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Vision Research 44 (2004) 2413–2424
Vision Research
www.elsevier.com/locate/visres

Wider recognition in peripheral vision common to different subtypes of dyslexia

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Received 23 April 2003; received in revised form 3 November 2003

Abstract

Italian children ($n = 125$) were classified into dyslexics, poor readers and ordinary readers. The dyslexics were further classified into the Boder and Bakker subtypes. The children were tested with the form-resolving field (FRF), which measures central and peripheral visual recognition. Dyslexics show higher correct identification of letters in the periphery, supporting the notion of a different distribution of lateral masking. A numerical characterization of individual FRFs—C2R—reliably distinguishes between dyslexics and ordinary readers. The wider distribution of recognition, similar across the various subtypes of dyslexia, suggests a general characteristic of visual perception, and possibly a different visual-attentional mode.

Keywords: Dyslexia; Lateral masking; Peripheral vision; Visual attention

1. Introduction

In the last few decades, research on developmental dyslexia has pointed to phonological deficits as the main cause of reading difficulties (Bradley & Bryant, 1983; Liberman, Schankweiler, Fischer, & Carter, 1974). In recent years, however, renewed interest has been devoted to the visual aspects of reading and dyslexia. Slaghuis and Lovegrove (1984) suggested that longer visible persistence of previous fixations may mask the currently fixated text, thus interfering with the process of letter identification. Since interference from previous fixations is normally prevented by an inhibitory process from the transient visual subsystem on the sustained pathways, these effects had been interpreted as a consequence of an inadequate inhibition of the sustained system by the transient subsystem (but see also Burr, Morrone, & Ross, 1994, for counterevidence). These phenomena were later described as the "magnocellular deficit" hypothesis, where the magnocellular pathway was suggested to correspond to the transient system, and the parvocellular pathway to the sustained system (Livingstone, Rosen, Drislane, & Galaburda, 1991). Since then, many studies have contributed further data to support it (e.g. Slaghuis & Ryan, 1999). The hypothesis of a magnocellular deficit as an alternative, although controversial, explanation for developmental dyslexia has been strongly advocated by Stein and Walsh (1997). The main criticisms to the theory point to the evidence showing that impairment in visual tasks is highly dependent on the specific paradigm (Ben-Yehudah, Sackett, Malchi-Ginzberg, & Ahissar, 2001; Stuart, McAnally, & Castles, 2001) and extends beyond the magnocellular domain (Amitay, Ben-Yehudah, Banai, & Ahissav, 2002; Skottun, 2000). In this line of research, Hill and Lovegrove (1993) and Lovegrove and MacFarlane (1990) showed that reading difficulties are more evident when an individual is asked to read words embedded in text than single words. This may be interpreted as a lack of coordination between peripheral and foveal vision, and may be related to the phenomenon of lateral masking, which would also account for the dyslexics' greater difficulties at reading strings of letters than single letters (Bouma & Legein, 1977).

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doi:10.1016/j.visres.2004.05.001

Lateral masking, which is sometimes referred to as "visual crowding", is the process by which a visual stimulus becomes less recognizable when flanked by other visual elements (Flom, Heath, & Takahashi, 1963). If lateral masking in the periphery is not effective, visual information from the entire surroundings is simultaneously processed, which may result in confusion and unclear perception (Geiger, Lettvin, & Zegarra-Moran, 1992). While Bouma (1970) conceived lateral masking as a fixed property of the interactions between central and peripheral vision, Geiger and Lettvin (1986) demonstrated, with the phenomena they called de-masking, that the information that is masked is not passively filtered in early processing but can be retrieved. Hence, lateral masking is considered by these authors as an active process, suppressing information that had been previously processed. The spatial distribution of lateral masking, in dyslexics and ordinary readers, was measured by Geiger and colleagues in a task where pairs of letters, one at the centre of gaze and one in the periphery (along the horizontal axis), were briefly presented. Eccentricity of the peripheral letters varied across presentations. While ordinary readers show a sharp decrease in the recognition rate of the peripheral letter with increasing eccentricity, adult dyslexic readers had a wider area of correct identification in the periphery of the right hemifield, (Geiger & Lettvin, 1987). By plotting the recognition rate of the peripheral letter against eccentricity (left and right of fixation), a distribution is obtained that Geiger et al. (1992) named FRF (form-resolving field). While the FRF of ordinary readers is about symmetrical, its shape in adult, English-native dyslexic readers is significantly wider on the right side, and does not fall off monotonically with eccentricity. Since the FRF of Hebrew-native dyslexics shows the same kind of asymmetric shape but is wider on the left side (the direction of reading in Hebrew), Geiger et al. (1992) concluded that asymmetry in the FRF of dyslexic readers is strongly correlated with the direction of reading. They thus proposed that the process of lateral masking is not only active, but also learned by practice and task-dependent (Geiger et al., 1992).

Further, Geiger, Lettvin, and Fahle (1994) observed that the FRFs of dyslexic children are less asymmetric than those of adult dyslexics, although still wider than those of normal readers. On the other hand, Geiger and colleagues showed that training dyslexic readers to learn a new strategy for reading results in a narrowing of the FRF in the right side (Geiger et al., 1994; Geiger & Lettvin, 2000).

Different dyslexia subtypes have been shown, in some cases, to be characterised by distinct patterns of impairment on auditory, visual or cross-modal tasks.

Among the well-known classification systems for subtypes of dyslexia is Boder's classification (Boder, 1973). It classifies dyslexics into dysphonetic (having difficulties especially with grapheme–phoneme conversion, i.e. with the indirect route for reading), dyseidetic (having difficulties with visual recognition of whole words, i.e. with the direct route for reading) and mixed (having both types of difficulties) subtypes.

