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Research report

Developmental dyslexia and spatial relationship perception

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ABSTRACT

According to wide literature, a global impairment in the temporal and spatial domains as well as an increased crowding effect is common of dyslexics. The aim of the study was to evaluate if such subjects suffer from a more general impairment of spatial relationship perception (SRP) and in particular from anomalous spatial relationship anisotropy (SRA) thus accounting both for their global perceptual distortions and abnormal crowding. SRP of 39 young disabled readers and 23 normal subjects were measured by a specifically designed psychophysical technique based on circular and elliptical target recognitions. A general impairment of SRP characterized by increased horizontal/vertical anisotropy was found in the dyslexic sample compared to the controls. In the second part of the experiment, reading efficiency and reading time were measured by MNREAD© reading cards in standard conditions and after increasing horizontal spatial extension of the sentence by different values. We suppose this modification could well compensate the abnormal anisotropy found in dyslexics. Data obtained in the two groups were compared. A strong correlation between reading efficiency (a parameter we have specifically devised) and horizontal spatial text relationship values were present in the patients ($r = .87$, $p < .01$), but not in the controls. The same was found taking into consideration mean reading time ($r = -.82$, $p < .01$). We therefore gather that an alteration of SRP, characterized by an increased anisotropy may be involved in developmental dyslexia.

1. Introduction

Developmental dyslexia is a specific reading disability that affects approximately 4–10% of the population of school age (Rutter, 1978; Shaywitz et al., 1990). It has been defined as a reading difficulty despite adequate instruction and education, normal intellective capacities and socio-cultural situation and not caused by reduced visual acuity or psychiatric pathologies (Remschmidt et al., 1994). Over the last three decades, visuoperceptive abnormalities have been found to be associated with this pathology, suggesting that visual system impairment may play a causal role.

However, the nature of this deficiency is not clear. At present the most widely accepted theory, mainly based on contrast sensitivity (Lovergrove et al., 1980, 1982, 1986, 1990; Martin and Lovergrove, 1984; Lovergrove, 1991; Livingstone et al., 1991; Lehmkuhle et al., 1993; Cornelissen et al., 1995) is that dyslexic readers suffer from a deficit in the magnocellular system (Stein and Walsh, 1997).The magnocellular or transient system is sensitive to high temporal and low spatial frequencies (Legge, 1978) and seems to promote the saccades triggering via inhibition of the parvocellular or sustained system, which in turn would support word fixation during reading (Galaburda and Livingstone, 1993; Stein and Walsh, 1997).

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Indeed, anatomical and electrophysiological evidences have been provided by the same authors but as pointed out by Skottun (2000) after reviewing the main bibliography, the final evidence for a contrast sensitivity magnocellular-related deficit in dyslexia remains controversial.

Instead there is increasing evidence that a global distortion of the visual space both in the temporal and spatial domains takes place in dyslexic subjects. Such finding would rely on the impairment of psychophysical tasks such as motion perception (Cornelissen et al., 1995; Eden et al., 1996; Demb et al., 1998; Slaghuis and Ryan, 1999; Talcott et al., 2000; Hansen et al., 2001; Wilmer et al., 2004), contour integration (Simmers and Bex, 2001), spatial localization (Stein, 1989; Stein et al., 1989) and spatial relations representation (Pontius, 1981).

Coherent motion perception measures the sensibility to the shift of an array of dots moving coherently at the same speed and in the same direction, embedded in a field of incoherently moving random dots. A consistent body of literature maintains that the threshold for coherent motion detection and speed discrimination is impaired in dyslexic readers. The threshold for coherent motion perception is higher in dyslexics at luminance levels ranging from .4 to 130 cd/m^2, both in young and adult subjects (Cornelissen et al., 1995; Eden et al., 1996; Slaghuis and Ryan, 1999; Talcott et al., 2000; Hansen et al., 2001). Similarly, dyslexics perform worse than controls in discriminating the difference in speed of two moving sine wave gratings (Demb et al., 1998).

In the spatial domain, Simmers and Bex (2001) measured the threshold in detecting contours of paths made of Gabor patterns within a field of randomly oriented distracter elements. They found sensibility to be reduced in dyslexic subjects by a factor of two or three compared to normal readers, thence suggesting that some deficit in global processing takes place.

Moreover, spatial localization seems to be affected in dyslexic children (Stein, 1989; Stein et al., 1989; Solman and May, 1990) as well as spatial relations representation (Pontius, 1981). In particular Solman and May (1990) showed that the size of spatial discrepancy was greater in disabled readers compared to normal readers when asked to point the location of a briefly displayed stimulus (shape or letter), and Pontius (1981) showed that almost 80% of the recruited sample of dyslexics had difficulty in the performance of a figure rotation task. It is noteworthy to pinpoint that both in the spatial and temporal domains the visual perception is affected by a certain degree of horizontal/vertical anisotropy, as shown for misalignment tasks (Yap et al., 1987; Westheimer, 2005), horizontal displacements (Westheimer, 2005; Feng et al., 2007) and motion detection perception (Van de Grind et al., 1993; Raymond, 1994).

Actually, it is difficult to establish a link between such heterogeneous anomalies that suggest a global distortion of the visual space and the typical dyslexic reading pattern.

Looking for more direct elements accounting for lexical disability, some investigations have suggested that dyslexics' reading is impaired by crowding (Bouma and Legein, 1977; Atkinson, 1991, 1993; Spinelli et al., 2002; O'Brien et al., 2005; Martelli et al., 2009). Crowding, described for the first time by Korte in 1923, is defined as the deleterious influence of nearby contours on visual discrimination (Levi, 2008). It relies on excessive feature integration, acting over a large area so as to comprise flanking stimuli together to the target (Pelli et al., 2004).

