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The relationship between visuo-spatial attention and nonword reading in developmental dyslexia

Andrea Facoetti
Istituto Scientifico "E. Medea" di Bosisio P, Lecco, Italy; Università degli Studi di Padova, Padova, Italy

Marco Zorzi
Università degli Studi di Padova, Padova, Italy

Laurie Cestnick
MGH-NMR Center, Harvard Medical School, Cambridge, MA, USA

Maria Luisa Lorusso and Massimo Molteni
Istituto Scientifico "E. Medea" di Bosisio P, Lecco, Italy

Pierluigi Paganoni
Azienda Ospedaliera di Bergamo, Bergamo, Italy

Carlo Umiltà and Gian Gastone Mascetti
Università degli Studi di Padova, Padova, Italy

Focused visuo-spatial attention was studied in 10 developmental dyslexic children with impaired nonword reading, 10 dyslexic children with intact nonword reading, and 12 normally reading children. Reaction times to lateralized visual stimuli in a cued detection task showed that attentional facilitation of the target at the cued location was symmetrical in the three groups. However, dyslexics with impaired nonword reading selectively showed a lack of attentional inhibition for targets at the uncued location in the right visual field. This result was replicated in a second group of 13 dyslexics with impaired nonword reading. Individual differences in the ability of right attentional inhibition across the entire sample of dyslexics accounted for 17% of unique variance in nonword reading accuracy after controlling for individual differences in age, IQ, and phonological skills. A possible explanation based on the role of spatial attention mechanisms in the graphemic parsing process is discussed. Our results suggest that focused visuo-spatial attention may be crucial for nonword decoding.

Correspondence should be addressed to Andrea Facoetti, Dipartimento di Psicologia Generale, Via Venezia, 8, 35131 Padova, Italy (Email: andreafacoetti@unipd.it).

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INTRODUCTION

Models of reading aloud (e.g., Coltheart, Rastle, Perry, Langdon, & Ziegler, 2001; Plaut, McClelland, Seidenberg, & Patterson, 1996; Zorzi, Houghton, & Butterworth, 1998a) converge in the assumption that oral reading involves the interaction between two different sources of phonological information. That is, upon presentation of a printed word, phonological codes are retrieved through a lexical–semantic pathway (or network) as well as assembled through a spelling–sound mapping process (see Zorzi, 2005, for a review). The latter allows readers to read unfamiliar words and nonwords. Both acquired and developmental disorders of reading have been generally discussed within this framework (e.g., Castles & Coltheart, 1993; Coltheart et al., 2001; Sprenger-Charolles, Colé, Lacert, & Serniclaes, 2000). Surface dyslexia is characterized by impaired reading of irregular words relative to regular words and nonwords and is thought to arise from damage to the lexical–semantic pathway. In contrast, phonological dyslexia would arise from damage to the sublexical procedure (Coltheart et al., 2001) or to the representation of phonological information (Harm & Seidenberg, 2000). Phonological dyslexics show great difficulties in reading unfamiliar words and nonwords compared to known words.

Phonological decoding, which is typically measured by examining children's nonword reading performance, is one of the most critical indices for successful reading acquisition (e.g., Share, 1995; Snowling, 2000; Ziegler & Goswami, 2005). Nonword reading is a crucial skill because it allows children to make the connection between novel letter sequences and words that are already stored in their phonological (spoken-word) lexicon. It is this ability to generalize (i.e., to assemble a phonological code for any string of letters) that allows the child to successfully decode and construct orthographic entries for thousands of new words during their first years of education (Share, 1995). Indeed, most longitudinal studies have shown that beginning readers use primarily the sublexical route both for reading aloud and for silent reading (for a recent review, see Sprenger-Charolles, Siegel, Béchennec, & Serniclaes, 2003). Writing systems, however, differ in the degree of spelling-to-sound consistency. For example, Italian, Spanish, and German have regular orthographies, in which letters or letter clusters consistently map onto phonemes. This has a dramatic effect on the speed at which reading skills are acquired (a "learning rate effect"; see Hutzler, Ziegler, Perry, Wimmer, & Zorzi, 2004) and on the severity of the reading disorder in dyslexics (Landerl, Wimmer, & Frith, 1997). Indeed, neuroimaging evidence suggests that Italian readers put more weight on phonological decoding (i.e., sublexical reading) than do English readers (Paulesu et al., 2000), but this difference disappears in dyslexics (Paulesu et al., 2001).

For decades researchers have been approaching reading and developmental dyslexia (hereafter, DD) from the standpoint not only of auditory and phonological contributions but also of *visual contributions* to these processes. Many studies have shown a specific deficit of the magnocellular (M) visual system in dyslexia (e.g., Eden et al., 1996; Galaburda & Livingstone, 1993; Sperling, Lu, Manis, & Seidenberg, 2003; see Stein & Walsh, 1997, for a review). However, the role of M deficit in dyslexia is hotly debated (e.g., Skutton, 2000; Stuart, McAnally, & Castles, 2001; Williams, Stuart, Castles, & McAnally, 2003), mainly because of the lack of a causal link between M processing and impaired reading of isolated words and nonwords. To complicate the picture, impaired performance on M-processing tasks appear to be associated with the phonological subtype of dyslexia (e.g., Borsting et al., 1996; Cestnick & Coltheart, 1999; Talcott et al., 1998) but not with the surface subtype (e.g., Borsting et al., 1996; Cestnick & Coltheart, 1999; Spinelli, Angelelli, Deluca, Dipace, Judica, & Zoccolotti, 1997; but see Sperling et al., 2003). This raises the possibility that different neuronal deficits underlie the various subtypes of dyslexia, although some researchers have argued that surface dyslexia is due to a mild phonological deficit as opposed to a severe phonological deficit in the phonological subtype (e.g., Stanovich, Siegel, & Gottardo, 1997).