A different subtyping system is Bakker's classification (Bakker, 1979, 1990) into P-types (relying on perceptual, analytical strategies for reading, which turns out to be slow, fragmented and hesitating), L-types (relying on linguistic, anticipatory strategies for reading, which allow for quicker reading but produce many, usually plausible and context-based errors) and M-types (mixed types, showing both slow, fragmented reading and many errors). In Bakker's model, the two subtypes are characterised by a different degree of involvement of the two cerebral hemispheres in the reading process, the right hemisphere being more activated in reading for P-types, the left one for L-types.

Both classification systems, therefore, suggest that visual functions can be impaired or underactivated in different dyslexia subtypes. However, in consideration of the different theoretical assumptions and the reliance on different parameters for classification (text reading speed and accuracy as opposed to reading different subsets of stimuli), the two types of classification will be analysed separately in this study.

Farmer and Klein's study (1995) suggested that Boder's subtypes of dyslexia can be related to the sensory modality in which the deficits are more evident: the visual modality in dyseidetic dyslexics, the auditory modality in dysphonetic dyslexics, and both modalities in the mixed subtype. It is not easy, yet, to trace a direct relationship with recent studies on visual and auditory processes in reading depending on the magnocellular system. Indeed, Ridder, Borsting, Cooper, McNeel, and Huang (1997) found that a decrease in spatial contrast sensitivity at high temporal frequencies (suggested to be a magnocellular function) was only present in dysphonetic and mixed subtypes, and not in dyseidetics. Moreover, studies on normal subjects failed to show a difference in visual temporal resolution between subjects who are better at irregular word reading and those who are better at non-word reading (Au & Lovegrove, 2001). As for Bakker's classification, Van Strien (1994) suggests that P-types have better visual abilities, while L-types have better linguistic, anticipatory strategies. Yet, P-types seem to read via the phonological route, like dyseidetic dyslexics, whereas L-types' reading abilities are more similar to Boder's dysphonetics (Licht, 1989, 1994).

Cestnick and Coltheart (1999) even proposed an association between visual and phonological (non-word reading) skills, and suggested two possible explanations: simple anatomical adjacency of two functionally unrelated systems on the one hand, or, on the other hand, the fact that reading non-words as opposed to words requires a serial left-to-right allocation of covert attention across the letter string, and that this process may depend on magnocellular functions. A similar explanation has been put forward by Facoetti and colleagues (Facoetti, Lorusso, Paganoni, Umiltà, & Mascetti, 2003; Facoetti, Paganoni, & Lorusso, 2000; Facoetti, Turatto, Lorusso, & Mascetti, 2001), along with data that clearly support the hypothesis of a visual-attentional deficit in developmental dyslexia. It could thus be suggested that the particular perceptual strategy described by Geiger et al. (1992) may also be expressed as a diffused mode of attention, proposed by Facoetti and colleagues (Facoetti et al., 2000, 2003) as the characteristic of dyslexic reading.

The present study aims at verifying the distribution of visual recognition in Italian dyslexic and ordinary readers, and further at comparing the various subgroups of dyslexics, both according to known classification systems (Boder's and Bakker's) and to other possibly relevant variables, such as the degree or severity of the reading difficulty.

2. Methods

2.1. Participants

Participants were 125 children, native Italian speakers, aged between 8 and 16 years. They were classified into three groups: dyslexics, poor readers and ordinary readers or controls. Eighty-one children were diagnosed as dyslexics (14 females and 67 males), 17 as poor readers (5 females and 12 males) and 27 were ordinary readers (16 females and 11 males). The three groups were comparable with respect to age and school grade. Mean age of the dyslexic group was 10.52 (standard deviation—SD = 2.43), 10.11 (3.03) for poor readers and 11.08 (1.67) for ordinary readers. The mean attended grade was 5.32 (1.9) for the dyslexic group, 5.29 (1.79) for poor readers and 5.56 (1.74) for ordinary readers, with no significant differences between the groups on both variables according to t-tests ($p > 0.05$).

The reading disabled children had been referred to the Unit of Cognitive Psychology and Neuropsychology of Scientific Institute "E. Medea", or to the corresponding units of the collaborating centres, because of learning difficulties. Assessment and diagnosis were performed at either Scientific Institute "E. Medea" or at Bergamo Hospital.

2.1.1. Dyslexic children

The children diagnosed with developmental dyslexia met all the following criteria: Full-scale IQ (measured with the Wechsler Intelligence Scale for Children—WISC-R) equal to, or higher than, 85; at least 1 SD below age mean of either accuracy or speed scores in reading aloud of a text; at least 1 score below 2 SDs on any of the reading and spelling tests which were included in the psychometric testing.

Moreover, they had no reports of neurological or psychiatric problems, nor major emotional and social problems. Their language comprehension, assessed through the abridged version of the Token Test (Di Simoni, 1978) was not inferior to 2 SD with respect to age norms.

The dyslexic children have been further classified according to Boder's and Bakker's subtypes, as described later.

2.1.2. Poor readers

Those children whose reading scores fell between 1 and 2 SDs below age norms, but who did not meet all the reading criteria for a diagnosis of dyslexia (see above), were considered as "poor readers" and their results have been separately analysed. Of the 17 poor readers in the present sample, 12 were ex-dyslexics previously treated, and 5 were newly diagnosed cases.