Two main theories have been advocated to explain its psychophysical basis. Reciprocal inhibitory effect by nearby letters was proposed initially by Estes (1972, 1974) and Bjork and Murray (1977) and more recently by Chung et al. (2001). As an alternative, crowding has been attributed to a spatial mislocalization leading the features of adjacent letters to be mixed and melted (Wolford, 1975; Krumhansl, 1977; Krumhansl and Thomas, 1977; Strasburger and Rentschler, 1995; Wilkinson et al., 1997; Parkes et al., 2001; Levi et al., 2002; Pelli et al., 2004; Strasburger, 2005). Whatever its effect is on letters perception, crowding is characterized by the critical center-to-center spacing between target and flankers, that is the threshold separation between target and flankers beyond which the target becomes recognizable. Its value is .1° in the normal fovea (Bouma, 1970; Toet and Levi, 1992; Liu and Arditi, 2000) and increases with eccentricity by a constant ratio of about 0.4–0.5 (Bouma's law) (Bouma, 1970; Toet and Levi, 1992). Hence, the critical spacing describes the size of the integration fields within which features are subjected to suppression or mislocalization.

Interestingly, crowding is found to be anisotropic (Feng et al., 2007; Levi, 2008) so that horizontally arranged flanks are more effective than verticals for stimuli projected along the horizontal meridian. This characteristic may be related to the anisotropy of the spatial integration fields across the central 10° visual field as found in normal subjects (Bouma, 1970; Toet and Levi, 1992).

Due to this anisotropy, such interaction fields are elliptical in shape in periphery, with the main axis radially oriented toward the fixation point (Toet and Levi, 1992). Although it has not been investigated so far, it is arguable that crowding reinforcement in dyslexic subjects may be related to anisotropic changes of the interaction zones. However it is unlikely that abnormal crowding in disabled readers may directly account for the other global configuration-related alterations as mentioned before, since the effect of the interaction zones is thought to be local, promoting the integration of single features across neighbour regions for tasks involving acuity and hyperacuity (see Levi et al., 1985).

In line with the previous findings, we have recently found that a mild global horizontal/vertical asymmetry characterises the visual space of normal subjects (Aleci et al., 2010). Thence, as a starting hypothesis, we wonder if such an asymmetry may dictate at the same time the physiological anisotropy of the interaction zones as well as the mild horizontal/vertical asymmetry found to be proper of different tasks in the spatial and temporal domains.

Upon this theoretical basis, increased asymmetry of the overall visual space in dyslexic readers on one hand could augment the anisotropy of the interaction zones, thus reinforcing crowding and on the other hand it may account for the reported global distortion of the visual space.

Therefore, in the first part of this experiment we measured the amount of spatial anisotropy in disabled readers without using integration tasks as in previous studies but by directly evaluating the spatial relationship perception (SRP) of the subjects along the horizontal and vertical meridians of the visual field. We define SRP as the visual function able to detect the difference between the extent of an arbitrary shape, such

as an ellipse, along the vertical and horizontal coordinates. The shortest focal axis length which allows the subject to correctly recognize the ellipse without mixing it up with a circle reflects his SRP sensitivity.

Under this perspective, we consider the visual system as isotropic if SRP sensitivity is the same for horizontal and vertical ellipses, i.e., if the threshold is independent of the stimulus orientation. Otherwise spatial relationship anisotropy (SRA) takes place. In the current study, the direction of anisotropy is arbitrarily referred to as the less sensitive orientation. In this way, higher recognition thresholds for, e.g., horizontally-oriented stimuli are indicative of outward–inward anisotropy along the horizontal meridian reflecting a perceptual compression of the visual space from the nasal/temporal periphery toward the fixation point. In this case a barely horizontal ellipse is expected to appear as if it was "stretched" along the vertical axis and/or "squeezed" along the other, being misperceived as a circle. Equally, a circle is expected to be misperceived as a vertical ellipse.

2. Methods – part I

2.1. Participants

Forty-two dyslexic readers (28 males, 14 females, mean age 8.4 ± 1.9) and 23 normal subjects as a control group (13 males, 10 females, mean age 9.2 ± 2.0) took part in the experiment.

Selection criteria were those previously outlined by Stanley and Hall (1973): presence of developmental dyslexia, that is to say a reading delay of 2.5 years or more below the expected one for their age level, average to above-average intellectual ability, normal IQ as measured by Wechsler Intelligence Scale for Children (WISC-R) scale, performance equal to normal readers in other academic subjects, normal visual acuity [Best Corrected Visual Acuity (BCVA) $\geq$ 60/60] without gross behavioural problems and auditory impairment. Mean reading speed (expressed as syllable per second) and accuracy (or correctness, expressed as number of errors calculated on the amount of read text) of the recruited dyslexics resulted to be below -2 standard deviation (SD) from normative data (Remschmidt et al., 1994) as evaluated by MT reading test (Cornoldi and Colpo, 1981; Cornoldi et al., 1981).

The members of each group were randomly recruited from the same urban school so that both of them were correctly matched for age and socio-cultural contest.

Exclusion criteria were BCVA $<$ 60/60, eso/exotropy, poor convergence, general or ophthalmological diseases, phonological alterations, myopia/hyperopia $\geq \pm 2$ diopters, astigmatism $\geq \pm 1$ diopters, auditory impairment, behavioural problems, IQ $<$ 90 (as measured by WISC-R scale) and poor collaboration.

The parents of all subjects were contacted by phone and their informed consent was obtained after explanation of the aim, nature and possible consequences of the study. After being recruited, three dyslexic subjects showed very poor collaboration in performing the test and were excluded from the experiment. All applicable institutional and governmental regulations concerning the ethical use of human volunteers were followed. The research obeys the tenets of the Declaration of Helsinki.

2.2. Experimental procedure

SRP thresholds and SRA of each subject were evaluated by means of a psychophysical test conceived on purpose (Aleci et al., 1998, 2010) in our Department and operating on a personal computer (Hp Compaq 1702) with a flat 15″ liquid crystal screen (screen resolution of at least 1024×768 pixels). In order to avoid the rectilinear screen edge being used as a reference cue on the curvature judgement, the frame was covered by a grey cardboard mask, leaving a sinusoidal circumferential profile. The experiment was performed during the late morning in a dimmed room (illuminance: .15 lux) in monocular conditions. The order of the tested eye (left/right) was randomized.