In the study by Cestnick and Coltheart (1999; also see Davis, Castles, McAnally, & Gray, 2001), performance with Ternus apparent movement displays (measuring M system functions) was related to nonword reading ability but not to irregular word reading ability. As a possible interpretation of their findings, Cestnick and Coltheart (1999) suggested that nonword reading requires a serial left-to-right allocation of covert attention across the letter string, a process that requires intact M-system processing and/or some form of visuo-spatial attention involved in Ternus motion perception. Indeed, there is evidence that the M system plays a crucial role in focusing of attention (e.g., Steinman, Steinman, & Lehmkuhle, 1996; for a review, see Vidyasagar, 1999).

Phonological assembly requires a *graphemic parsing process*, which is the segmentation of a letter string into its letter constituents (e.g., Coltheart et al., 2001). Even connectionist models of reading assume a preprocessing stage that sorts letters (or graphemes) into slots according to a graphosyllabic template (e.g., Plaut et al., 1996; Zorzi et al., 1998a). Thus, phonological assembly involves not only appropriate phonological skills but also precise visuo-spatial processing mechanisms. Focused visuo-spatial attention is likely to be extremely important for letter parsing and segmentation. It is well known that focused visuo-spatial attention enhances visual processing not only in terms of processing speed but also of improved sensitivity (i.e., spatial resolution) and reduced interactions with "near" stimuli (spatial and temporal masking; e.g., Braun, 2002; Carrasco & McElree, 2001).

Indeed, some studies suggest that focused visuo-spatial attention is more important for nonword reading than for word reading. For instance, Sieroff and Posner (1988) used spatial cueing to manipulate focused visual attention during reading. Participants made more errors in reporting the letters from the unattended side of nonwords than from that of words (also see Auclair & Sieroff, 2002). Moreover, patients with hemispatial neglect make more errors on the contralesional side of nonwords than on that of words (e.g., Sieroff, Pollatsek, & Posner, 1988). Crucially, patients with severe neglect dyslexia show preserved lexical–semantic access in reading (Ladavas, Shallice, & Zanella, 1997a; Ladavas, Umiltà, & Mapelli, 1997b), suggesting an interaction between the attentional system and the different reading routes. That is, the lexical–semantic route is much less affected by neglect than the phonological route because the latter requires a narrower attentional focus to control the sequence of parts of the input string to be admitted to the spelling-to-sound translation process (Ladavas et al., 1997a).

Several studies have shown deficits of visuo-spatial attention in DD. Brannan and Williams (1987) demonstrated that, compared to normally reading subjects, poor readers were not able to rapidly focus visuo-spatial attention. A series of studies conducted by our group has shown slowed and asymmetric focusing in dyslexic children, which affect automatic control of visuo-spatial attention (e.g., Facoetti et al., 2003a, 2003b; Facoetti, Paganoni, Turatto, Marzola, & Mascetti, 2000b; Facoetti, Turatto, Lorusso, & Mascetti, 2001; for recent reviews, see Facoetti, 2004; Hari & Renwall, 2001).

The issue of whether visuo-spatial attention deficits are causally linked to reading disorders in dyslexic children is still hotly debated (for a recent review, see Ramus, 2003). Evidence in favour of a relation between visuo-spatial attentional and reading disorder comes from a recent study showing that dyslexics' ability to read improves following a specific training that improves their visuo-spatial attentional focusing (Facoetti, Lorusso, Paganoni, Umiltà, & Mascetti, 2003c; also see Geiger & Lettvin, 1999). However, a relation between focused visuo-spatial attention and nonword reading skills has yet to be established. The aim of the present study was to investigate the possible link between impaired nonword reading and focused visuo-spatial attention in DD.

Covert visuo-spatial attention is typically investigated with a spatial cueing paradigm (see Figure 1), in which attention is focused across

