordance with Kronbichler et al. (2002), dyslexic readers did not perform worse than control readers in the coherent motion task. Thus, because dyslexic and normal readers did not differ in coherent motion sensitivity, the group differences in eye movement patterns observed during pseudoword reading can not be explained in terms of group difference in the functionality of the magnocellular system. Furthermore, although no differences were observed between dyslexic and control readers in the eye movement patterns during string-processing, we examined whether the interindividual variance in the eye movement patterns was related to coherent motion sensitivity. However, no relationship was found between any of the eye movement measures during string-processing and the participants' functionality of the magnocellular system.

12. General discussion

The aim of Experiments 1 and 2 was to explore possible visual perceptual and oculomotor deficits in dyslexic children. More specifically, two main consequences of a possible magnocellular deficit in dyslexic readers were proposed and subsequently investigated. A first assumption was that dyslexic readers suffer from a perceptual impairment, which is substantial enough to hinder them from accurately perceiving a word they have to read. It was expected that if dyslexic readers do have such a perceptual and oculomotor deficit this impairment should manifest itself during the string-processing task in an eye movement pattern that is different from those of control readers. Furthermore, it was of interest to what extent the divergent eye movement patterns of dyslexic children during pseudoword reading can be explained in terms of magnocellular deficits, that is, to what degree the dyslexic readers' higher number and longer duration of fixations during pseudoword reading reflect a higher effort in perceiving these novel items.

The present study did not reveal any differences in the eye movement patterns of dyslexic and control readers during string-processing (and therefore, confirmed results by Olson, Conners, & Rack, 1991, from a related task). This absence of differences between dyslexic and normal readers is of particular relevance, since the consonant strings presented in the string-processing task had almost the same visual characteristics as pseudowords and the perceptual and oculomotor demands that were required during the string-processing task were very close to those required during pseudoword reading – the string-processing task therefore was of immediate relevance for reading. Because of this immediate relevance for reading, a strong inference can be drawn: Dyslexic readers do not seem to have difficulties in the accurate perception of letters during reading and the control of their eye movements.

Most often, the absence of differences between dyslexic and control readers in visual tasks is countered by the proponents of the magnocellular deficit hypothesis with the argument that a study's dyslexic sample was somehow specific, one that does not have any magnocellular impairments and that "it is illogical to conclude that the absence of evidence for some aspects of a magnocellular deficit in some dyslexics is evidence of its absence in all." (Stein & Walsh, 1997). However, in the present study, substantial interindividual variance was found in magnocellular performance – that was not related to eye movement patterns during string processing.

The absence of any differences in eye movement patterns during string processing furthermore suggests that the divergent eye movement patterns of dyslexic readers during pseudoword reading solely reflect their difficulties in "the reading" process. This finding is supported by evidence from Olson, Conners, and Rack (1991) and from Hyönä and Olson (1995) who compared dyslexic readers' eye movements with those of younger, reading level matched controls and did not find any differences. Similarly, Olson, Kliegl, and Davidson (1983) showed that when dyslexic readers were confronted with a text appropriate for their reading level, their eye movement patterns were comparable to those of normal readers at that particular reading level. Therefore, a second important conclusion of the present study is that dyslexic readers' eye movements during reading are neither dysfunctional nor erroneous – but a mirror of their reading difficulties.

The string-processing task used in the present study provides an empirical link between the magnocellular deficit hypothesis and reading that had been missing up to now, since the tasks (e.g., the coherent motion task) that were used to test the sensitivity of the magnocellular system were only of indirect relevance for reading. By all means, it might be the case that a deficit in the functionality of the magnocellular system has an effect on – for example – saccadic suppression and the control of visually guided eye movements. However, the consequences of these deficits do not seem to be substantial enough to affect perception and oculomotor control during reading and therefore are not as drastic as described by the proponents of the magnocellular deficit hypothesis. Dyslexic readers seem to be able to accurately perceive the

visual information which is necessary for reading and to move their eyes accurately during reading.

Although the functioning of the magnocellular system might not affect visual perception and oculomotor control during string-processing and reading, the functioning of the magnocellular system is potentially correlated with reading skill. Even though several studies (e.g., Johannes, Kussmaul, Münte & Mangun, 1996; Ramus et al., 2003; Skottun, 1997) failed to replicate the finding of a magnocellular deficit in dyslexic readers, the magnocellular framework is well elaborated and numerous studies did find a such a deficit and its neurophysiological correlates. However, the mere existence of differences between dyslexic and normal readers does not prove the relevance of these differences for reading. In fact, the present study could not confirm the supposedly drastic consequences of the functionality of the magnocellular system (as they are proposed by the proponents of the magnocellular deficit hypothesis) on visual perception and oculomotor control during reading. Furthermore, the results of the present study suggest that there is no relationship between the functioning of the magnocellular system and visual perception and oculomotor control during the string-processing tasks. Thus Frith and Frith (1996) could be right with their claim that a possible magnocellular deficit in dyslexic readers does not directly cause their reading difficulties, but rather is a marker of a genetic deviation. As Frith and Frith state, perhaps this genetic deviation does manifest itself in several ways (for example in a magnocellular deficit) that are not related to the reading disorder and in other ways that do affect reading. Therefore, even though Stein, Talcott and Walsh (2000) might be right with their statement that "[. . .] the idea that many, if not most, developmental dyslexics have mildly impaired development of the visual magnocellular system has taken firm root" – it just remains to be decided whether this is a correlational or a causal relationship.

Clearly, further research is necessary and the present study's results have to be replicated with other dyslexic samples by using perhaps different string-processing tasks. However, in any case an additional task of immediate relevance for reading should be included in future studies on visual perception and oculomotor control of dyslexics.

Acknowledgment

Appendix A

See Table A.1.

Table A.1
Examples for the stimulus material for Experiment 1

Three letter consonant strings	Four letter consonant strings	Four letter pseudowords
Experimental stimuli		
GDR	LBQD	DREV
DSB	LQWB	GINZ
FRC	DMGL	PUKS
Target stimuli		
TTC	QQGP	
MMF	LFFD	
ZBB	VPLL	

Appendix B

See Table A.2.

Table A.2
Examples for the stimulus material for Experiment 2

Five letter consonant strings	Six letter consonant strings	Six letter pseudowords
Experimental stimuli		
RHNBM	QDWKSX	liribi
VHLBW	LTCBNQ	anleni
QLXTV	MWTFHG	lafima
Target stimuli		
NNNML	HHHXGL	
HVVVL	GDDDMH	
KXXXM	RTBBBF	

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