Each stimulus (white coloured with luminance of 160 cd/m^2) consisted either of an ellipse whose major axis was randomly oriented along the *y*- or *x*-meridian or a circle, displayed on a 40 cd/m^2 grey background centred at fixation. Mean target size subtended a visual angle of 300 arc min at a 50 cm viewing distance.

Ellipse target eccentricity was expressed as a percent "interaxis ratio" (IR):

$$\mathrm{IR}(\%) = f(x) - f(y)/f(m_{x,y}) \times 100$$

where $f(x)$ *and* $f(y)$ are the values of the *x*- and *y*- axes and $f(m_{x,y})$ is the higher value between them. Of course, a circle has an IR of 0 (zero). The IR tested range was $\pm$34% and 1% point matches a difference between the two axes of 3.3 arc min at the viewing distance.

Before the test started, a lapse of time of about 15 min was left so as to allow subjects to reach the best confidence with the environment and the operator, skilled in psychophysics, who supervised the examination. Soon after, every subject performed a short training exercise made up of a sequence of 10 easily detectable targets which he was asked to name aloud while pressing the corresponding button on the keyboard at the same time. In this way the subjects became acquainted with the psychophysical procedure and the operator could ensure the right correspondence between the intended answer and the relative chosen button. The examination started with the onset of a white flickering point (34.2 arc min wide, 6.6 Hz, total duration: 1000 msec) at the center of the screen, aimed to keep fixation before the test stimulus appeared. Immediately after the last winking, the target was displayed for 200 msec. Observers were instructed to identify the displayed target either as a circle or as a horizontal or vertical ellipse by pressing one of three different keys on the PC keyboard, according to a forced triple choice procedure (3AFC). The vertical or horizontal orientation of the ellipses (plus 15 circles) was presented in a randomized order.

The SRP threshold along the horizontal and vertical orientations is achieved through a variation of the main axis length of the target according to the staircase weighed up–-down method (Kaernbach, 1991), based on the truncated (or simple up–down) staircase procedure (Dixon and Mood, 1948), and adapted so as to work separately for the *x*- and *y*-axes orientation of the targets. In fact, even though the stimulus orientation was randomized between trials, the answer deriving from a horizontal stimulus influenced only the

subsequent horizontal presentation without any effect on the computation of the main axis length of the next vertical target and vice versa. In this way the computations of the threshold for the two classes of ellipses were independent.

According to Dixon and Mood (1948), the a priori probability for a correct answer as a function of stimulus main axis length is assumed to be a cumulative normal distribution. As pinpointed by Treutwein (1995) the staircase thus modified converges to a target probability higher than 50%.

Such an adaptive procedure is widely accepted and commonly used by the ophthalmologists in clinical perimetry to measure the differential light sensitivity in different points of the visual field (Lachenmayr and Vivell, 1993; Weijland et al., 1996; Anderson and Patella, 1999).

Once the thresholds referred to the horizontal (HT) and the vertical meridians (VT) were obtained, the SRA could be computed as their difference taken as an absolute value, so that higher SRAs express higher outward–inward anisotropy along the horizontal meridian.

The experiment was conducted in a double masking fashion. For both groups mean threshold values were compared by double-tailed *t*-test for independent groups, after verifying normality by means of Kolmogorov–Smirnov test. Correlation analysis was performed by Pearson test. Grubbs analysis was used to detect outliers. Significant level was set at *p* value of .05. In the 'Results' section, SD is given in brackets after mean values.

3. Results – part I

Fig. 1a shows mean SRP thresholds and SRA in the two groups. Mean VT and HT in dyslexic subjects were higher than those obtained in the control group. In particular mean HT was 9.16 (±3.85) in the disabled readers versus 5.86 (±1.90) in the controls and mean VT was 5.73 (±2.94) versus 3.64 (±1.75), $p < .001$ in both cases.

Mean SRA as indicator of a visuoperceptive departure from an *x* to *y* matching condition was then computed (Fig. 1b).

Overall outward–inward SRA along the horizontal meridian was found in 33 subjects out of 39 (84.6%) in the dyslexic group, and in 20 subjects out of 23 (86.9%) among the normal readers. However such effect in disabled readers was greater compared to normal subjects by almost 50% (4.40 ± 2.59 *vs* 2.36 ± 1.75, $p \leq .01$).

Considering the mean SRA + 1 SD as a cut-off in controls, (in accordance to the criterium used by Spinelli et al., 2002),