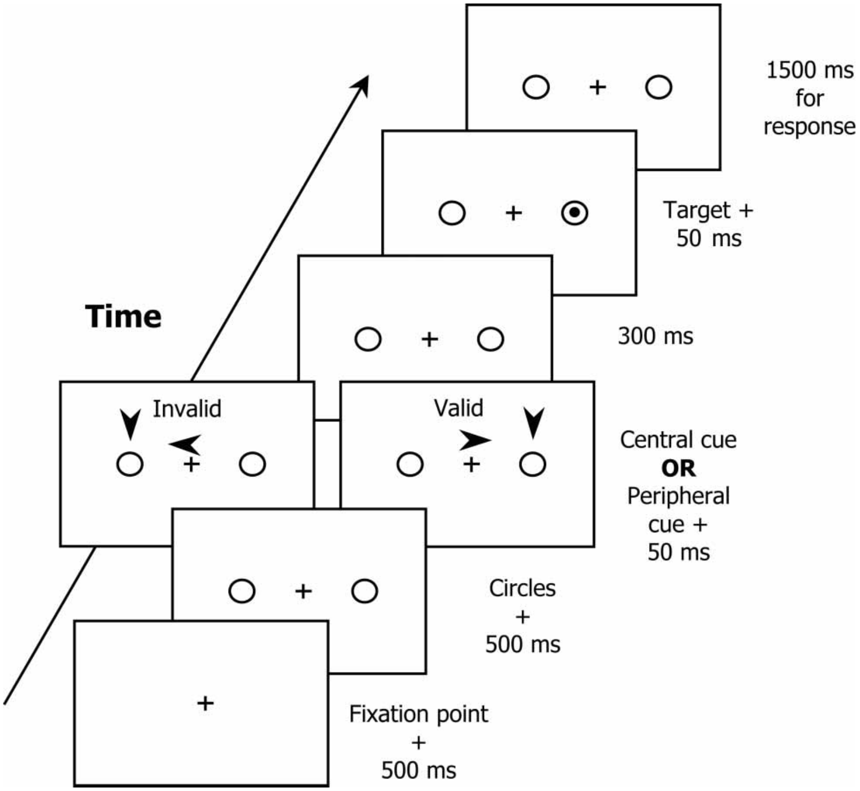

Figure 1. *Schematic representation of the display used in the cued detection task.*

locations without eye movements. The cue can be valid (when the target appears in the cued location) or invalid (when the target appears in the uncued location). In the valid cue condition reaction times (RTs) are generally faster than in the invalid cue condition (e.g., Posner, 1980). Faster RTs in the valid cue condition index *attentional facilitation* (i.e., enhanced processing at selected location), whereas slower RTs in the invalid cue condition index *attentional inhibition* (i.e., suppressed processing at unselected location). Accordingly, the accepted view is that attention directed to a visual field facilitates selection of information in that region, meanwhile causing inhibition of information in the contralateral visual field (e.g., Facoetti, 2001; Rafal & Henik, 1994).

Visuo-spatial attention is asymmetrically distributed in dyslexic subjects (for a recent review, see Hari & Renvall, 2001). Dyslexic adults differed consistently in both temporal order judgement and line motion illusion tasks from normal readers, showing a clear advantage for stimuli in the right visual hemifield (RVF) over those in the left visual hemifield (LVF; Hari, Renvall, & Tanskanen, 2001). In the same vein, dyslexic children were shown to be slower in detecting stimuli presented in the LVF (but not in the RVF) than their controls when visuo-spatial attention was focused on a central object (Facoetti & Molteni, 2001). Crucially, when attention is focused in the RVF, target detection in the LVF is abnormally slowed in dyslexics compared to normal readers. In contrast, when attention is focused in the LVF, target detection in the RVF is not slowed in dyslexics whereas it is in normal readers, suggesting a specific deficit of the right attentional inhibitory mechanism in dyslexics (Facoetti et al., 2001). Note that, although larger cueing effects are typically taken to signal attentional deficits, it is plausible that also smaller cueing effects signal attentional deficits. Specifically, larger cueing effects indicate an attentional filter that operates too efficiently (i.e., a smaller attentional focus), whereas smaller or absent cueing effects indicate a less efficient attentional filter (i.e., a larger attentional focus). This would be the interpretation of the finding that irrelevant flanking distractors presented in the LVF produce a smaller interference effect in dyslexics than in normal readers, whereas irrelevant flanking distractors presented in the RVF produce a larger interference effect in dyslexics than in normal readers (Facoetti & Turatto, 2000). In conclusion, there is evidence in support of the hypothesis of a specific deficit in *right attentional inhibition* (i.e., a large focus in the RVF) and/or a "left mini-neglect" (i.e., a small focus in the LVF) in dyslexia (Facoetti et al., 2001; Hari et al., 2001).

Thus, assuming that nonword reading involves the segmentation of a letter string into its components, which requires serial left-to-right focusing of visuo-spatial attention by spatial suppression of flanking letters, we should expect that the right attentional inhibition (hereafter, RAI) deficit is a specific mark of developmental dyslexics with impaired nonword reading. To this aim, the present study compared two groups of developmental dyslexics, one impaired and the other intact in nonword reading, and a control group of normally reading children in a covert attention focusing task. Furthermore, we asked whether the RAI deficit is a good predictor of nonword reading accuracy in dyslexic children.

EXPERIMENT 1

Method

Participants

Focused visuo-spatial attention was studied in 20 DD children (18 males and 2 females) and in 12 control children (9 males and 3 females) without reading difficulties.

DD children were between 7 and 13 years old (mean age 11.35 years) and had been diagnosed as dyslexics based on standard exclusion criteria. Their performance (speed and/or accuracy) in reading was 2 standard deviations below the norm on at least one of the age-standardized Italian tests included in the battery (i.e., text reading: MT test for speed and accuracy in reading, Cornoldi, Colpo, & Gruppo, 1981; single word and nonword reading: battery for the assessment of developmental reading and spelling disorders, Sartori, Job, & Tressoldi, 1995). Dyslexic participants were selected on the basis of: (a) the absence of a spoken language impairment; (b) a full-scale IQ greater than 85, as measured by the Wechsler Intelligence Scale for Children–Revised (Wechsler, 1986); (c) normal or corrected-to-normal vision and hearing; (d) the absence of attention deficit disorder with hyperactivity (ADHD, because it is highly comorbid with DD[1]), as evaluated through *DSM-IV* diagnostic criteria (American Psychiatric Association, 1994); and (e) right manual preference.