2.1.3. Ordinary readers

Ordinary readers were recruited through the media and at local schools; as reported by their parents, their school achievements were in the normal range and they had no neurological or emotional problems.

All the children who participated in the study had normal or trivially corrected-to-normal vision.

2.2. Psychometric testing and classification procedures

All the children were tested for IQ, reading and spelling abilities.

In the group of children referred for reading difficulties, IQ was assessed by the WISC-R (Wechsler, 1986). Reading and spelling abilities were assessed with the following tests:

(a) *Text reading*: Prove MT di Correttezza e Rapidità nella Lettura (Cornoldi, Colpo, & Gruppo, 1986), an Italian test providing accuracy and speed scores in reading aloud age-normed texts.
(b) *Single word and non-word reading*: Batteria per la Valutazione della Dislessia e della Disortografia Evolutiva (Sartori, Job, & Tressoldi, 1995), an Italian reading and spelling assessment battery, also providing speed and accuracy scores for each grade.
(c) *Single word, non-word and sentence dictation*: Batteria per la Valutazione della Dislessia e della Disortografia Evolutiva (Sartori et al., 1995), giving accuracy scores for each grade.
(d) *Metaphonological tasks*: Phoneme elision (cancelling the first two phonemes of orally given words) and phoneme synthesis (integrating sequentially presented phonemes into words) (Cossu, Shankweiler,

Liberman, Katz, & Tola, 1988). Scores are expressed as total number of errors on the whole list of 20 words. In this test, only age means are provided as normative data. Therefore, raw scores have been used instead of normalized scores.

According to *Boder's classification* system, the children were classified as dyseidetic if their accuracy scores on single word reading were lower than −2 SDs, and accuracy scores for non-word reading were above −2 SDs. Or, they were classified as dysphonetic if their accuracy scores for word and non-word reading showed the opposite pattern (i.e. above −2 SDs for single word reading and lower than −2 SDs for non-word reading). The difference between the two scores (for words and non-words), in both cases, had to be at least 0.5 SD. In all other cases the children were classified as mixed types (Boder, 1973). This classification procedure had been chosen after various analyses of the distribution of the scores in the sample. It was chosen so as to be compatible with the definition of the subtypes by Boder (1973) and with the models of classical neuropsychology, to have significantly different performances in the different groups, and to obtain a reasonable number of subjects in each subgroup. According to *Bakker's classification*, the children were labelled as "P-types" if their percentage of "time-consuming" errors in text reading was at least 60% and text reading speed was lower than −1 SD; as "L-types" if their percentage of "substantive" errors was at least 60% and their text reading speed was above −1 SD; in all other cases, children were classified as "M-types".

Ordinary readers were assessed on text reading only. Their reading scores for accuracy and speed, assessed with the MT test, were in the normal range. Their scaled scores in the WISC-R Vocabulary and Block Design subtests were above 7.

The results of reading and spelling tests for the three groups of children (dyslexics, poor readers and ordinary readers) are shown in Table 1 (*z*-scores calculated according to age norms).

The psychometric results of the comparisons of subtypes are shown in Tables 2 and 3.

According to Boder's classification, 10 subjects were classified as dysphonetics, 14 as dyseidetic, and 51 as mixed types. Six children could not be classified because their reading was too severely impaired to perform on the whole single-word and non-word reading tests.

The children who had been classified as dysphonetic were significantly better than mixed types in word reading accuracy ($p < 0.05$). Children who had been classified as dyseidetic were significantly better than mixed types in text reading accuracy ($p < 0.005$), word reading speed ($p < 0.05$), non-word reading speed and accuracy ($p < 0.005$). On the whole, the children in the mixed subgroup appear to have greater reading difficulties than the other subgroups.

According to Bakker's model, 6 children were classified as L-types, 35 as P-types and 40 as M-types. Bakker's P-types were significantly slower than L-types on non-word reading ($p = 0.05$), and made more errors than M-types on sentence writing from dictation ($p < 0.05$). L-types were significantly faster than M-types in both word and non-word reading ($p < 0.05$). The percentage of children in each subgroup does not reflect exactly the figures described by Boder and Bakker, respectively, but the differences may be due to the transparency of Italian orthography, that allows correct reading of practically all words via the slow, phonological route (thus explaining the relatively high percentage of dyseidetic and P-types), while the high percentage of mixed types seems to be due to severity factors, as suggested before.

After psychometric testing, all the children underwent FRF measurement.

2.3. Apparatus and stimuli for measuring the form-resolving field (FRF)

The apparatus for the FRF measurement was a copy of the one used by Geiger et al. (1992, 1994). It consisted

Table 1
Means and standard deviations (in parentheses), expressed in *z*-scores, from psychometric testing in the various groups

Group	*n*	Text reading speed	Text reading accur.	Word reading speed	Word reading accur.	Nword reading speed	Nword reading accur.	Word dictat.	Nword dictat.	Senten. Dictat.	Pho-neme elision (errors)	Pho-neme synthes. (errors)
Ordinary readers	27	0.53 (0.24)	0.49 (0.43)									
Dyslexic readers	81	−3.2 (3.9)	−3.08 (2.59)	−4.78 (5.27)	−3.05 (2.79)	−3.59 (3.46)	−2.35 (1.97)	−3.56 (3.73)	−0.49 (1.44)	−5.46 (5.81)	3.60 (3.80)	5.34 (3.85)
Poor readers	17	−0.3 (0.6)	−0.30 (0.51)	−0.92 (1.25)	−0.96 (1.36)	−1.15 (0.88)	−0.07 (0.82)	−1.61 (1.45)	0.24 (0.93)	−1.53 (1.48)	2.50 (2.10)	5.14 (3.13)

Notes: Accur. = accuracy; Dictat. = dictation; Nword = non-word; Senten. = sentence.

