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Space representation in children with dyslexia and children without dyslexia: Contribution of line bisection and circle centering tasks

Stéphanie Vieira [a,b], Patrick Quercia [c], François Bonnetblanc [a,b], Carine Michel [a,b,*]

[a] Université de Bourgogne, Dijon, Campus Universitaire, UFR STAPS, BP 27877, F-21078 Dijon, France
[b] INSERM U1093, Cognition, Action et Plasticité Sensorimotrice, F-21078 Dijon, France
[c] Département d'ophtalmologie, Centre Hospitalier Universitaire, Dijon, France

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ABSTRACT

Line bisection tasks (different space locations and different line lengths) and circle centering tasks (visuo-proprioceptive and proprioceptive explorations, with left or right starting positions) were used to investigate space representation in children with dyslexia and children without dyslexia. In line bisection, children with dyslexia showed a significant rightward bias for central and right-sided locations and a leftward bias for left-sided location. Furthermore, the spatial context processing was asymmetrically more efficient in the left space. In children without dyslexia, no significant bias was observed in central lines but the spatial context processing was symmetrical in both spaces. When the line length varied, no main effect was shown. These results strengthen the 'inverse pseudoneglect' hypothesis in dyslexia. In the lateral dimension of the circle centering tasks, children showed a response bias in the direction of the starting hand location for proprioceptive condition. For radial dimension, the children showed a forward bias in visuo-proprioceptive condition and more backward error in proprioceptive condition. Children with dyslexia showed a forward bias in clockwise exploration and more accurate performance in counterclockwise exploration for left starting position which may be in accordance with leftward asymmetrical spatial context processing in line bisection. These results underline the necessity to use the line bisection task with different locations as an appropriate experimental paradigm to study lateral representational bias in dyslexia. The contribution of the present results in the understanding of space representation in children with dyslexia and children without dyslexia is discussed in terms of attentional processes and neuroanatomical substrate.

1. Introduction

Developmental dyslexia is classically described as a neurological condition afflicting the school-age population that persists throughout the lifespan (Habib, 2000). This mild hereditary neurological disorder manifests as a persistent difficulty in learning to read sometimes associated with sensory difficulties in the visual, auditory and tactile domains, problems with balance and motor control (Nicolson & Fawcett, 1990; Quercia, Demougeot, Dos Santos, & Bonnetblanc, 2011; Ramus, 2003;

* Corresponding author at: Université de Bourgogne, INSERM U1093, UFR STAPS, BP 27877, F-21078 Dijon, France. Tel.: +33 03 80 39 90 06; fax: +33 03 80 39 67 02.
E-mail address: carine.michel@u-bourgogne.fr (C. Michel).

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Stein & Walsh, 1997; Vieira, Quercia, Michel, Pozzo, & Bonnetblanc, 2009) with otherwise normal intellectual functioning and educational opportunities (for a review see Shaywitz, 1998). Several theories have been proposed to account for the various deficits in these numerous functions. One of the most influential theories is the phonological theory of dyslexia. The phonological theory postulates that children with dyslexia have a specific impairment in the representation, storage and/or retrieval of speech sounds. It explains reading impairment of dyslexia by appealing to the fact that learning to read an alphabetic system requires learning the grapheme–phoneme correspondence, i.e. the correspondence between letters and constituent sounds of speech. If these sounds are poorly represented, stored or retrieved, the learning of grapheme–phoneme correspondences, the foundation of reading for alphabetic systems, is affected accordingly (Ramus et al., 2003). An alternative theoretical approach gives a primary explanatory role to the sensory and/or motor symptoms. This approach has led to the formulation of theories of dyslexia tracing the cause of reading disability back to auditory processing deficits (via the phonological deficit) (e.g. Cantiani, Lorusso, Valnegri, & Molteni, 2010), visual dysfunction (Lovegrove, Heddle, & Slaghuis, 1980), and/or cerebellar dysfunction (Nicolson & Fawcett, 2011; Nicolson, Fawcett, & Dean, 2001). This theory accounts for reading disabilities both through auditory–phonological and visual–spatial deficits, and encompasses all known cognitive, sensory and motor manifestations of dyslexia (see Stein & Walsh, 1997 for a review). Furthermore, early indicators of dyslexia could be detected at preschool and primary education as psychomotor ability (e.g. spatio-temporal orientation, grapho-motor ability), neuro-physiological development and cognitive mechanisms (e.g. auditory and visual perception, short term memory), phonological awareness, prereading and prewriting skills (Kujala & Näätänen, 2001; Rouse & Fantuzzo, 2006; Temple et al., 2003; Zakopoulou et al., 2011).