A total of 10 dyslexic children were impaired in nonword reading (hereafter, DDN−), and 10 dyslexic children had intact nonword reading (hereafter, DDN+). Dyslexic participants were assigned to the two groups according to their reading accuracy on a standardized list of Italian nonwords (Sartori et al., 1995). DDN− were 1.5 standard deviations below the age-standardized norm (Z-score), whereas DDN+ were above the cut-off point. Nonword reading accuracy was −3.64 Z-score for the DDN− group and −0.61 Z-score for the DDN+ group, $t(18) = 6.44$, $p < .001$.

Our classification of the dyslexics according to nonword reading performance does not conform to the approach that employs nonword reading accuracy relative to irregular word reading accuracy to individuate surface and phonological DD

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[1] All our previous studies on visuo-spatial attention and DD except one (i.e., Facoetti et al., 2000b) controlled for the presence of ADHD. In other cited studies (i.e., Brannan & Williams, 1987; Hari & Renvall, 2001) the comorbidity of ADHD was not specified.

subtypes (Castles & Coltheart, 1993). The latter approach is less straightforward in shallow orthographies such as Italian, because spelling–sound irregularity is limited to the suprasegmental level (that is, stress assignment). The increased weighting of phonological decoding (i.e., sublexical processing) in Italian compared to English makes a selective nonword reading impairment very unlikely: Indeed, DDN− and DDN+ groups were equally impaired at reading words; Z-scores −5.75 and −4.01, respectively, $t(18) = 1.62$, $p > .1$.[2]

Phonological skills, indexed by the number of errors in a phoneme-blending task (e.g., "m-a-n" to "man") on a list of 20 Italian words did not show significant differences between the two dyslexic groups ($p > .1$). Finally, the two dyslexic groups were matched for age and IQ (for details see Table 1).

A total of 12 control children (mean age 11.4 years) with normal IQ (global IQ 110) were also selected, recommended as normal readers by their teachers. They were at or above the norm on an age-standardized Italian reading test (i.e., text reading: accuracy 0.5 and speed 0.4 Z-score; Cornoldi et al., 1981). The control group was matched for chronological age and IQ to the DD. All participants' parents gave informed consent.

Apparatus and procedures

Covert focused attention was measured in a dimly lit room (1.5 cd/m^2 luminance). Participants sat in front of a monitor screen (15 in. and 0.5 cd/m^2 background luminance), with their head positioned on a headrest so that the eye–screen distance was 40 cm. The fixation point consisted of a cross (1° of visual angle) appearing at the centre of the screen. Two circles (2.5°) were presented peripherally (eccentricity 8°), one to the left and one to the right of the fixation point. The target (a dot of 0.5°) was preceded by a spatial cue (1.5° arrow appearing in the centre or in the periphery), which could be valid (80% of the trials) or invalid (20% of the trials). Stimuli were white and had a luminance of 24 cd/m^2. Participants were instructed to keep their eyes on the fixation point throughout the duration of the trial. Eye movements were monitored by means of a video-camera system. Any eye movement larger than 1° was detected by the system, and the corresponding trial was discarded but not replaced.

Each trial started with the onset of the fixation point accompanied by a 1,000-Hz warning signal tone. After 500 ms, the two circles were displayed peripherally, and 500 ms later the cue was shown for 50 ms. Then, after 300 ms, the target appeared for 50 ms inside one of the two circles (cue–target delay = 350 ms). On valid trials, the target was presented inside the circle indicated by the cue, whereas on invalid trials the target appeared in the circle on the opposite side. At target onset, participants were instructed to react as quickly as possible by pressing the spacebar on the computer keyboard. The maximum time allowed for responding was 1,500 ms, and intertrial interval was 1,000 ms. Catch trials, in which the target was not presented, and participants did not have to respond, were intermingled with normal trials (see Figure 1). The experimental session consisted of 208 trials divided into two blocks (one of central cues and one of peripheral cues) of 104 trials each. Block sequence was counterbalanced within participants. Trials were distributed as follows: 64 valid trials (32 on each side), 16 invalid trials (8 on each side), and 24 catch trials.

Results

Errors (responses on catch trials and missed responses) were less than 2.5% and were not

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[2] As noted by one anonymous referee, the word-reading impairment associated to normal nonword reading ability in the DDN+ group (Z-scores: −4.01 vs. −0.61, respectively), $t(9) = 4.51$, $p < .002$, might suggest a surface dyslexic profile. However, such a diagnosis cannot be firmly established because participants did not read a specific list of irregular words. Moreover, note that DDN+ children are much less frequently found than DDN− children. In the current study, only 10 DD in an unselected consecutive sample of 33 dyslexic children conformed to the criteria for the DDN+ group.