Table 2
Means and standard deviations (in parentheses) for psychometric testing in the various subtypes according to Boder's classification

Type	*n*	Age	Text reading speed	Text read. accur.	Word read. speed	Word read. accur.	Nword read. speed	Nword read. accur.	Word dictat.	Nword dictat.	Sent. dictat.	Phon. elision (errors)	Phon. synthesis (errors)
1	10	10.65	−2.19	−2.63	−3.41	−1.20	−2.52	−2.27	−3.09	−0.41	−3.92	1.60	4.90
		(2.34)	(3.02)	(1.14)	(2.53)	(1.78)	(2.43)	(1.89)	(5.59)	(1.32)	(3.15)	(2.22)	(2.77)
2	14	10.32	−1.61	−1.54	−2.21	−2.82	−1.32	−0.87	−2.50	−0.14	−5.43	3.14	5.54
		(3.38)	(0.51)	(0.90)	(0.87)	(1.35)	(1.44)	(0.82)	(2.66)	(1.58)	(5.49)	(3.46)	(3.57)
3	51	10.72	−3.65	−3.37	−5.77	−3.46	−4.43	−2.79	−3.91	−0.53	−5.81	3.84	4.90
		(2.15)	(4.27)	(2.14)	(6.11)	(3.12)	(3.37)	(2.04)	(3.54)	(1.36)	(6.41)	(4.01)	(3.77)

If not otherwise specified, scores are expressed as *z*-values.
Notes: Type 1 = dysphonetic; Type 2 = dyseidetic; Type 3 = mixed; Accur. = accuracy; Nword = non-word; Sent. = sentence; Dictat. = dictation; Phon. = phonemic.

Table 3
Means and standard deviations (in parentheses) for psychometric testing in the various subtypes according to Bakker's classification

Type	*n*	Age	Text read. speed	Text read. accur.	Word read. speed	Word read. accur.	Nword read. speed	Nword read. accur.	Word dictat.	Nword dictat.	Sent. dictat.	Phon. elision (errors)	Phon. synthesis (errors)
L-types	6	10.77	−0.92	−2.18	−1.04	−2.02	−0.86	−1.99	−1.66	−0.12	−2.50	2.67	3.83
		(1.77)	(0.64)	(1.56)	(1.44)	(1.72)	(0.81)	(2.08)	(1.96)	(1.26)	(2.58)	(2.16)	(2.93)
P-types	35	10.72	−4.00	−2.81	−5.87	−2.87	−4.52	−2.20	−4.37	−0.51	−7.55	3.57	4.79
		(3.01)	(4.57)	(1.59)	(6.58)	(2.75)	(4.40)	(1.82)	(3.69)	(1.23)	(7.73)	(4.33)	(4.18)
M-types	40	10.31	−2.88	−3.44	−4.37	−3.41	−3.18	−2.55	−3.12	−0.53	−4.08	3.78	6.11
		(1.93)	(3.48)	(3.30)	(3.80)	(2.96)	(2.24)	(2.12)	(3.88)	(1.67)	(2.86)	(3.50)	(3.57)

If not otherwise specified, scores are expressed as *z*-values.
Notes: Accur. = accuracy; Dictat. = dictation; Nword = non-word; Sent. = sentence; Phon. = phonemic.

of three slide projectors, each equipped with a flat field lens and a fast electronically activated mechanical shutter (Vincent Ass.). The slides were back-projected onto the same location on a white diffusing screen. The size of the image of the slide on the screen was 48 × 32 cm (subtending 39° × 26° of visual angle from 70 cm distance). The first projector carried a slide with a central black fixation point; the second one carried the stimulus slide with black letters on it; the third carried a blank "eraser" slide. A blank eraser was chosen, rather than a structured one, to avoid introducing a disadvantage for dyslexics, due to backward masking. A specially designed timer controlled electronically the opening and closing of the shutters, the order of presentation of the slides on the screen and the duration of the presentation. The rise and fall times of the shutters were 3 ms each. By interspersing the opening and closing of the three shutters, stimuli durations as short as 3 ms were achieved and luminance changes on the screen, during transitions between slide presentations, were minimal (<10%). A direct optical device was preferred to presentation on a CRT (PC screen), in order to ensure adequate spatial and temporal resolution (Geiger & Lettvin, 1998, 2000). Stimulus duration was determined individually for each subject, and ranged between 3 and 60 ms. Each stimulus consisted of two upper-case letters, one at the fixation point (centre) and the other in the periphery along the horizontal axis. The eccentricity of the peripheral letter varied from 2.5° to 12.5° from the fixation point, in 2.5° steps to the left and right. Twenty stimuli were presented at each eccentricity. In half of the slides, the peripheral letter appeared to the left of the central letter, while in the other half it appeared to the right, in random order. The two letters on each slide were different and were chosen from a fixed set of 10 upper-case Helvetica-medium letters. Letter height subtended 35 min of visual arc, and letter contrast was 90%. Each letter appeared once at each of the eccentric positions, and twice in central position.