1.1. *Dyslexia and spatial attention*

Dyslexia is known to co-occur with other developmental disorders (e.g. Snowling, 2012). The evidence for visual–spatial or auditory attention deficits in children with dyslexia and adults is mixed (e.g., Gooch, Snowling, & Hulme, 2011). In children with dyslexia the manifestations of visuo-spatial disturbances take different forms. They may manifests as deficits in target stimuli distinction amongst distractive stimuli (Casco, Tressoldi, & Dellantonio, 1998; Iles, Walsh, & Richardson, 2000; Wright, Conlon, & Dyck, 2012), as increase in the time necessary for the identification of visual stimuli (Buchholz & Aimola Davies, 2007; Hari, Valta, & Uutela, 1999; Visser, Boden, & Giaschi, 2004), as a diffuse spatial distribution with difficulties in focally orienting visual attention (Facoetti, Paganoni, & Lorusso, 2000) or as an alteration of the processes used for flexibility of attention (Facoetti, Lorusso, Paganoni, Umiltà, & Mascetti, 2003; Facoetti & Turatto, 2000). It is likely that these deficits contribute to reading disorders in dyslexia. It has been shown that the visual attention span, which corresponds to the amount of distinct visual elements which can be processed in parallel in a multi-element array, is reduced in children with dyslexia (Bosse, Tainturier, & Valdois, 2007). Even if the phonological and visual attentional processing skills may contribute independently to reading performance (Valdois, Bosse, & Tainturier, 2004), visual attention span could appear as a second and distinct cognitive factor in the origin of dyslexia (Peyrin et al., 2012).

1.2. *Asymmetrical distribution of spatial attention in dyslexia*

In addition to these attentional disturbances in dyslexia, lateralized visuo-spatial impairments which concern the left part of the space have been shown. In psychological temporal order judgement and line motion illusion task, adults with dyslexia processed stimuli in left visual hemifield more slowly than normal readers (Hari, Renvall, & Tanskanen, 2001). Children with dyslexia exhibited a reduced interference effect in the left visual field (left inattention) concomitant with a strong interference effect in the right visual field (Facoetti & Turatto, 2000) and asymmetrical distribution of spatial attention (left inattention) measured by reaction times with spatial gradient paradigm (Facoetti & Molteni, 2001). Many studies showed that lesion to the right parietal cortex elicit left attentional deficits (e.g. Posner, Walker, Friedrich, & Rafal, 1987; Smania et al., 1998). These findings point out to a reduced right parietal cortex functioning in children with dyslexia during visual information processing (e.g. Hari et al., 2001; Lorusso, Facoetti, Toraldo, & Molteni, 2005; Sireteanu, Goertz, Bachert, & Wandert, 2005) and more generally on supramodal spatial attention (Stein & Walsh, 1997).

1.3. *Space representation in dyslexia*

Asymmetrical spatial attention is responsible for asymmetrical distribution of space representation which is considered as the mental representation of the environment topographically structured and mapped across the brain (Bisiach, Luzzatti, & Perani, 1979). The most classical task used to assess space representation is the line bisection where individuals have to estimate the centre of horizontal lines (Jewell & McCourt, 2000). Children with dyslexia exhibit a small rightward bias in a perceptual (Sireteanu et al., 2005) and manual (Waldie & Hausmann, 2010) bisection tasks. In a recent study we observed a significant rightward bias in line bisection with a preservation of the context spatial processing when using a cueing paradigm (geometric symbols placed on the extremities of the lines). Indeed children with dyslexia showed a displacement of their spontaneous rightward bias in the direction of the unilaterally cued extremities. This means that children with dyslexia showed a distinctive bias in space representation with an intermediate level between left neglect (mild rightward bias in space representation compared to brain damaged neglect patients) and pseudoneglect (healthy preservation of the attentional modulation of the space representation) that we have proposed to name 'inverse pseudoneglect' in a previous study (Michel, Bidot, Bonnetblanc, & Quercia, 2011).