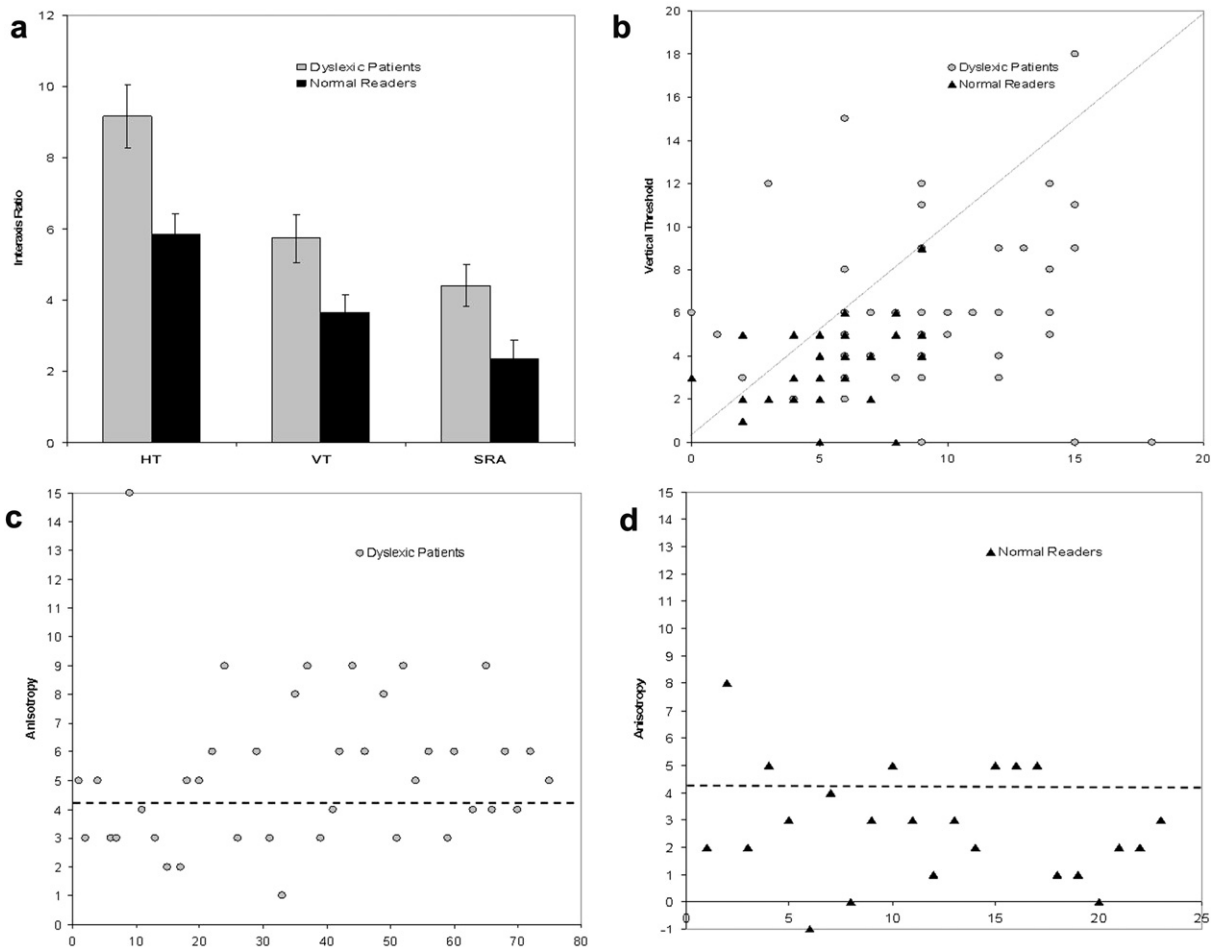

Fig. 1 – Results part I. (a) SRP in dyslexic and control subjects. (b) Departure from isotropy in dyslexic (circles) and normal eyes (triangles). The diagonal line represents isotropy. (c and d) Isotropy distribution in dyslexic (circles) and normal subjects (triangles). The dotted horizontal line represents the cut-off level (mean SRA in controls + 1 SD).

anisotropy value above this level was present in 56% of the dyslexics and in 26% of normal readers (Fig. 1c and d).

No correlation was found between age and SRP thresholds in both groups (HT, VT, SRA in dyslexics: r values respectively were .01, −.1, .4, $p \geq .05$. HT, VT, SRA in controls: r values respectively were −.27, −.24, −.05, $p \geq .05$). This suggests that the performance of the task is not dependent on cognitive or intellective development.

No statistical differences ($p > .05$) were found for HT, VT and SRA between right and left eye both in dyslexics and in controls. Besides, no differences were found between the dominant and fellow eye. Considering that all recruited subjects were right-handed, it can be argued that SRP does not depend neither on ocular nor on hand dominance.

Therefore impaired SRP occurred in the majority of the disabled readers. Such a defective condition was characterized by an outward–inward SRA which on average resulted to be nearly doubled compared to normal readers. As a working hypothesis this finding may relate to the reinforcement of extrafoveal crowding which would characterise the dyslexics' visual system, according to Bouma and Legein (1977) and Martelli et al. (2009).

To test this possibility, in the second part of the study the rectangular area occupied by the reading string was "stretched" along the horizontal axis so as to compensate the anisotropy found in dyslexics. As a consequence an improvement of the processing of sequential stimuli and finally an improvement of reading performance are expected. On the contrary, a compression of the string would favour dyslexics' outward–inward SRA, thereby hampering further their reading disability.

4. Methods – part II

4.1. *Participants*

A few months after the end of the first experiment, 14 disabled readers (10 males, 4 females, mean age 9.3 ± 2.3) and 14 normal subjects (8 males, 6 females mean age 9.1 ± 2.0), who were available to be further examined, were recalled to assist in the second part of the study. Individual reading scores found in subjects who participated in the Exp. 2 are shown in Table 1.

Mean age of the two subgroups who took part in the second experiment as well as spatial relationship thresholds and anisotropic values were not statistically different compared to the same data obtained from the two original samples recruited in the first experiment ($p > .05$ in all cases, unpaired double tail t-test).

4.2. *Experimental procedure*

Reading time (Rtm) and reading efficiency (RE) have been evaluated by means of MNREAD test (©2000 J. Stephen Mansfield, Minnesota, Italian version), both in standard conditions and after horizontally stretching the printed sentence. As a counter-check dyslexics were tested even in the opposite condition, which is after compression of the string, expecting this time a worsening of their performance.

Table 1 – Rtm and RE of the sample recruited in the Exp. 2.