2.4. Procedure for measuring the FRF

The procedure was the same as in Geiger et al. (1992). The subjects sat at a distance of 70 cm from the screen in a dimly lit room. They were asked to gaze at the fixation point. After a verbal warning, the stimulus slide was projected replacing the fixation point slide and followed by the blank eraser, which was projected for 2.5 s, after which the fixation point was presented again to start a new cycle. The subject was requested to name the two letters specifying their positions. After presenting all the stimuli, a plot of correct identification of the peripheral letter, as a function of eccentricity, was made. This plot is the FRF. The score of correct identification of the central letters was given numerically. The random order of the side of presentation of the peripheral letter prevented the possibility that the children try to anticipate its presentation by shifting their gaze to either side of the fixation point. Furthermore, fixation was visually controlled by the experimenter, and 100% recognition of the central letter was considered as confirming that fixation was kept in the centre of the screen.

The stimulus duration (which we name T_{eff} for "effective duration") was determined individually for each subject, before the actual measurement. The chosen duration was the time at which the subject's recognition was about 100% at 2.5°, and just below 100% at 5°. This normalization procedure, called auto-scaling, prevents saturation effects. The other purpose of normalisation is to determine the relative central vs. peripheral rate of recognition at the optimal duration time for each individual and by that be able to compare across subjects. The duration of stimulus presentation was kept constant throughout the actual measurement.

Note: The experiments conducted in this study had been approved by the ethical committee of the Institute and were undertaken with the understanding and written consent of the children's parents.

3. Results

3.1. FRF measurement

Fig. 1 shows three FRF plots of the averages of correct recognition of the peripheral letters in the stimuli, as a function of eccentricity. Separate plots are shown for dyslexics, poor readers and ordinary readers.

1. At a visual inspection of the plots, it can be seen that the FRFs of dyslexics and ordinary readers are clearly different. A repeated-measure analysis of variance (ANOVA) was performed on accuracy data, with side (left vs. right) and eccentricity as within-subject factors, and group (dyslexics vs. poor readers vs. ordinary readers) as between-subject factor. All main effects were highly significant (group—$F(2,122) = 4.00$, $p = 0.021$, $\partial\eta^2 = 0.062$; side—$F(1,122) = 33.59$, $p < 0.001$, $\partial\eta^2 = 0.216$; eccentricity—$F(4,488) = 943.04$, $p < 0.001$, $\partial\eta^2 = 0.885$) and so were 2-way interactions (group × eccentricity—$F(8,488) = 5.06$, $p < 0.001$, $\partial\eta^2 = 0.077$; group × side—$F(2,122) = 8.01$, $p = 0.001$, $\partial\eta^2 = 0.116$; side × eccentricity—$F(4,488) = 10.87$, $p < 0.001$, $\partial\eta^2 = 0.082$) and 3-way interaction (group × side × eccentricity—$F(8,488) = 3.95$, $p < 0.001$, $\partial\eta^2 = 0.061$). Post hoc tests (Newman–Keuls) for the various eccentricities show that the dyslexics and poor readers have significantly higher recognition rates than ordinary readers in the right side, at 10° and 12.5°, while only dyslexics differ significantly from ordinary readers at 7.5° (all ps < 0.05). In the left side

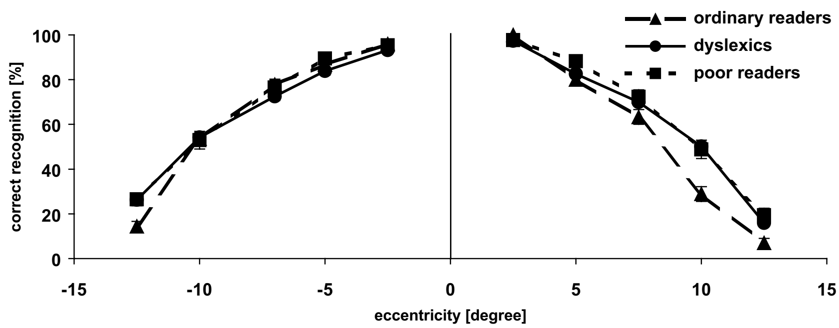

Fig. 1. The FRFs of ordinary readers ($n = 27$), dyslexic readers ($n = 81$) and poor readers ($n = 17$). The measure is average correct recognition (%) of the peripheral letter in the letter pairs, at the different eccentricities. Means and standard deviations of each group at the various eccentricities are reported in Table 4.

with respect to fixation, ordinary readers have significantly lower recognition rates than the other two groups at −12.5° only ($p < 0.005$). Means and standard deviations are presented in Table 4.

2. The FRFs of dyslexics and poor readers are visually similar and do not differ significantly at any eccentricity.
3. In addition, average stimulus duration is significantly longer ($F(2,122) = 6.10$, $p < 0.005$, $\partial\eta^2 = 0.091$) for dyslexics (mean = 10.99, SD = 6.57) than for ordinary readers (mean = 6.94, SD = 1.63).

3.2. The FRF as a numerical diagnostic tool

Since the differences in recognition between individual dyslexics and ordinary readers lie in the overall shape of the FRF to a greater extent than in the specific values at each eccentricity, it seemed helpful to use a numerical index that could represent the characteristics of each individual FRF plot. In order to characterize an individual FRF, we calculated "Criterion 2" (C2), which is the ratio between the recognition rate at 2.5° and the sum of the recognition rates at 10° and 12.5°. C2 can be calculated for the left (C2L) and for the right side (C2R) with respect to the fixation point.