Table 1. *Means of age, global IQ, reading and writing scores, and phoneme-blending errors in the two DD groups*

		DDN−[a]		*DDN+*[a]		*Comparison*	
		M	*SD*	*M*	*SD*	*t(18)*	*p*
Age[b]		11.4	2.32	11.3	2.41	0.94	.93
Global IQ		104.2	9.58	100.4	11.26	0.81	.43
Nonword reading	*Z*-score	−3.64	1.22	−0.61	0.85	−6.44	<.001
	Errors	17.1	6	5.1	3.8	5.33	<.001
Word reading	*Z*-score	−5.75	2.29	−4.01	2.52	1.62	.12
	Errors	17.2	7.3	12.9	9.6	1.12	.27
Text reading	*Z*-score	−2.62	2.3	−1.94	1.2	−0.79	.44
	Errors	21.9	15.7	15.2	5.6	1.2	0.25
Nonword writing	*Z*-score	−1.48	1.5	−0.94	1.5	−0.77	0.45
	Errors	5.6	4.2	5.1	4	0.26	0.8
Word writing	*Z*-score	−4.52	3.2	−3.11	5.4	−0.71	.49
	Errors	7.1	5.3	5.8	7.8	0.44	.67
Phoneme blending	Errors	5.3	3.7	8.2	4.6	−1.52	.15

Note: DD = developmental dyslexia. DDN− = developmental dyslexia, impaired in nonword reading. DDN+ = developmental dyslexia, intact nonword reading.

[a]$N = 10$. [b]In years.

analysed. Outliers were defined as RTs faster than 150 ms or more than 2.5 standard deviations above the mean. Outliers were excluded from the data sets before the analyses were carried out. In the present experiment, this resulted in the removal of approximately 2% of all observations. Eye movements were about 2% of total trials. Mean correct RTs were analysed with a four-way analysis of variance (ANOVA) in which the three within-subjects factors were cue condition (valid and invalid), target location (RVF and LVF), and cue location (central and peripheral). The between-subjects factor was group (DDN−, DDN+, and normally reading children).

The cue main effect (i.e., RT difference between invalid and valid conditions) was significant, $F(1, 29) = 23.77$, $MSE = 4{,}429.40$, $p < .0005$; RTs were faster in valid trials (405 ms) than in invalid trials (446 ms). The Group × Target Location interaction was significant, $F(2, 29) = 4.05$, $MSE = 3{,}524.67$, $p < .05$, indicating that RTs varied across groups according to target location. In normal readers, the RT difference between the LVF (424 ms) and the RVF (432 ms) was not significant (−8 ms, $p > .5$); DDN+ children showed the same pattern, with a nonsignificant RT difference (−3 ms, $p > .5$) between the LVF (434 ms) and the RVF (437 ms); in contrast, there was a significant RT difference (39 ms, $p < .01$) between the LVF (432 ms) and the RVF (393 ms) in DDN− children (see Figure 2).

However, these findings should be interpreted in the light of the three-way Cue

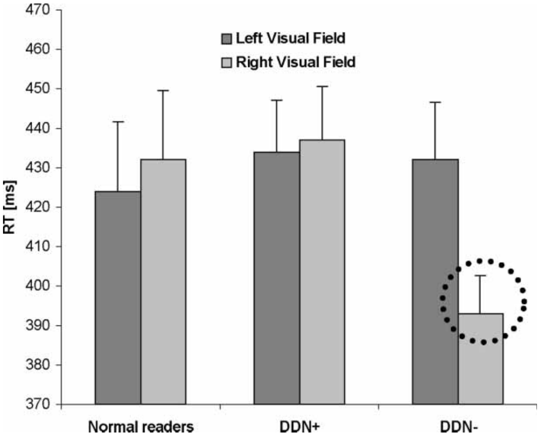

Figure 2. *Mean reaction times (RTs) and standard errors as a function of group (DDN−, DDN+, and normally reading children) and target location (left visual field and right visual field) in Experiment 1.*

Condition × Group × Target Location interaction, which was also significant, $F(2, 29) = 3.46$, $MSE = 2{,}658.31$, $p < .05$. Planned comparisons revealed that the effect of cue validity was significant in both visual fields for both normally reading children (41 ms in LVF and 39 ms in RVF; both $p < .05$) and DDN+ children (47 ms in LVF and 69 ms in RVF; both $p < .05$). The cue effect was similar across the visual fields ($p > .5$). In contrast, DDN− children showed a different RT pattern: In the LVF the cue effect was present (54 ms, $p < .01$, they were slower on invalid trials), whereas in the RVF the cue effect was absent (−6 ms, $p > .7$, they were not slower on invalid trials). This result suggests a lack of attentional inhibition in the RVF when the attentional focus was covertly oriented to the LVF (i.e., RAI deficit). Moreover, in the invalid cue condition RTs to right targets were faster in DDN− children than in both normal readers and DDN+ children (both $p < .01$), which is consistent with a RAI deficit in the former group. The cue effect for target detection in both visual fields in DDN−, DDN+, and normally reading children is shown in Figure 3.

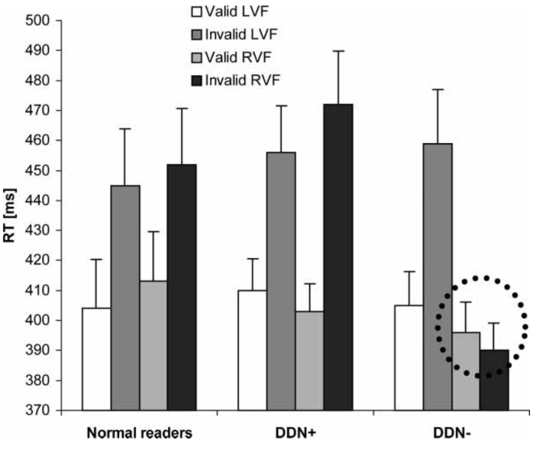

Figure 3. *Mean reaction times (RTs) and standard errors as a function of group (DDN−, DDN+, and normally reading children), cue condition (valid and invalid), and target location (LVF = left visual field, RVF = right visual field) in Experiment 1.*

To confirm these findings, the same spatial cueing task was administered to a new group of DDN− children in Experiment 2. This also allowed us to evaluate whether the RAI deficit is a good predictor of nonword reading accuracy across the entire sample of dyslexics.