Dyslexics	Rtm	RE
1	11	26.69
2	14.8	19.84
3	17.4	16.85
4	16.9	17.39
5	11.6	25.28
6	8.2	25.29
7	63.4	3.25
8	14.8	9.92
9	23.8	11.02
10	36	8.18
11	25	5.88
12	27.6	5.32
13	37.0	7.94
14	9.8	29.99
Mean	22.66	15.20
SD	14.91	9.0
Controls	Rtm	RE
1	8.4	24.7
2	17	12.21
3	10.6	27.73
4	13	22.59
5	6.8	43.22
6	7.2	40.82
7	13.2	22.25
8	7	41.99
9	11.2	18.6
10	10.07	29.2
11	7.74	38
12	12.06	24.4
13	12.26	24
14	10.18	20.4
Mean	10.5	27.9
SD	2.9	9.5

MNREAD test (Ahn et al., 1995) is made up of 19 sentences of the same length and number of characters (60). The reading material used for the experiment concerned the same school level both for controls and for the disabled readers. Character size in MNREAD cards varies from 1.3 to −.5 logMAR (Snellen from .05 to .32) . The print size chosen for our experiment subtended a horizontal angle of 24 min arc per character at the given viewing distance. Words were those typically found in Italian elementary school reading material. Subjects were asked to read 14 of these sentences aloud in binocular conditions: four were presented in standard conditions, while in the others the rectangular space filled by the printed text was increased along the horizontal axis and proportionally reduced along the vertical, so as to keep the area constant, by 14.5% (two sentences), 23% (two sentences), 29% (two sentences) or decreased by 23% (two sentences) and 29% (two sentences). We will refer to these conditions as H_0, $H_{+14.5}$, H_{+23}, H_{+29}, H_{-23} and H_{-29}. Taking two letters "o" as samples, center-to-center spacing turned out to be respectively 25.92, 27.54, 28.62, 29.16, 23.76 and 22.68 min arc and character size ranged from a minimum of 17 min arc for H_{-29} to a maximum of 30.9 min arc for H_{+29}.

The spatial relationship modification of the MNREAD samples was performed by an appropriate graphic software running on a certified LCD computerized optotype equipment (VistaVision®).

Light reflection from the flat surface of the cards was 112 cd/m^2, contrast was 100%. The experiment was performed during the late morning and each time the operator was unaware of the kind of subject under examination (if case or control).

Before the test started, subjects were asked to read four extra sentences (whose scores were not included in the final computation) to become acquainted with the experimental procedure. Later on, they were required simply to read each sentence aloud time after time without stopping to correct any mistakes. No recommendation was made so as to be as quick and accurate as possible.

Rtm and efficiency (E) were obtained for each H-condition.

Rtm, i.e., the time spent to read the sentence was automatically measured by the software timer, synchronized with a button to be pressed as soon as the subject completed his/her reading performance.

E is an index computed according to the following equation:

$$E = (n/\mathrm{Rtm})\mathrm{SQR}[w/(m+1)]$$

where n is the number of characters in the sentence (spaces included), Rtm is the reading time in seconds, SQR is square root, w is the number of words contained in each sentence and m is the number of misspelled words.

Linear regression analysis was performed taking 95% as a confidence interval. To test differences in Rtm and E as a function of the H-condition, one-way analysis of variance (ANOVA) was carried out along with Tukey–Kramer Multiple Comparison test.

5. Results – part II

Table 1 and Fig. 2 a and b show mean Rtm and E in both groups. As expected, mean Rtm is higher (22.6 ± 14.9 *vs* 10.5 ± 2.9 sec, $p < .05$) in dyslexic subjects compared to controls and, on the contrary, mean E is lower (15.2 ± 9.0 *vs* 27.9 ± 9.5 $p < .05$).

Fig. 2c depicts the regression trend of Rtm at every H-condition in dyslexic readers. Mean Rtm decreases as the area occupied by the written line is stretched along the horizontal axis from H −29% until H +29% ($r = -.82$, $p < .05$). A similar but direct correlation is found in disabled readers for mean E ($r = .89$, $p = .01$). On the contrary, in the control group no significant correlation was found ($r = -.12$ and $r = .43$, respectively for Rtm and E, $p > .05$ in both cases, Fig. 2d).

Setting the cut-off for pathologic anisotropy beyond 1 SD from the mean normal value (Spinelli et al., 2002), in the second part of the study seven dyslexics (50%) resulted to be within the normal range.

The effect of changing the spatial relationship of the string on E and on Rtm was significant in dyslexic readers ($p < .01$),