That is

$$C2 = \frac{\%\text{ correct at }2.5^\circ}{\%\text{ correct at }10^\circ + \%\text{ correct at }12.5^\circ}$$

A repeated-measure ANOVA with side (left vs. right C2) as a within-factor and group as a between-factor confirmed what had been previously observed on the single eccentricities. Besides the two main effects of group ($F(2,122) = 10.15$, $p < 0.001$, $\partial\eta^2 = 0.143$) and side ($F(1,122) = 49.08$, $p < 0.001$, $\partial\eta^2 = 0.287$), there was in fact a significant group × side interaction ($F(2,122) = 20.99$, $p < 0.001$, $\partial\eta^2 = 0.256$). Post hoc tests (Newman–Keuls) showed that average C2R values were significantly smaller for dyslexics (mean = 1.77, SD = 1.20) and poor readers (mean = 1.67, SD = 0.96) than for ordinary readers (mean = 4.11, SD = 2.80), while no differences were found for C2L (means = 1.44, 1.28 and 1.53, and SDs = 1.18, 0.33 and 0.55, respectively).

After testing and refining on previous data from elsewhere (Geiger & Lettvin, 2000), C2R as a diagnostic tool was empirically set to values shown below:

$$C2R = \begin{cases} > 2 \Rightarrow \text{ordinary reader}, \\ \leqslant 2 \Rightarrow \text{dyslexic}. \end{cases}$$

To evaluate the discriminating power of the FRF by using C2R to distinguish dyslexic children from ordinary readers, a receiver operating characteristic (ROC) curve was computed. The results show that 91% of the dyslexic children and 78% of ordinary readers were classified correctly, when the cut-off value of C2R was set to 2, as shown above (i.e. 9% false negatives and 22% false positives).

Table 4
Means and standard deviations (in parentheses) for FRF values at the various eccentricities, for ordinary readers, dyslexics and poor readers

Group	n	−12.5°*	−10°	−7.5°	−5°	−2.5°	2.5°	5°	7.5°*	10°*	12.5°*
Ordinary readers	27	14.44 (11.55)	53.70 (11.82)	77.78 (12.51)	86.67 (12.40)	95.93 (6.36)	100.00 (0.00)	80.00 (10.38)	63.33 (17.32)	28.89 (17.17)	7.04 (10.31)
Dyslexics	81	26.30 (17.78)	54.20 (18.02)	72.47 (16.40)	83.83 (16.09)	93.21 (8.64)	97.41 (7.87)	82.59 (13.58)	70.00 (14.32)	50.12 (16.92)	15.93 (12.12)
Poor readers	17	26.47 (11.69)	52.94 (16.11)	76.47 (14.12)	89.41 (8.99)	95.29 (6.24)	97.65 (4.37)	88.24 (7.28)	72.35 (13.00)	48.82 (16.91)	19.41 (12.98)

The values represent the mean percentage of correctly recognized letters at each eccentricity. Negative values stand for the left visual hemifield. Asterisks mark the eccentricities at which significant differences were found between groups in the ANOVA.

3.3. The FRFs of the various subtypes of dyslexia

The FRF plots of Boder subtypes, shown in Fig. 2, are similar and ANOVA (with side and eccentricity as within-factors and subtype as between-factor) did not show any significant interaction. As seen in Fig. 3, the same is true for the various Bakker subtypes. An ANOVA on C2R, with subtype as a between-factor, confirmed the absence of significant differences across subtypes (all $p\text{s} > 0.05$).

Moreover, comparison of dyslexic subtypes and ordinary readers (including ordinary readers as a separate subtype) in two ANOVAs, one according to Boder's classification and the other according to Bakker's classification confirmed that C2R is significantly larger in dyslexic readers regardless of subtype (all $p\text{s} < 0.001$). The results of the ANOVAs are shown in Table 5. Asterisks mark the subtypes that were found in post hoc tests (Bonferroni) to be significantly different from ordinary readers. All these results have been confirmed with non-parametric analyses (Kruskal–Wallis), considering the small number of subjects in some subgroups.

4. Discussion

Based on rigorous psychometric measures, 125 Italian children were classified into three distinct groups: dyslexics, poor readers and ordinary readers. The dyslexic children were further classified according to Bakker and Boder subtypes.

All the children participated in a non-reading measure of visual perception—the FRF—which measures recognition of letters presented in the centre and in the periphery of the visual field simultaneously.

The FRFs of the children who were diagnosed as dyslexic or poor readers show that their visual recognition rate of letters in the periphery to the right of fixation is significantly higher than that of ordinary readers. This is apparent both from the data obtained at each separate eccentricity, and in the characterisation of the FRF plot by C2R (expressed by the ratio between the recognition rate near the fixation point and in the periphery). These findings are similar to those previously described in children (Geiger et al., 1994) and in adults (Dautrich, 1993; Geiger & Lettvin, 1987, 2000; Geiger et al., 1992; Perry, Dember, Warm, & Sacks, 1989). By

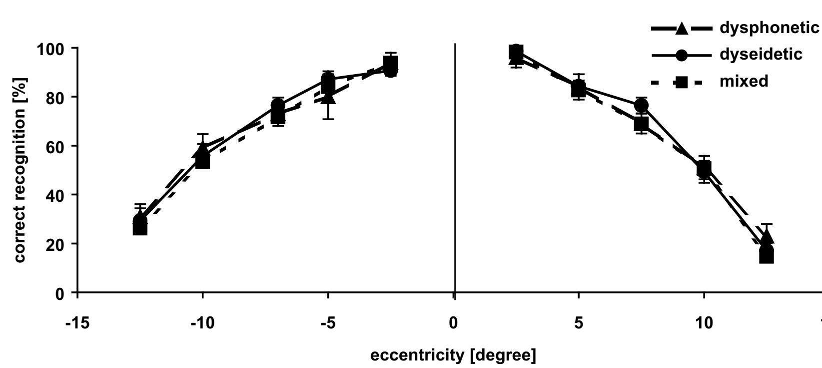

Fig. 2. The FRFs of the three subgroups of dyslexic readers according to Boder's classification (dysphonetics, $n = 10$; dyseidetics, $n = 14$; mixed types, $n = 51$). The measure is average correct recognition (%) of the peripheral letter in the letter pairs, at the different eccentricities.