1.4. Objectives

1.4.1. Line bisection tasks

To better identify the distinctive characteristics of the space representation in children with dyslexia by comparison to children without dyslexia, two experimental paradigms were driven in the present study. The first one explored space representation by using different experimental variables that change the involvement of the cerebral hemispheres as line length and line placement (Bultitude & Aimola Davies, 2006; Reuter-Lorenz, Kinsbourne, & Moscovitch, 1990). In individuals without dyslexia the right inferior parietal cortex involved in line bisection is responsible for a left (pseudoneglect) controlateral bias of orientation (Fink, Marshall, Shah, et al., 2000; Fink, Marshall, Weiss, Toni, & Zilles, 2002; Fink, Marshall, Weiss, & Zilles, 2001; Foxe, McCourt, & Javitt, 2003). The magnitude of pseudoneglect is increased by stimulus factor that would be expected to increase the involvement of the right hemisphere, such as left presentation (McCourt & Jewell, 1999; Milner, Brechmann, & Pagliarini, 1992) or long line length because leftward spontaneous orientation of attention favours the left part of the stimulus (McCourt & Jewell, 1999). On the contrary, in neglect patients the typical rightward bias is greater when lines are located to the left of the patient's midline (Cubelli, Pugliese, & Gabellini, 1994; Nichelli, Rinaldi, & Cubelli, 1989) and when the length of the lines increases (e.g. Bisiach, Bulgarelli, Sterzi, & Vallar, 1983; Halligan & Marshall, 1989). If the rightward representational bias of children with dyslexia can be assimilated to a neglect-like symptom in line bisection as previously proposed (e.g. Sireteanu et al., 2005; Waldie & Hausmann, 2010), it would increase from right- to left-sided locations and should increase with the stimulus line length. Conversely if this rightward bias can be assimilated to an 'inverse pseudoneglect' manifestation, i.e. a rightward bias with a healthy processing of the spatial context, as we proposed (Michel et al., 2011), its amplitude would decrease (or reverse to become leftward) from right- to left-sided locations and with the increase of line length. Therefore the present work was aimed to clarify whether the behavioural performance of children with dyslexia in line bisection is related to neglect-like or inverse pseudoneglect hypothesis.

1.4.2. Circle centering tasks

Because the representation of external space requires the integration of information from multiple sensory modalities, the second experimental paradigm explored whether the rightward representational bias in dyslexia is restricted to visual modality or is whether the sign of a bias in a supramodal level of space representation by using a visuo-proprioceptive and proprioceptive circle centering tasks. Contrary to tactile line bisection, circle centering avoids any counting strategy which could mask any representational bias and force participants to rely on explicitly spatial representations of the stimulus (Girardi, McIntosh, Michel, Vallar, & Rossetti, 2004; McIntosh, Rossetti, & Milner, 2002). Furthermore historically, allocation of attention has been studied along a single axis of space, as a left–right dichotomized phenomenon, but disorders of attention on the radial axe of space have been shown (i.e. Shelton, Bowers, & Heilman, 1990). Therefore another major interest of the circle centering is to consider simultaneously, in the same task, horizontal and radial dimensions.

2. Methods

2.1. Participants

Thirty-two children participated in the present experiment. The group of 16 children without dyslexia (eleven females; 10.31 ± 0.44 years) was age-matched with the group of 16 children with dyslexia (seven females; 10.91 ± 0.64 years) (t-test, $p > 0.4$). In both groups the children had normal or corrected-to-normal vision. All children were native French and they gave their informed consent prior to their inclusion in the study which was approved by the regional ethics committee of Burgundy (C.E.R.). All the children with or without dyslexia of the present study showed no attention deficit/hyperactivity disorder (ADHD), no dyspraxia and no dysgraphia. Furthermore they showed no delayed psychomotor development, no neurological past history and no psychiatric past history. They did not undergo psychotropic or antiepileptic drug therapy.

In France the diagnosis of dyslexia is given by a speech therapist. The inclusion criteria for the present study included at least 18–24 months of school retardation for literacy impairment with a normal IQ. Due to ethical considerations, some speech therapists refused to communicate IQ but confirmed that IQ values were normal. For the children with dyslexia, we collected 10/16 values (mean $IQ \pm SE = 113 \pm 3.52$, range = [95;130]). In complement to the diagnosis all children of our experiment were given one test of reading abilities (leximetric global validated test 'de l'Alouette'). This made it possible to estimate for each child, a reading age, based on the time required to read a 265 words text and the number of errors (Lefavrais, 2000). Reading discrepancies (real age-reading age) were 29.75 ± 3.61 months for children with dyslexia whereas no reading difficulty was shown in children without dyslexia.

Line bisection and circle centering tasks were administered by both C Michel (associate professor, PhD) and S Vieira (graduate student).

