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Research report

Auditory and visual automatic attention deficits in developmental dyslexia

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Abstract

Several studies have provided evidence for a phonological deficit in developmental dyslexia. However, recent studies provide evidence for a multimodal temporal processing deficit in dyslexia. In fact, dyslexics show both auditory and visual abnormalities, which could result from a more general problem in the perceptual selection of stimuli. Here we report the results of a behavioral study showing that children with dyslexia have both auditory and visual deficits in the automatic orienting of spatial attention. These findings suggest that a deficit of selective spatial attention may distort the development of phonological and orthographic representations that is essential for learning to read.

Theme: Disorders of the nervous systems

Topic: Developmental disorders

Keywords: Dyslexia; Reading; Auditory spatial attention; Orienting of attention; Inhibition of return; Multimodal attention

1. Introduction

Developmental dyslexia is defined as a specific reading disorder despite normal intelligence and teaching, and in the absence of any manifest sensory deficit [1]. Studies have provided evidence for a phonological deficit in developmental dyslexia [4]. However, the problems of dyslexic children extend beyond the skills directly involved in reading. Indeed, recent studies provide evidence of spatial and temporal processing deficits in dyslexia [42,22]. Also, dyslexics show visual abnormalities [19] as well as deficits in processing tactile stimuli [20], in balance and motor control [33], which could result from a more general problem in the selection of stimuli [22].

The magnocellular (M) theory of dyslexia [42] holds that the crucial disorder is a neurodevelopmental impairment of a crossmodal system responsible for processing rapid streams of stimuli. The information processed by the M system ends in the posterior parietal cortex (PPC), which is the basic area of multimodal spatial attention [11]. There is evidence that a supramodal space representation exists in the PPC with convergence of both auditory and visual inputs [17], and there is also evidence of crossmodal cells in PPC [2]. Thus, the neural pathways previously thought to be sensory-specific are in fact strongly modulated by signals from other modalities [37]. The PPC may be involved in spatial selection independently of modality [9] through a multimodal map that would be used for orienting attention in both the auditory and visual modalities [47].

In fact, the deficits in dyslexia often manifest themselves in the auditory modality with problems in speech–sound perception (phoneme discrimination) in the presence of background noise [10]. Also, dyslexic children have difficulties in discriminating between acoustically similar

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sounds [44] and in processing rapid sound sequences [21,25]. That could be due to impaired 'magnocells' in the medial geniculate nucleus [18]. Evidence for an auditory spatial selection deficit in dyslexics was provided by Asbjornsen and Bryden [3]. These auditory perception deficits are likely related to an inability to rapidly shift auditory attention in order to discriminate properly the features of the sound [22]. In fact, several studies demonstrated that phoneme identification may be substantially influenced by the spatial distribution of auditory attention [30,31], providing strong evidence that selective spatial attention may act to facilitate auditory perception.

In addition, it is clear that many visuospatial selection functions contribute to reading and that selective attention to words or string of words requires a filter controlled by rapid visual orienting [5]. Thus, spatial attention deficits may degrade the perception of visual elements like letters and words, during reading [19]. Difficulties with reading could be due to sluggish orienting [15,16,24].

Recent studies suggest that the causal link from the M deficit to reading and phonological impairments involves automatic capture of attention [22,23].

In the present study, we measured the covert automatic capture [34] of both auditory and visual attention in 17 children diagnosed with specific reading disorder or dyslexia, and seven control children with normal reading skills, who were matched for age and IQ.

2. Materials and methods

In test 1 the participants fixated the central point of a visual display, and a non-informative auditory cue, delivered by headphones, preceded the onset of a subsequent target tone in the left or right ear. In test 2, we measured the automatic orienting of visual attention in the same children. Participants fixated the central point of a display, and a non-informative visual cue preceded the onset of a subsequent target in the left or right visual field. After variable intervals from the onset of the spatial cue (stimulus onset asynchrony, SOA) a target stimulus was presented at the cued or uncued location. Faster responding to cued targets at the shorter interval reflects the facilitatory effect of automatic orienting of attention towards the cue (*attentional facilitation*). Slower responding to the target at the cued location at the longer cue-target interval reflects inhibition of return (*IOR*). This inhibitory effect is attributed to the withdrawal of attention [28] and favors orienting towards novel locations [26].