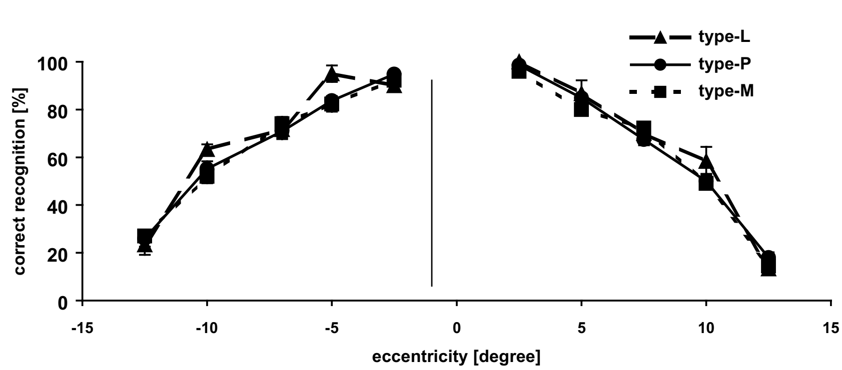

Fig. 3. The FRFs of the three subgroups of dyslexic readers according to Bakker's classification (L-types, $n = 6$; P-types, $n = 35$; M-types, $n = 40$). The measure is average correct recognition (%) of the peripheral letter in the letter pairs, at the different eccentricities.

Table 5
Means and standard deviations (in parentheses) for stimulus duration (T_{eff}) and for C2R in the various subgroups (dyslexia subtypes according to Boder's and Bakker's classification, and ordinary readers), along with results of the ANOVAs

Group	n	T_{eff}	ANOVA		C2R	ANOVA	
			F (main effect of subgroup)	Post hoc (Bonf.)		F (main effect of subgroup)	Post hoc (Bonf.)
Ordinary readers	27	6.94 (1.63)			4.11 (2.80)		
Dyslexia subtypes according to Boder							
Dysphonetics	10	15.40 (15.53)	$F(3,109) = 5.65$,	**	1.43 (0.41)	$F(3,109) = 13.81$,	**
Dyseidetics	14	10.79 (5.92)	$p = 0.001$,		1.70 (0.76)	$p < 0.001$,	**
Mixed	51	9.91 (2.95)	$\partial\eta^2 = 0.135$	**	1.84 (1.39)	$\partial\eta^2 = 0.275$	**
Dyslexia subtypes according to Barker							
L-types	6	14.17 (7.39)	$F(3,116) = 3.72$,		1.47 (0.37)	$F(3,116) = 14.42$,	**
P-types	35	10.13 (3.18)	$p = 0.01$,	**	1.83 (1.56)	$p < 0.001$,	**
M-types	40	11.28 (8.39)	$\partial\eta^2 = 0.088$	**	1.76 (0.89)	$\partial\eta^2 = 0.272$	**

Effect sizes ($\partial\eta^2$) are reported. Asterisks mark the subgroups that were found to be significantly different from ordinary readers in post hoc tests (Bonferroni).

using C2R as an index, with 2 as cut-off value, 91% of the dyslexic children and 78% of normal readers were correctly classified.

The numerical index expressed by C2R gives a quantitative measure of the perceptual differences of people with dyslexia, which was previously described only qualitatively by the shape of the FRF. The FRF, together with C2R, can therefore be considered as a useful diagnostic tool to complement assessment of reading performance, especially in those cases where the latter is not reliable (e.g. children assessed in a language that is not their mother-tongue). In this perspective, further studies would be needed to verify whether this "different" FRF is specific to dyslexia, or it is also found in other developmental disorders.

For the moment being, it can be stated that the different extent of perception to the right of fixation, as measured by the FRF—wider for dyslexic readers and narrower for ordinary readers—is general to the dyslexic population. The various analyses performed with the psychometric classification took into account both the comparison between different kinds of stimuli (Boder: words vs. non-words) and other reading parameters such as speed and type of errors (Bakker: fragmentations, repetitions vs. substitutions and anticipations). None of these parameters, however, produced subclassifications showing any differences in FRF characteristics. Moreover, the FRFs of poor readers (many of which were ex-dyslexics) are similar to those of dyslexic children and wider than those of ordinary readers.

The absence of significant differences in the FRFs of the various subtypes of dyslexia classified according to Bakker or Boder, suggests that a wider FRF is a characteristic general to dyslexic readers, and that it has more to do with the organization of visual perception than with the subsequent processes of stimulus analysis that distinguish the various subgroups (e.g. using more phonologically-based or more lexical strategies). Moreover, it suggests that this characteristic distribution of recognition across the visual field does not reflect the differences in visual–perceptual functions across subtypes of dyslexia, that have been described by several authors (see Farmer & Klein, 1995, or Ridder et al., 1997, relating to Boder's subtypes, and Van Strien, 1994, relating to Bakker's subtypes).

Indeed, the fact that the FRFs of dyslexic and ordinary readers are quite similar in the left side (both "broad") and only differ on the right side of fixation, could suggest that a process of "narrowing to the right" characterizes children who learn to read normally (rather than "broadening to the right" characterizing dyslexic readers). Indeed, a similar, although slight, asymmetry of the FRF in ordinary readers, narrower in the direction of reading, can also be seen in the data reported by Geiger et al. (1994) on German children, by Geiger et al. (1992) on adult English and Hebrew-native readers, or by Zegarra-Moran and Geiger (1993) on adult Italian readers. The last authors, in addition, reported a symmetric FRF measured with non-verbal symbols in pre-school children.