EXPERIMENT 2

Method

Participants

A total of 13 new DDN− children (11 males and 2 females) were recruited for this experiment. They were between 8 and 13 years old (mean age 9.31 years and mean IQ 110) and had been diagnosed as dyslexics based on standard exclusion criteria (for details of diagnostic criteria see Experiment 1). Nonword reading accuracy was −2.9 *Z*-score (for details see Table 2).

Apparatus and procedures

The same apparatus and procedures as those in Experiment 1 were used.

Table 2. *Means of age, global IQ, reading and writing scores, and phoneme-blending errors in the DDN− children in Experiment 2*

		DDN−[a]	
		M	*SD*
Age[b]		9.3	1.3
Global IQ		110	16
Nonword reading	*Z*-score	−2.9	1.1
	Errors	16.1	3.2
Word reading	*Z*-score	−2.8	1
	Errors	14.4	4.7
Text reading	*Z*-score	−2	1.5
	Errors	16	8.6
Nonword writing	*Z*-score	−1.83	2.2
	Errors	7.8	5.5
Word writing	*Z*-score	−4.22	3.8
	Errors	10.2	6.5
Phoneme blending	Errors	6.1	3.7

Note: DDN− = developmental dyslexia, impaired in nonword reading.
[a] *N* = 13. [b] In years.

Results

Errors were less than 4% and were not analysed. In the present experiment, outliers resulted in the removal of approximately 3% of all observations. Eye movements were about 3% of total trials. Mean correct RTs were analysed with a three-way ANOVA in which the within-subjects factors were cue condition (valid and invalid), target location (RVF and LVF), and cue location (central and peripheral).

The Cue Condition × Target Location interaction was significant, $F(1, 12) = 8.88$, $MSE = 4{,}186.86$, $p < .02$. DDN− children showed a significant cue effect in the LVF (65 ms, $p < .001$) but not in the RVF (−10 ms, $p > .5$). Moreover, RTs to visual targets were faster in the RVF than in the LVF only in the invalid ($p < .01$) but not in the valid ($p > .3$) cue condition. Overall, the results of Experiment 2 (see Figure 4) replicate those of Experiment 1 and show a clear RAI deficit.

The results of Experiment 1 showed a small tendency to a left inattention in DDN− children (i.e., the cueing effect in the LVF was 54 ms for DDN− compared to 41 ms for normal readers). DDN− children in the present experiment showed an even larger cueing effect in the LVF (65 ms). Thus, we repeated the analysis of Experiment 1 combining the two DDN− groups (for a total of 23 DDN− children) to increase the statistical power. The three-way Cue Condition × Group × Target Location interaction was still significant, $F(2, 42) = 5.97$, $MSE = 3{,}047.34$, $p < .005$. More interestingly, in the invalid cue condition RTs to left targets were significantly slower in DDN− children (499 ms) than in DDN+ children (457 ms) and normal readers (445 ms; ps $< .05$). Thus, in DDN− children these results are compatible with the "left mini-neglect" hypothesis put forward by Hari et al. (2001). In contrast, in the invalid cue condition RTs to right targets were significantly faster in DDN− children (418 ms) than in DDN+ children (472 ms) and normal readers (452 ms; ps $< .05$). Thus, these results appear compatible also with the "right hyper-attention" (and/or large attentional window in the RVF) hypothesis put forward by Facoetti and Molteni (2001).

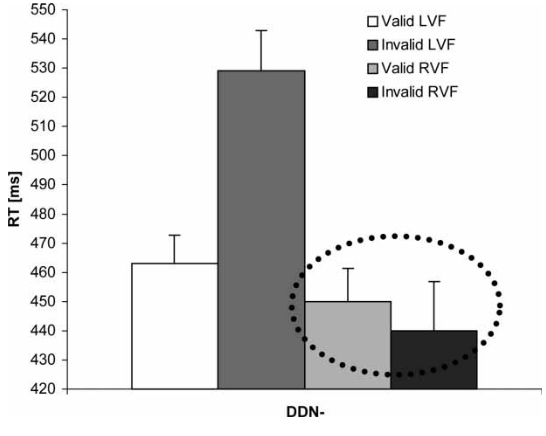

Figure 4. *Mean reaction times (RTs) and standard errors as a function of cue condition (valid and invalid) and target location (LVF = left visual field, RVF = right visual field) in DDN− children in Experiment 2.*

The relationship between visuo-spatial attentional deficit and nonword reading in dyslexic children

Having established that only DDN− children show a visuo-spatial attention dysfunction as a group, we wished to explore the relationship between individual measures of RAI (indexed by the RT difference between invalid and valid cue condition for targets in the right visual field) and nonword reading across our entire sample of dyslexic children ($n = 33$; i.e., all dyslexics of Experiments 1 and 2 including those classified as DDN+). Nonword reading accuracy was measured on a standardized list of 48 Italian nonwords, whereas word reading accuracy was measured on a standardized list of 102 Italian words (Sartori et al., 1995). Correlations between RAI, left attentional inhibition (LAI; indexed by the RT difference between invalid and valid cue condition for targets in the left visual field), age, global IQ, word and nonword reading accuracy in 33 DD children are shown in Table 3.