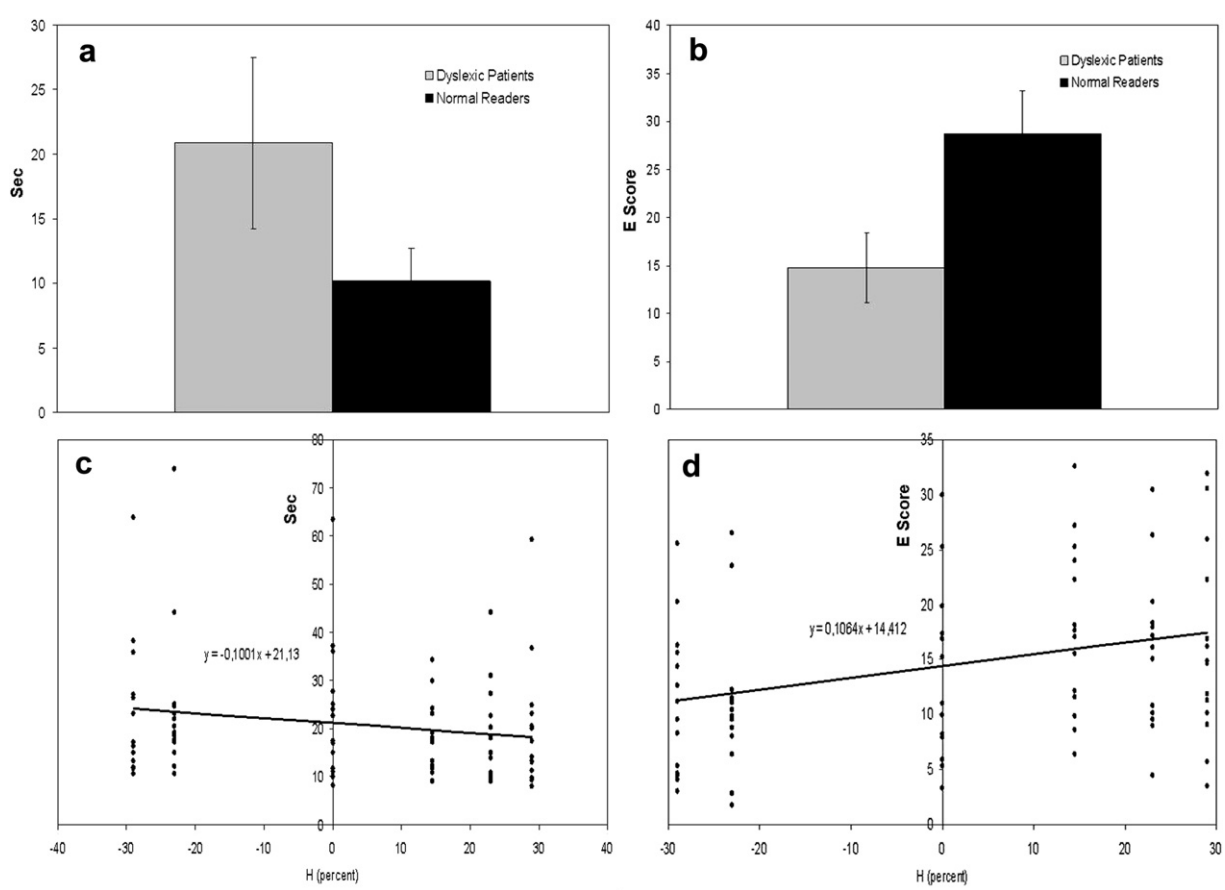

Fig. 2 – Results part II. (a,b) Mean Rtm and E in dyslexic and control subjects. (c,d) Linear regression between reading performance (Rtm and E) and the H-conditions in disabled readers.

as revealed by repeated measures ANOVA. In particular Tukey–Kramer Multiple Comparison test showed statistical differences for E between H_{+29} and H_{-23} ($q = 4.55$, $p < .05$), H_{+29} and H_{-29} ($q = 4.48$, $p < .05$), H_{+23} and H_{-23} ($q = 4.47$, $p < .05$), H_{+23} and H_{-29} ($q = 4.40$, $p < .05$), $H_{+14,5}$ and H_{-23} ($q = 6.47$, $p < .001$) and $H_{+14,5}$ and H_{-29} ($q = 6.40$, $p < .001$). Similarly, statistical differences were found for Rtm between H_{+23} and H_{-23} ($q = 5.69$, $p < .01$), H_{+23} and H_{-29} ($q = 4.47$, $p < .05$), $H_{+14,5}$ and H_0 ($q = 4.68$, $p < .05$), $H_{+14,5}$ and H_{-23} ($q = 6.24$, $p < .001$) and $H_{+14,5}$ and H_{-29} ($q = 5.02$, $p < .01$).

These results support the idea that the spatial relationship modification of the area occupied by the string has an effect on reading performance in dyslexic subjects. In particular RE and Rtm improve as a function of the H-widening.

6. Discussion

Under the ophthalmological point of view, the main characteristic of developmental dyslexia is the dissociation between normal single letter recognition, that is visual acuity, and abnormal sequential words recognition, that is to say reading capacity.

In effect the mix-up of similar or mirror letters, the inversion of syllables within the word as well as the perception of "twisted words", "jumping" and "melting" proper of this condition, have led many researchers to postulate a visual processing impairment.

Actually, different and apparently heterogeneous alterations involving the global visual perception in both the temporal and spatial domain are found to affect dyslexic readers. In particular impaired motion perception (Cornelissen et al., 1995; Eden et al., 1996; Demb et al., 1998; Slaghuis and Ryan, 1999; Talcott et al., 2000; Hansen et al., 2001; Wilmer et al., 2004), contour integration (Simmers and Bex, 2001), spatial localization (Stein, 1989; Stein et al., 1989) and spatial relations representation (Pontius, 1981). Nevertheless, such anomalies *per se* do not seem able to account for the clinical patterns.

Instead, abnormal crowding has been recently advanced to play a direct role in affecting the reading performance of dyslexics (Bouma and Legein, 1977; Atkinson, 1991, 1993; Spinelli et al., 2002; O'Brien et al., 2005; Martelli et al., 2009).

Threshold related to crowding can be described in terms of critical spacing, i.e., the least distance between target and flankers beyond which the target becomes recognizable. Instead, within this region features are suppressed or, as an alternative hypothesis, they are mislocated or pooled (see in the Introduction). In effect Petrov and Popple (2007) and Petrov et al. (2007) stated that the source of crowding is a positional uncertainty due to a perceptual localization shift of the peripheral characters toward the fixation point, which takes them to be pooled with the inward elements. This hypothesis is supported by Liu and Arditi (2001) who described the confusion patterns between crowded letters in normal subjects in terms of confusion matrices. Indeed, such a spatial mislocalization generates errors such as the confusion between mirror symmetric configurations and positional inversions, both of them typical of the dyslexic reading.

As already mentioned in the Introduction section, spatial interaction zones in normal subjects are anisotropic (Bouma, 1970; Toet and Levi, 1992), so that they appear to be elliptical in shape in periphery, with the long axis radially oriented toward the fixation point.

By using targets radially or tangentially arranged with respect to the fixation point, critical spacing is found to be more effective when the layouts are oriented along the horizontal meridian of the visual field compared to the vertical (Feng et al., 2007); moreover, feature integration along the x-axis is characterized by a marked outward–inward anisotropy (Bouma, 1970, 1973; Krumhansl and Thomas, 1976, 1977; Chastain and Lawson, 1979; Wolford and Shum, 1980; Chastain, 1982; Legge et al., 2001; Bex et al., 2003; Petrov and Popple, 2007; Petrov et al., 2007).