It should also be considered that small differences between the various studies in the FRF testing procedure (mainly related to the auto-scaling procedure) might account for the slight differences in the FRF profiles (more or less asymmetric). Moreover, different degrees of orthographic transparency of the various languages and different educational systems, besides differences in number, age and stage of reading acquisition of participants, may manifest themselves in the FRF. Nonetheless, if confirmed by further studies, the finding of a progressive "narrowing" of the FRF on the right side in normal readers would further support the idea, proposed by Geiger et al. (1992), that lateral masking (conceived as a learned and task-dependent visuo-perceptual mechanism that determines the region of saliency) is involved in the process of learning to read, and that dyslexic children fail to learn how to mask irrelevant information. More specifically, the "lack of narrowing" of the FRF could be related to a less efficient masking of the peripheral stimulus, by both the central stimulus and the self-masking of the icon's parts, possibly due to an inappropriate learned perceptual strategy (Geiger & Lettvin, 1987, 1999; Geiger et al., 1992).

Indeed, as noted by Geiger et al. (1992, 1994), this difficulty should be interpreted as a manifestation of an underlying cause, genetically and/or physiologically determined, rather than as an ultimate explanation of dyslexia. Reduced lateral masking could offer an explanation for the dyslexics' frequent reports of unclear, unstable perception of letters within words, confusions of perceptually similar letters, inversions and omissions within the letter strings to be read. Similarly, the inability to mask the text surrounding the word currently read makes confusion across words likely (Geiger & Lettvin, 1999). Studies showing a narrowing of the FRF along with improvement in reading following training of a different visual strategy in reading and of a more focused attentional mode (Geiger et al., 1992, 1994) suggest that visual strategies (or attentional mode) can be modified and more effective reading strategies can be learned.

Unlike in previous studies (Geiger et al., 1994; Perry et al., 1989), where the average stimulus duration was similar for dyslexics and ordinary readers, in this study the average stimulus duration was longer for dyslexics than for ordinary readers. This might be due to a slower decoding process, that could also be interpreted in the light of the magnocellular hypothesis of a deficit in perceiving rapidly presented stimuli. An alternative explanation (which does not exclude the previous one) suggests that the higher lateral masking found in dyslexics near the centre (Atkinson, 1991; Bouma & Legein, 1977; Geiger & Lettvin, 1987; Geiger et al., 1992) requires longer stimulus durations (T_{eff}) in order to achieve 100% correct recognition at 2.5° (auto-scaling procedure).

An additional interpretation of our results is that the broader FRF observed in dyslexic children could depend on their difficulty to focus attention in the centre and hence to inhibit the information coming from the periphery, i.e. on a more diffused attentional state (Facoetti et al., 2000). It is known that spatial orienting and spatial focusing of attention are subserved by a neurofunctional system involving the right parietal lobes (Corbetta & Shulman, 2002), which are receiving inputs from the magnocellular (transient) pathways (Breitmeyer & Ganz, 1976; Steinman, Steinman, & Lehmkuhle, 1996). It has been demonstrated that these attentional functions are impaired in dyslexic children (Facoetti et al., 2000, 2001, 2003).

This connection between reading difficulties and attentional functions might be related to the hypothesis of a magnocellular deficit in dyslexia, considering that the transient system gives inputs to the attentional areas and it cannot be excluded that the magnocellular pathways constitute the defective part of the whole system. Indeed, Iles, Walsh, and Richardson (2000) showed that dyslexic subjects who were impaired on low-level psychophysical tasks that are thought to be subserved by the magnocellular system (enhanced motion coherence thresholds), also exhibited deficits in higher-level visual processing depending on parietal functions (visual search tasks). However, consistent evidence has been collected in the last years, showing that visual deficits are neither specifically nor exclusively related to tasks supported by the magnocellular pathway (Amitay et al., 2002; Skottun, 2000; Williams, Stuart, Castles, & McAnally, 2003). Although our data can also be interpreted in an attentional framework, it should be noted that a "broader focus" (or a more diffused attentional mode) has been described in attentional studies of dyslexia in the right part of the visual field (Facoetti et al., 2001), while a more symmetric distribution of attentional resources seems to emerge from the results of the present study. This may be due to the different kinds of tasks involved. Nevertheless, the finding of a difficulty to inhibit information coming from the (right) periphery is common to these two types of study.

Whatever its nature, the difficulty to concentrate on the fixated area and to suppress the information from the periphery appears to interfere both with a sequential left-to-right scanning strategy characteristic of slow, phonological decoding (dyseidetics, P-types), and with a quick, visual recognition of words in a direct way (dysphonetics, L-types). In the first case, the mechanism would clearly have to do with the efficiency of the sequential scanning, while in the second case it would be the correct and precise perception and/or representation of the word in all its parts to be affected.

Further studies will be needed to clarify the nature of this "broader right focus" and its exact relationship with reading and dyslexia. More precisely, longitudinal studies could shed light on the developmental processes that lead to the final shape of the FRF, and studies of pre-school children at-risk for dyslexia may reveal the presence of differences already before learning to read. On the other hand, a deeper understanding of attentional mechanisms and of the role they play in reading may help better define how a "different attentional mode" can interfere with all the subsequent steps in the reading process.

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