Partial correlations controlling for age and IQ showed a highly significant correlation between

Table 3. *Correlations between right attentional inhibition, left attentional inhibition, age, global IQ, and word and nonword reading accuracy in the DD children*[a]

	RAI	*LAI*	*Age*	*IQ*	*Word*	*Nonword*
RAI	—					
LAI	−.04	—				
Age	.28	.12	—			
IQ	−.44*	.18	−.22	—		
Word	−.23	−.07	−.54*	.03	—	
Nonword	−.58*	.16	−.36*	.16	.44*	—

Note: DD = developmental dyslexia. RAI = right attentional inhibition. LAI = left attentional inhibition.

[a] $N = 33$.

*$p < .05$.

RAI and nonword reading accuracy, $r(29) = .55$, $p < .005$. In contrast, nonword reading accuracy did not significantly correlate with LAI ($p > .2$).

To determine predictive relationships between RAI deficit and nonword reading in a more stringent way, a three-step fixed-entry multiple regression equation was computed on the individual data of the 33 DD children. The dependent variable was nonword reading accuracy, and the predictors were (a) age, (b) full IQ, and (c) RAI. Overall, the regression model accounted for 40% of the variance. Importantly, the RAI measure entered last accounted for 26.1% of unique variance in nonword reading accuracy (see Table 4 and Figure 5).

The same multiple regression equation was computed using word reading accuracy as the dependent variable. The age measure entered first accounted for 29.5% of unique variance in word reading (see Table 5). The other variables were not significant.

Table 4. *Percentage of variance in nonword reading explained by the different predictors in the three-step, fixed-entry multiple regression equation*

Step		R^2	*p-value*
1	Age	.134	<.05
2	IQ	.004	ns
3	RAI	.265	<.005

RAI = right attentional inhibition.

Finally, we repeated the regression analysis on nonword reading accuracy with a measure of phonological skills as an additional predictor. Thus, a four-step fixed-entry multiple regression equation was computed on the individual data of the 33 DD children. Phonological skill was indexed by the number of errors in a phoneme blending task. The dependent variable was nonword reading accuracy, and the predictors were (a) age, (b) full IQ, (c) phoneme blending, and (d) RAI. Overall, the regression model accounted for 55% of the variance. Importantly, the RAI measure entered last accounted for 17.2% of unique variance in nonword reading accuracy (see Table 6).

Discussion

The main result of the present study is that dyslexic children with impaired nonword reading (DDN− group) did not show a cueing effect in the RVF, which indicates a lack of attentional inhibition to unattended visual stimuli in the RVF when attention is focused to the LVF (i.e., a RAI deficit). This suggests that DDN− children have an asymmetric attentional window that is more extended to the right side, which is the direction of reading for Italian readers. This in turn implies a reduced ability to suppress distracting information in the RVF (e.g., Facoetti & Turatto, 2000; Geiger & Lettvin, 1999). Although a similar asymmetry of visuo-spatial attention has been found with a "mixed" (i.e., nonselected) group of dyslexics (Facoetti & Molteni, 2001; Facoetti et al., 2001), the present study clearly shows that this pattern characterizes only the dyslexics with impaired nonword reading. Moreover, individual differences in RAI across our entire sample of dyslexic children turned out to be good predictors of nonword reading accuracy, accounting for 26% of unique variance after controlling for individual differences in age and IQ.

Asymmetries of visuo-spatial attention in adult dyslexics have also been found by Hari et al. (2001; see Hari & Renvall, 2001, for review), but they have not been considered to be causally connected to the reading disorder. However, our results suggest a specific link between focusing of

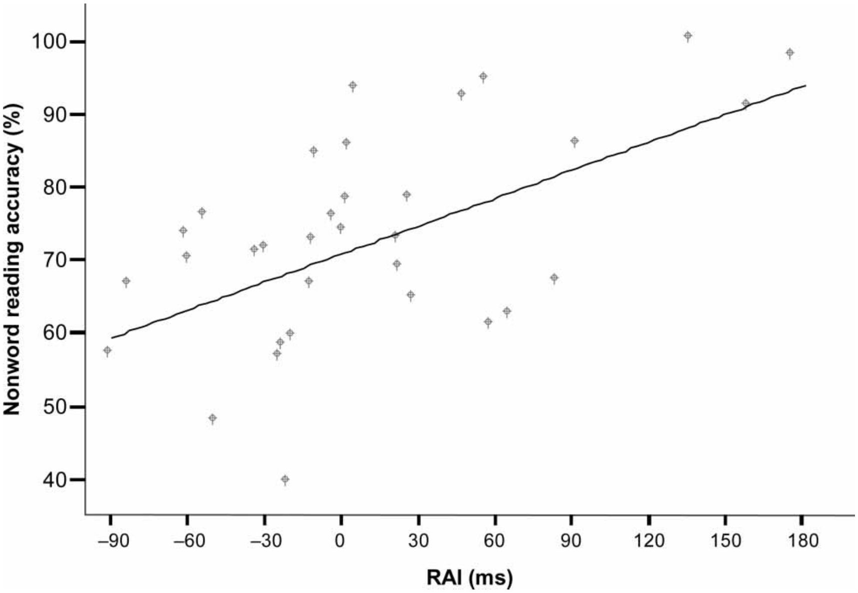

Figure 5. *Scatter plot of the relationship between right attentional inhibition (RAI, i.e., the RT difference between invalid and valid cue condition to targets in the right visual field) and nonword reading accuracy (percentage of correct responses) across the entire sample of developmental dyslexic children (N = 33). The regression line results from the equation 70.8 + (0.13 × RAI), which accounts for 33% of the variance.*