2.1. Participants

Seventeen children with developmental dyslexia, ranging in age between 9 and 13 years, were selected from a sample of children referred to the Scientific Institute "E. Medea" for learning difficulties. Children (age 10.9 years) had been diagnosed as dyslexic based on standard criteria [1]. Their performance in reading aloud a text and/or single words and/or single non-words was 2 standard deviations (S.D.s) below the norm on age-standardized Italian tests [8,36]. Table 1 shows descriptive data for the dyslexic children.

Dyslexic participants were 11 males and six females selected on the basis of: (1) a full scale IQ greater than 85 as measured by the Wechsler Intelligence Scale for Children-Revised (WISC-R) [48]; (2) normal or corrected-to-normal vision and hearing; (3) the absence of attention deficit disorder with hyperactivity [1]; and (4) right manual preference. Seven normal readers (age 10.1 years) were also selected, recommended as normal readers by their teachers. They were at or above the norm (accuracy +0.7 and speed +0.6 S.D.) on age-standardized single word Italian reading test [36]. Normally reading children were of at least average intelligence, as measured by two WISC-R [48] sub-tests (Vocabulary=10.6 standard score and Block Design=13.6 standard score). The two groups of children did not differ for chronological age ($P>0.05$). All participants' parents gave informed consent.

2.2. Apparatus and stimuli

Tests were carried out in a dimly lit (luminance of 1.5 cd/m^2) and quiet room (approximately 50 dB SPL). Participants sat in front of a monitor screen (15 inches and with a background luminance of 0.5 cd/m^2), 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 center of the screen.

2.2.1. Test 1: auditory attention

The sounds were presented by Sennheiser HD270 headphones. A single pure tone of 1000 Hz was used as auditory cue and a single pure tone of 800 Hz was used as target. The cue and target sounds were presented for 40 ms at approximately 65 dB SPL.

2.2.2. Test 2: visual attention

Two circles (2.5°) were presented peripherally (eccen-

Table 1
Descriptive data (means) of the dyslexic children

Participants	Age	Full IQ	Verbal IQ	Performance IQ	Text comprehension	Text reading	Word reading	Non-word reading
6 females 11 males	10.9 years	99.9	94.9	107.2	0.1	Accuracy −1.5 Speed −2.2	Accuracy −1.7 Speed −3.1	Accuracy −1.8 Speed −2.9

tricity 8°), one to the left and one to the right of the fixation point. The peripheral cue consisted in an offset (duration 40 ms) and an onset of a circle. A dot (0.5°) in the center of one of the two circles was the target stimulus (duration 40 ms). Stimuli were white and had a luminance of 24 cd/m^2.

2.3. Procedure

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. In the auditory attention test, after 500 ms the cue was presented. In the visual attention test, after 500 ms, the two circles were displayed peripherally, and 500 ms later the cue was shown. The target was presented after one of two SOAs (auditory attention: 100 or 250 ms; visual attention: 250 or 400 ms). On each 'response' trial a location cue presented in either the left or the right location was followed by a target presented in either the left or the right location. In contrast, on catch trials the target was not presented and participants did not have to respond. Catch trials were intermingled with response trials. On response trials, the probability that the target would appear in the same location as (a valid trial) or in a different location from (an invalid trial) the cue was 50% (i.e., there were an equal number of valid and invalid trials: cue location was non-predictive of target location). Participants were instructed to react as quickly as possible to the onset of the target by pressing the spacebar on the computer keyboard. Both simple reaction times (RTs) and error rates were recorded by the computer. The maximum time allowed to respond was 1500 ms. The inter-trial interval was 1000 ms. The experimental session consisted of 160 trials divided into two blocks of 80 trials each. Trials were distributed as follows: 32 valid trials (16 for each cue-target delay), 32 invalid trials (16 for each cue-target delay), and 16 catch trials (20% of total trials). The administration sequence of the two tests were counterbalanced across subjects.

3. Results

3.1. Test 1: auditory attention

Errors, that is responses on catch trials and missed responses, were less than 2% and were not analyzed. Outliers were defined as RTs faster than 150 ms or more than 2.5 standard deviations above the mean and 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 1% of total trials.

Mean correct RTs were analyzed with a mixed three-way analysis of variance (ANOVA) in which the two within-subject factors were cue condition (valid and invalid) and SOA (100 and 250 ms). The between-subject factor was group (dyslexics and normally reading children).