2.2. Material and methods

2.2.1. Line bisection tasks

For the line bisection task where the spatial location varied, 18 black lines of 250 mm length and 1 mm width were presented one by one on A4 sheets. The set of lines was randomly distributed across three spatial locations (six lines for each location). Each stimulus sheet was presented one at a time on an empty table. The objective centre of the lines was randomly located in front of the subject's body midline or 30 cm to the right or to the left of the body midline. In the central position, the viewing distance was approximately 45 cm. The order of presentation of the three line locations (left, central and right) was counterbalanced.

For the line bisection task where the length varied, six black lines of 50, 150 and 250 mm length and 1 mm width were presented one by one horizontally and centrally on A4 sheets. The set of 18 lines was presented in front of the subject's body midline. Each line was presented one at a time on the table. The order of presentation of the three line lengths (long, medium and short) was counterbalanced.

In both tests of line bisection, children were asked to set a mark on the centre of the line with a pen. They used their right hand. The order of both line bisection tests (test with different spatial locations and test with different line lengths) was counterbalanced between the participants. For both bisection tasks, children were asked to keep their eyes closed between each trial in order to avoid any perceptive distortion of the line during the handling of the sheet by the experimenter. During the visual exploration, the hands were positioned so as not to hide any part of the line.

2.2.2. Circle centering tasks

All the children had to perform a circle centering task, adapted from McIntosh et al. (2002). A 20 cm diameter circular groove cut centrally into a 5 mm thick square cardboard (40 cm $\times$ 40 cm) was placed on a table in front of the children, centred on their body midline. The task was performed using a pen held in the right hand. On each trial, the pen was placed by the experimenter in the circumference groove at one of two points: left or right with respect to the children. The children were then asked to make one full (clockwise or counterclockwise) exploration of the circumference groove and then to indicate with the pen the centre of the circle. The task was first performed with vision (visuo-proprioceptive condition) and then without vision (proprioceptive condition). Each child performed 32 trials at each administration of the task: 16 trials in visuo-proprioceptive condition followed by 16 trials in proprioceptive condition. A break of some minutes was taken between each condition. For each condition, 8 trials were performed with the hand starting on the left and 8 trials with the hand starting on the right. From each starting position there were 4 trials with clockwise exploration and 4 trials with counterclockwise exploration. The direction of exploration (clockwise and counterclockwise) and starting position of the hand (left and right) were counterbalanced, and trial order was randomized. Children were free to move their head and trunk. Before beginning the protocol they were invited to explore the stimulus using their right hand and were given up to a few trials.

For both line bisection and circle centering, children used their right hand to perform the tasks. Whatever the handedness of the participants there is right hemisphere dominance for visuo-spatial representation which is responsible for pseudoneglect bias in the line bisection (Hécaen & Sauguet, 1971; Masure & Benton, 1983; Scarisbrick, Tweedy, & Kuslansky, 1987). Therefore, the use of the right hand for all the participants acted in the same way on the interhemispheric balance for visuo-spatial functions.

2.3. Data analysis

In both line bisection and circle centering tasks, the biases of estimation were established using the usual method which involved measuring the distance (to the nearest 0.5 mm) from the objective centre. For line bisection tasks, when the participants set a mark with a pen on the right of the objective centre of the line, the deviation was given a positive value. When the participants set a mark on the left of the objective centre, the deviation was given a negative value. For the lateral dimension of the circle centering tasks, when the participants indicated the centre of the circle on the right of the objective centre, the deviation was given a positive value. When the participants indicated the centre of the circle on the left of the objective centre, the deviation was given a negative value. For the radial dimension of the circle centering tasks, the forward subjective estimation of the centre was given a positive value. The backward subjective estimation of the centre was given a negative value.

For line bisection tasks, two independent analyses of variance were driven. For the line bisection task where the spatial location varied, we analyzed the response bias using an ANOVA with locations (left, centre, right) as a within-subject factor, and group (children without dyslexia and children with dyslexia) as a between-subjects factor. For the line bisection task where the line length varied, we analyzed the response bias using an ANOVA with lengths (short, medium, long) as a within-subject factor, and group (children without dyslexia and children with dyslexia) as a between-subjects factor. For the circle centering tasks, two independent ANOVA were driven, one for the lateral dimension and one for the radial dimension. Each analysis used starting position (right/left), sensory modality (visuo-proprioceptive/proprioceptive) and exploration way (clockwise/counterclockwise) as a within-subject factors, and group (children without dyslexia and children with dyslexia) as a between-subjects factor.

The specific post hoc effects were analyzed by Tukey's honestly significant difference (HSD) test when necessary. All statistics were performed by the STATISTICA software package (release 10). An alpha level of 0.05 was used to determine statistical significance. In the manuscript, mean and standard errors are presented in parentheses.