There is evidence that even visual space perception both in the temporal and spatial domain results to be mildly anisotropic in normal subjects. In the temporal domain, for example, coherence motion sensitivity is directionally anisotropic as asymmetry in motion detection has been described along the outward–inward horizontal direction and it is found to be higher along the horizontal axis compared to the vertical (Van de Grind et al., 1993; Raymond, 1994). Interestingly, the shape of the isothreshold curves for motion detection is elliptical (Van de Grind et al., 1993), matching the shape of the so-called attentional window, (Pan and Eriksen, 1993) and of the integration fields as found by Toet and Levi (1992).

In the spatial domain, the sensitivity referred to misalignment tasks is anisotropic as threshold differences have been referred between radially- and tangentially-oriented configurations (Yap et al., 1987; Westheimer, 2005). Threshold for horizontal displacements is higher compared to verticals (Westheimer, 2005; Feng et al., 2007). Westheimer (2005) reckoned that anisotropy, expressed as a ratio between the two orientation thresholds, is about .82 and .77 respectively for lines and dots. Such data are altogether in accordance with the mean anisotropy found in the current investigation (.62). Even the shape of the so-called attentional focus (referring to the region of the visual field) where a filtering function promotes the recognition of a particular target (see Cave and Bichot, 1999 for a review) is suggested to be elliptical, with the main axis oriented along the locations of the targets (Pan and Eriksen, 1993).

It is arguable that anisotropy of both the spatial interaction zones (i.e., at a local level) and of tasks involving a wider representation of the visual space may be based on a more general visual space distortion which encompasses and explains both aspects.

In the case that a general distortion turned out to be greater in dyslexics, then their overall increased anisotropy is expected to reflect both on the local integration fields (thus accounting for enhanced crowding) and on more global tasks in the temporal and spatial domain found to be impaired as well.

In other terms this possible occurrence would aid to illuminate the connection between abnormal crowding on one hand and the heterogeneous anomalies involving the global perception of visual space on the other in disabled readers.

In the current experiment SRP along the horizontal and vertical meridians of the visual field and its anisotropy were measured by means of a technique that is independent from integration tasks. In the recruited normal sample, threshold

discrimination for elliptical and circular targets turned out to be higher for horizontal compared to vertical stimuli.

In a previous experiment, Regan and Hamstra (1992) measured in four normal volunteers the aspect ratio discrimination threshold, i.e., the minimum ratio between height and width required by an ellipse to be discriminated from a circle. Under this perspective, the aspect ratio discrimination threshold can be likened to the SRP threshold. The authors used a two-temporal alternative forced-choice paradigm and subjects were required to discriminate between a reference stimulus and a test stimulus. According to their experimental procedure, an ellipse was judged to be a circle for aspect ratio discrimination thresholds between 1.014 and .995, corresponding to a value lower than 1.4%.

Such results differ to a certain degree from those found in this research, though some procedural and conceptual differences in the two experiments make the data comparison difficult to perform.

Firstly, Regan and Hamstra adopted a two-temporal alternative forced-choice paradigm and the observer was asked to compare the test stimulus with a reference stimulus which was either a circle or a horizontal/vertical ellipse of different aspect ratios. In their case thresholds were estimated by Probit analysis. On the contrary, we used a forced triple choice-like procedure and the threshold was estimated by means of a staircase 4-2-1 derived algorithm. Secondly, in our study no reference stimulus was adopted. Besides, in our research the mean size of the stimuli was five times larger, the luminance level was kept fixed at a value of 160 cd/m^2 rather than being randomly varied from 43 to 129 cd/m^2 and the presentation time was shorter (200 msec *vs* 1.5 sec). Lastly, we performed the test in monocular conditions, and the age of the recruited normal subjects was considerably lower. In particular the extrafoveal projection, the shorter presentation time, the lower age of the sample and the monocular viewing could account for the higher thresholds found in our investigation. However Regan and Hamstra found discrimination threshold to be lower when a circle is presented as the reference stimulus and increases as its aspect ratio moves away from the unity. Even though the anisotropy degree was not expressly investigated, it can be argued by the inspection of Fig. 6 (page 1852) that little differences in discrimination threshold resulted between the horizontal and vertical axes considering respectively horizontal and vertical ellipses as reference stimuli (Regan and Hamstra, 1992).

In the current study horizontal stimuli are correctly identified up to about 6% eccentricity. Below this value ellipses are often mixed up with circles, as if an outward–inward attraction or collapse exerted toward the fixation point occurred along the horizontal meridian. Such a result is in line with the anisotropy proper of the model proposed by Petrov and Popple (2007) and Petrov et al. (2007) as well as the anisotropy found by Feng et al. (2007) for perpendicularly oriented layouts.

Therefore, the obtained results suggest mild overall vertical/horizontal anisotropy which characterises the visual field of normal subjects. This finding seems coherent with the anisotropic behaviour proper of crowding-related interaction zones and of other heterogeneous and more global visual tasks as already reported.

As far as we know, the effects abnormal spatial relationship anisotropy can have on the reading performance of dyslexic subjects have not yet been investigated.

Compared to the control group, we obtained two main findings in disabled readers: their sensitivity is lower along both the vertical and horizontal axes and, as their difference widens, increased mean spatial relationship anisotropy.

In effects, our dyslexic sample showed overall higher thresholds for both vertical and horizontal axes compared to the control group.

Recently, Greenwood et al. (2009) measured in a cross-like stimulus the accuracy of judging the horizontal line position (above or below the stimulus midpoint) in the presence or absence of nearby flankers. In addition to a systematic and selective perceived anisotropic offset consistent with the flanking structure, they showed that the addition of crowding flankers produced a strong positional threshold elevation. They addressed this finding to positional averaging so that the observed response is predicted by weighted average of position estimates. In the same way and as suggested by Watt and Andrews (1982) and Parkes et al. (2001) averaging the estimate of the local orientations distributed along the more and less curved contours of the elliptical stimuli employed in our experiment may have a detrimental effect on the overall sensitivity along both the horizontal and vertical axes by "normalizing" the elliptical target into a circular configuration. This effect would serve the purpose to simplify the perception of curvilinear configurations (Solomon et al., 2004; Greenwood et al., 2009), in periphery. Thence, increased positional averaging could be a possible solution.