The group main effect was significant, $F(1,22)=5.66$, $P<0.05$; RTs were faster in normally reading children (395 ms) than in dyslexic children (476 ms). Also, SOA main effect was significant, $F(1,22)=30.23$, $P<0.0001$; RTs were faster at 250 ms SOA (416 ms) than at 100 ms SOA (456 ms). The cue condition×SOA interaction was significant, $F(1,22)=4.83$, $P<0.05$, indicating that cue effect (RT difference between invalid and valid condition) varied across SOAs. At 100 ms SOA, the cue effect was significant (attentional facilitation=17 ms, $P<0.05$); in contrast, at 250 ms SOA, the cue effect was not significant (IOR=−6 ms, $P>0.05$).

However, these findings should be interpreted in the light of the three-way group×cue condition×SOA, which was also significant, $F(1,22)=6.62$, $P<0.02$. Planned comparisons showed that in normally reading children RT to detect the auditory tone was faster in the valid than in the invalid cue condition (attentional facilitation=28 ms, $P<0.05$) when the SOA was 100 ms. In contrast, RT was slower in the valid than in the invalid cue condition (IOR=−24 ms, $P<0.05$) when SOA was 250 ms. In comparison to controls, in the valid cue condition children with dyslexia did not show significantly faster RTs at the shorter SOA (7 ms, $P>0.05$) or slower RTs at the longer SOA (11 ms, $P>0.05$).

Fig. 1 shows RTs for the detection of the auditory target in two cue conditions (valid and invalid) and at two SOAs (100 and 250 ms), in dyslexic and control children.

3.2. Test 2: visual attention

Errors, that is responses on catch trials and missed responses, were less than 3% and were not analyzed. Outliers were defined as RTs faster than 150 ms or more than 2.5 standard deviations above the mean and 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 4% of total trials.

Mean correct RTs were analyzed with a mixed ANOVA in which the two within-subject factors were cue condition (valid and invalid) and SOA (250 and 400 ms). The between-subject factor was group (dyslexics and normally reading children).

The group main effect was significant, $F(1,22)=8.04$, $P<0.01$; RTs were faster in normally reading children (352 ms) than in dyslexics children (396 ms). The group× cue condition interaction was significant, $F(1,22)=4.54$, $P<0.05$, indicating that cue effect varied across groups. Normal readers revealed an IOR of −10 ms whereas the dyslexics manifested a facilitation of 7 ms. IOR was predicted with long SOAs [26]. In fact, IOR occurred in

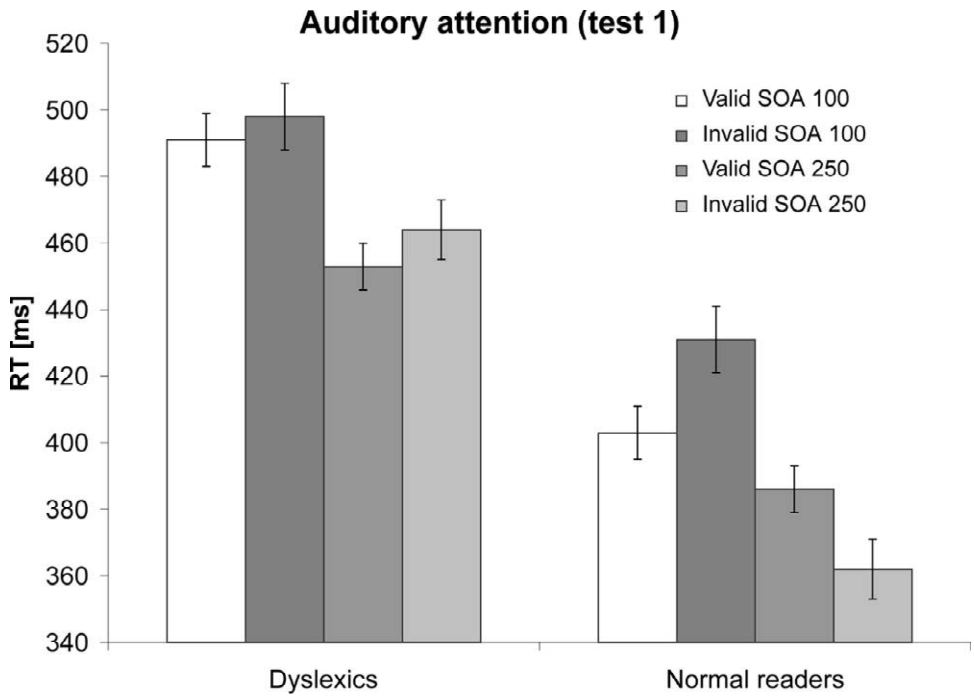

Fig. 1. Mean reaction times (RTs) in the auditory attention test as a function of group (dyslexic and normal readers), cue condition (valid and invalid) and SOA (100 and 250 ms).