visuo-spatial attention and the ability to read via the sublexical route (which is crucial for nonword reading). DDN− children do not inhibit right stimuli when they covertly orient visuo-spatial attention to the left, whereas DDN+ children do and are indistinguishable from normally reading children. Given that a spatial selection mechanism operating on graphemes appears to be a basic component of the phonological assembly process, we suggest that the RAI deficit impairs graphemic parsing, which could affect all subsequent spelling-to-sound conversion processes.

More importantly, in dyslexic children the RAI accounts for 17% of unique variance even after controlling for individual differences not only in age and IQ but also in phonological skills (i.e., phoneme blending ability). This result clearly shows that in dyslexic children visuo-spatial attention (i.e., inhibitory process in the RVF) is crucially involved in phonological reading independently of pure auditory–phonological mechanisms.

Computational models of reading (Zorzi, 2005, for a review) implicitly or explicitly assume some

Table 5. *Percentage of variance in word reading explained by the different predictors in the three-step, fixed-entry multiple regression equation*

Step		R^2	*p-value*
1	Age	.295	<.005
2	IQ	.015	ns
3	RAI	.033	ns

RAI = right attentional inhibition.

Table 6. *Percentage of variance in nonword reading explained by the different predictors in the four-step, fixed-entry multiple regression equation*

Step		R^2	*p-value*
1	Age	.132	.05
2	IQ	.005	ns
3	Phoneme blending	.249	<.005
4	RAI	.172	<.01

RAI = right attentional inhibition.

form of graphemic parsing to achieve the level of representation on which the spelling-to-sound conversion mechanism operates. Thus, some models assume that the input is segmented into single letters that are serially and individually processed (e.g., Coltheart et al., 2001), whereas others assume segmentation into sublexical units (simple and complex graphemes) that are assigned to specific slots according to their position in the syllable (i.e., a graphosyllabic template; e.g., Plaut et al., 1996; Zorzi et al., 1998a). Regardless of how this process is exactly conceived, it clearly requires focusing of visuo-spatial attention on each sublexical unit (single letter or letter cluster), inhibiting the flanking units (Whitney & Cornelissen, 2005). The role of visual attention mechanisms in reading is more explicit in the computational model of Ans, Carbonnel, and Valdois (1998), which assumes two reading modes, "global" versus "analytic", which differ in the kind of visual attentional processing that they involve.

Our contention that efficient focusing of visuo-spatial attention is crucial for the phonological reading route (and thus to achieve competent nonword decoding skills) is supported by several lines of evidence. First, neuropsychological studies on patients with neglect dyslexia suggest an interaction between the attentional system and the different reading routes. Hemispatial neglect severely affects the phonological route but has little effect on lexical-semantic access (e.g., Ladavas et al., 1997a; Ladavas et al., 1997b; Sieroff et al., 1988), suggesting that reading unfamiliar words and nonwords requires a narrower attentional focus to control the sequence of parts of the input string to be admitted to the spelling-to-sound translation process (Ladavas et al., 1997a). Second, performance in serial visual search (a task requiring focusing of visuo-spatial attention) has been shown to correlate with reading performance (Casco, Tressoldi, & Dellantonio, 1998). Note that developmental dyslexics were shown to be impaired in serial visual search (e.g., Vidyasagar & Pammer, 1999). Good and poor readers also differ in their ability to attend information inside the focus of attention and to ignore information outside the focus of attention (e.g., Facoetti, Paganoni, & Lorusso, 2000a; Klein & D'Entremont, 1999). Accordingly, Kinsey, Rose, Hansen, Richardson, and Stein (2004) have recently shown a stronger relationship between visuo-spatial attention and nonword reading than between visuo-spatial attention and irregular word reading. Finally, and more importantly, improving right visuo-spatial selection in dyslexics has been shown to beneficially affect their ability to read nonwords (Geiger & Lettvin, 1999).

We note that efficient learning of sublexical spelling-to-sound mappings requires not only graphemic parsing but also accurate representations at the phoneme level (e.g., Harm & Seidenberg, 1999; Zorzi, Houghton, & Butterworth, 1998b, for connectionist simulations). In effect, several authors have argued that the core problem in DD is a deficit in phonological representation and memory (e.g., Goswami, 2000; Snowling, 2000). It is important to note that both word reading and writing as well as phonological abilities are not significantly different in DDN− in comparison to DDN+ children. Therefore it appears very unlikely that a simple association between visuo-spatial attentional deficits and nonword reading disability is selectively present in DDN− children. In addition, our result showing that in dyslexics children RAI accounts for 17% of unique variance after controlling for individual difference in phonological ability is not compatible with a purely phonological-based deficit of DD, as suggested by Ramus (2003).

However, a limitation of the present study is that a full characterization of the phonological skills of dyslexic readers was not of primary concern. Future studies should be able to compare in a more stringent way the predictive value of attentional versus phonological abilities for the development of nonword reading skills.

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