A possible explanation of our results could rely on unstable fixation.

In effect there is evidence that dyslexic children suffer from unstable eye fixation (Pavlidis, 1978; Stein and Fowler, 1982; Eden et al., 1994). As found by Stein and Fowler by using a modified version of the Dunlop test, in 52% to 63% of their sample this deficit has been related to poor motor eye dominance (Stein and Fowler, 1982). Also Eden et al. (1994) showed fixation instability to be greater in dyslexic than in normal readers at a close distance and related such result to defective eye dominance. Impairment of fixation would reflect on abnormalities in saccadic sequential activation, thus affecting reading performance, as discussed by Biscaldi et al. (1998). Indeed, its precision is maintained to be crucial for correctly extracting the visual information during reading (Nazir et al., 1992).

Our second finding is that disabled readers suffer from higher horizontal/vertical asymmetry compared to the control group, as the consequence of a lower sensibility along the horizontal axis compared to the vertical. So as in normal subjects, even more in disabled readers the differential sensibility along the two orthogonal directions may result from the different amount of fixation instability, which has been reported to be greater in the horizontal direction compared to the vertical one (.15° *vs* .12°) (De Luca et al., 1999).

An unexpected result derived from the computation of mean SRP is that the ratio of the averaged VT and HT in the two samples turned out to be almost exactly the same. This suggests that reduction in SRP sensitivity leads to a proportional increase in SRA, at least for threshold values ranging

from 3.64 to 9.16. The data we have collected are definitely not sufficient to provide a possible explanation for this result. However we report that for many visual tasks such as orientation discrimination (Mäkelä et al., 1993) or spatial accuracy (Levi and Klein, 1986; Levi et al., 1987), as well as crowding itself, a proportionality coefficient accounts for the different performance in the peripheral visual field compared to the more central locations. In these cases the performance can be made equivalent to the foveal one by simply scaling the peripheral stimulus by a multiplicative factor which is a function of eccentricity. Such a finding has been related to the spatial oversampling proper of peripheral visual field (Levi and Klein, 1986; Levi et al., 1987). In a future investigation we intend to measure in normal subjects SRP and SRA at different eccentricities across the visual field thus comparing the obtained results to those actually found in the central visual region of dyslexic subjects. This, with the aim to assess whether the processing of the spatial relationships in the central visual field of dyslexics matches the one in the peripheral visual field of normal readers.

Whatever it be, dyslexic subjects tend to perceive horizontal ellipses as if they were circles. The perceptual result of such anisotropy may be an outward–inward contraction along the horizontal meridian causing distance between letters and words to be reduced. As a consequence, characters placed beyond the critical spacing turn out to be located within its boundaries, becoming crowded.

Indeed, in the second part of the study we have found a significant correlation between reading performance of the disabled readers and the modified H-conditions of the written text, from a shrinking value of −29% to a squeezing value of +29%. Our results are in agreement with those found by Spinelli et al. (2002), who estimated that artificially increasing spacing between letters leads to a reduction of vocal reaction time in about half of the subjects and by Martelli et al. (2009) who stated that critical spacing is wider in dyslexic readers compared to controls.

It is possible that this model could aid to illuminate on peculiar aspects of dyslexic reading, that is the frequent confusion between mirror letters and syllables. In effect discrimination threshold for mirror gratings (i.e., 180° phase shift) is far higher compared to non-mirror stimuli in the peripheral visual field (Bennett and Banks, 1987, 1991) and such phenomenon is markedly anisotropic, being more evident for tangential rather than for radially-oriented stimuli (Bennett and Banks, 1991). The same effect occurs for mirror letters, in particular when they are flanked by other letters as shown by Chung (2010). According to the same author, in fact, mirror letters produce a larger crowding in amplitude compared to non-mirrors and this threshold elevation does not depend on the similarity in their features but on the axis of symmetry. Moreover, such a specific loss in sensitivity for mirror-image stimuli increases greatly with the eccentricity (Rentschler and Treutwein, 1985; Bennett and Banks, 1987, 1991; Chung, 2010), due to reduced efficiency (E) in spatial phase encoding (Julesz, 1981; Braddick, 1981; Rentschler and Treutwein, 1985). Even though such a finding is not directly investigated in the current study, we can hypothesize that the anisotropic compression of the visual space along the horizontal axis may degrade the spatial phase encoding for stimuli presented at or near the fixation point at the level expected to occur at more peripheral loci. As a consequence, in disabled readers the recognition of mirror letters would be preferentially (and more) hampered compared to non-mirror letters.

However, only half (Spinelli et al., 2002) or two-thirds (Martelli et al., 2009) of the dyslexic sample improved their reading performance after artificially increasing space between letters and words, whilst for the remaining it was not the case. Upon this basis, the same authors argued that a definite causal role of crowding in developmental dyslexia cannot be established in all subjects and that other pathological conditions could aid the pathogenesis of the disease.

In the current study, 44% of the dyslexic children do not exceed the cut-off we adopted for abnormal anisotropy. This proportion is quite the same as accounted for abnormal crowding as reported by Spinelli et al. (2002). It follows that, as previously stated for crowding, increased anisotropy cannot explain the dyslexic pattern in all cases and at least for a percentage of them an alternative explanation, other than visuoperceptive, must be advanced. Among the controls, those who showed abnormal anisotropic values despite a normal reading rate (about 20%) may have used compensatory mechanisms.

In conclusion, in this research we have found in more than half of the recruited dyslexic an alteration in SRP characterized by abnormal vertical/horizontal anisotropy. It is arguable that crowding reinforcement along the horizontal axis in a wide proportion of dyslexic readers may be just one (and not isolated) manifestation of a global SRP imbalance. Indeed, if further confirmed, our results suggest that such an asymmetry may combine to bring about the other perceptual distortions involving the visual space proper of dyslexia, as already mentioned, thus providing a common frame for this multifaceted pathological condition.

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