normally reading children, whereas dyslexic children again showed some attentional facilitation. However, these findings should be interpreted in the light of the three-way group×cue condition×SOA interaction, which tended to be significant, $F(1,22)=3.54$, $P=0.07$. In normally reading children, RT to detect a visual target after an SOA of 250 ms was faster when the target was presented in the valid (357 ms) than in the invalid (363 ms) cue condition (6 ms, $P>0.05$). With an SOA of 400 ms, RT was slower in the valid (358 ms) than in the invalid (330 ms) cue condition (IOR=−28 ms; $P<0.05$). Children with dyslexia showed no significantly slower RTs in the valid than in the invalid cue condition (SOA 250=7 ms and SOA 400=8 ms; P values>0.05), indicating an absence of IOR similarly to what had happened with auditory stimuli (test 1).

Fig. 2 shows detection RTs in the two groups, in two spatial cue conditions and at two SOAs.

4. Discussion

Several studies provided evidence that auditory attention may be allocated to a specific location in response to an auditory spatial cue (e.g., Refs. [32,41]). Other studies demonstrated that auditory spatial attention may act to facilitate both auditory perception and phoneme identification [30,31]. Accordingly, recent studies supported the perceptual model of auditory spatial attention as a sensory gating [45,46]. Spatial attention may directly influence perceptual processing, so that stimuli at attended locations are analyzed more rapidly and/or intensively.

In addition, there is much evidence that phonological processing deficits are linked to difficulties in learning to read: phonological performances predict later reading ability, phonological processing deficits markedly distinguish children with dyslexia from children with normal reading skills, and training of phonological processing (phonemic awareness) has been shown to improve reading performance (e.g., Ref. [4]).

Our results indicated that automatic orienting of auditory attention was defective in dyslexic children. They showed neither attentional facilitation at the shorter interval nor IOR at the longer interval which instead were shown by normal readers. The generalisability of these data was confirmed by further analyses on a larger sample of normally reading children ($n=14$, attentional facilitation=26 ms at 100 ms SOA and IOR=−23 ms at 250 ms SOA; P values<0.05)[1].

The results of the auditory attention experiment provide

[1]Note: Spence and Driver [41] showed that no effects of auditory spatial cueing appeared in a simple detection task (in contrast to the equivalent visual task), although their results are consistent in direction (attentional facilitation=7 ms at 100 ms SOA and IOR=−5 ms at 1000 ms SOA). In an experiment using the same task as the present study, 15 normally reading adults showed smaller cue effects than children, but significant attentional facilitation (15 ms) at 100 ms SOA and significant IOR (13 ms) at 250 ms SOA. Other studies showed auditory attention effects by auditory spatial cues using simple detection tasks [38,27,6,29]. Buchtel et al. [6] suggest that auditory cueing null effects could be explained by stimulus source and intensity.

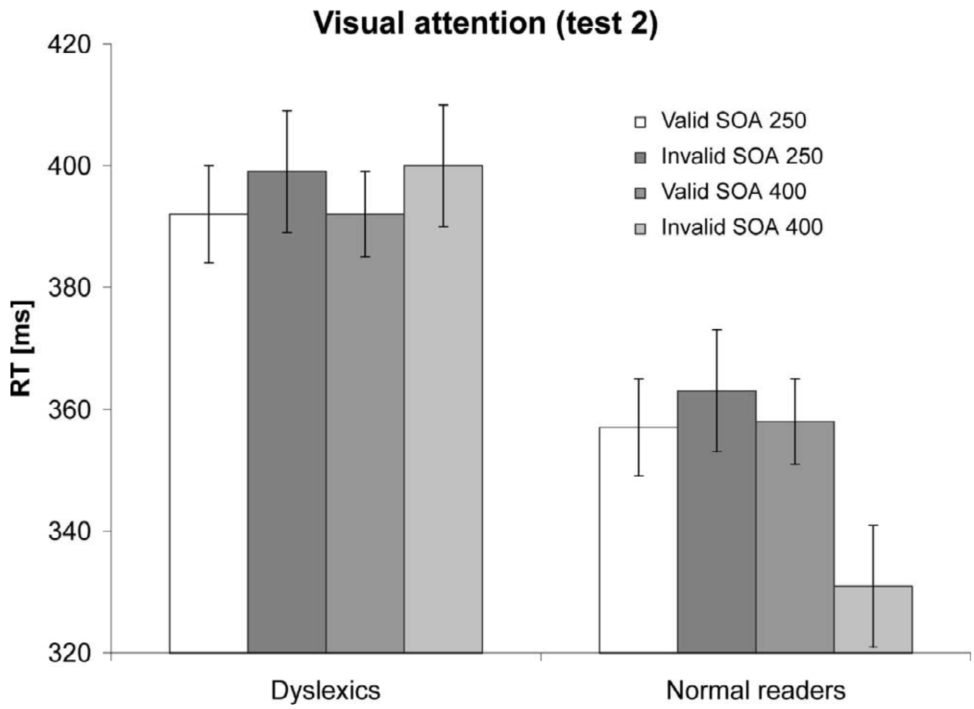

Fig. 2. Mean reaction times (RTs) in the visual attention test as a function of group (dyslexic and normal readers), cue condition (valid and invalid) and SOA (250 and 400 ms).

evidence that children with specific reading disorder or dyslexia are impaired in: (1) early enhancement of the auditory processing of cued information, and (2) late inhibition of the auditory processing of cued information. If one considers that attention selects competing auditory stimuli by a facilitation mechanism and an inhibition mechanism, both working as integrated processes of spatial selection, it can be suggested that in children with dyslexia there is a spatial selection deficit in the auditory modality. This result suggests a direct link between automatic auditory attention deficit and phonological processing impairment in dyslexia. Precisely, defective auditory spatial attention as shown in the present study could cause both phonological processing and phonological awareness deficits in dyslexic children. In fact, non-word reading (accuracy -1.8 and speed -2.9 Z scores), phonemic assembly (5/20 errors) and phonemic elision (3/20) were impaired in dyslexic participants. However, the deficit in phonological processing indicated by impaired non-word reading could find an alternative interpretation in the light of our recent study showing that only phonological dyslexics exhibit abnormal spatial inhibition during left-to-right covert orienting of visual attention [12].

In addition, the results of test 2 suggest also an impairment of automatic visual attention capture and orienting, confirming several studies [5,14–16,23,24]. It would seem, therefore, that those dyslexic children who show auditory attention deficits also have defective spatial orienting of visual attention.

The results of our two tests, therefore, suggest that a multimodal deficit both in auditory and visual automatic attentional orienting may also explain a wide variety of defective processing of rapid stimulus sequences in dyslexics [7,22]. The selective spatial 'filter' impairment reported here suggests that a PPC dysfunction [42] could be the neurological basis underlying dyslexics' attentional deficits [49]. A dysfunction of the PPC in dyslexics has also been suggested by Hari et al. [24], who showed a prolonged attentional dwell time in dyslexic adults.

The neurobiological substrate of spatial attention abnormality in dyslexia might be an M deficit (for a review, see Ref. [42]). In fact, a decreased M input to the dorsal visual stream would result in a bilateral dysfunction of the parietal cortex. However, Skottun [39] recently reviewed studies on contrast sensitivity, a line of research supporting the M deficit theory, finding evidence both for and against M deficits in dyslexia. In addition, Stuart et al. [43], examining evidence for an M deficit in dyslexia, concluded that a simple attentional dysfunction may explain many of these studies. Finally, also the results from other tasks offering evidence for M deficits, such as the ability to perceive global-dot motion (e.g., Ref. [40]), could be explained by a selection deficit, given that motion perception is strongly modulated by attention [35].

In summary, we provide evidence that dyslexic children do not show the auditory and visual IOR at the longer interval which is usually shown in normal readers. Moreover, dyslexics do not manifest early auditory attentional facilitation. Previously, other studies on visual attention of poor readers and dyslexic children showed that also attentional facilitation was not present at the earlier interval but only at the longer interval [5,15,16]. It would seem, thus, that a slower capture of attention, hampering the modulation of perceptual gating for both auditory and visual stimuli, may distort the development of phonological and orthographic representations that is essential for learning to read [22].

Finally, the present auditory and visual tests might aid also treatment of reading impairment in dyslexic children. In fact, recent studies [13,19] showed that dyslexics' ability to read improves following a specific training that improves their visual spatial selection and attentional orienting mechanisms. Stimulation of auditory spatial attention could also represent an effective solution for dyslexic children.

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