3. Results

3.1. Line bisection tasks

3.1.1. Line bisection with different spatial locations (Fig. 1)

For the line bisection task where the spatial location varied, a two-way ANOVA showed a significant main effect of location ($F_{(2,60)} = 51.27$; $p < 0.001$) and a significant interaction between group and location ($F_{(2,60)} = 3.35$; $p < 0.05$). In the group of children with dyslexia, post hoc comparisons showed significant difference between the performance of left and right locations and between the performances of left and central locations ($ps < 0.01$). Fig. 1 showed the leftward bias for left location and the rightward biases for central and right locations. All the biases in children with dyslexia were different from zero ($ps < 0.05$). In the group of children without dyslexia, post hoc comparisons showed significant differences between performance for all locations ($ps < 0.01$). Fig. 1 showed the leftward bias for left location and the rightward bias for right location in this group. Both biases for left and right locations were different from zero ($ps < 0.001$). The bisection mark for central location was not different from zero ($p > 0.8$).

3.1.2. Line bisection with different line lengths

For the line bisection task where the length of the lines varied, a two-way ANOVA on the bisection bias showed neither significant bias nor interaction on mean bias ($ps > 0.1$). In both children with dyslexia and children without dyslexia, the biases for the different space location were not significant from zero ($ps > 0.25$).

Bivariate correlations computed to examine the relationships between the reading discrepancy and the biases in line bisection (for different line lengths and different spatial locations) were not significant ($ps > 0.13$, $|rs| < 0.39$).

3.2. Circle centering tasks

3.2.1. Lateral performance (Figs. 2 and 3)

ANOVA showed a significant main effect of starting position (right/left) ($F_{(1,30)} = 17.41$; $p < 0.001$) and a significant interaction between starting position and sensory modality (visuo-proprioceptive/proprioceptive) ($F_{(1,30)} = 27.96$; $p < 0.001$) meaning that the effect of the starting position was stronger in proprioceptive condition. Fig. 2 showed that right starting position was responsible for rightward responses whereas left starting position was responsible for leftward responses in proprioceptive condition (post hoc, $p < 0.001$). Single-sample *t*-tests against zero showed a significant leftward bias for right starting position in visuo-proprioceptive condition, a rightward bias for the right starting position and a leftward bias for the left starting position in proprioceptive condition ($ps < 0.05$).

ANOVA showed also a significant main effect of the exploration way (clockwise/counterclockwise) ($F_{(1,30)} = 5.00$; $p < 0.05$), and a significant interaction between the exploration way and the sensory modality (visuo-proprioceptive/proprioceptive) ($F_{(1,30)} = 12.98$; $p < 0.01$), meaning that the effect of the exploration way was stronger in proprioceptive condition. Fig. 3 showed that clockwise exploration was responsible for the rightward bias which was significantly different from the leftward bias in counterclockwise exploration in proprioceptive condition (post hoc, $p < 0.001$). Single-sample *t*-tests against zero showed no significant bias ($p > 0.1$).

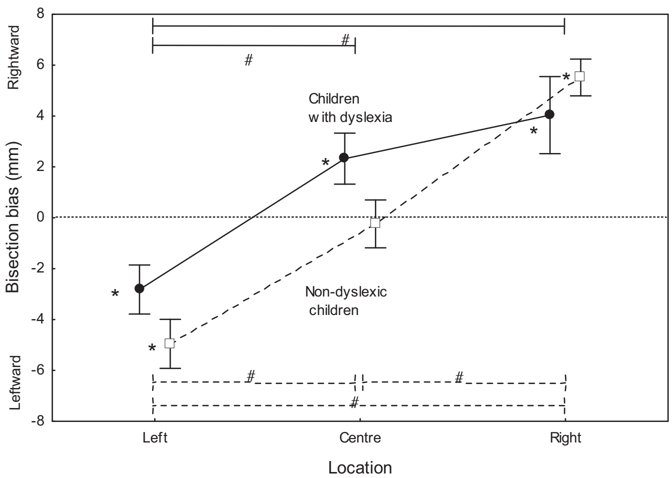

Fig. 1. Bisection responses when the space location of the lines varied. The black circles represent performance of children with dyslexia (mean ± SE) and the white squares represent the performance of children without dyslexia for the three spatial locations (left, centre and right). The horizontal dotted line corresponding to a 0 mm bias indicates the objective centre of the line. Leftward biases are indicated with a negative value and rightward biases with a positive value. The symbol * shows significant differences from zero and the symbol # shows significant post hoc differences.

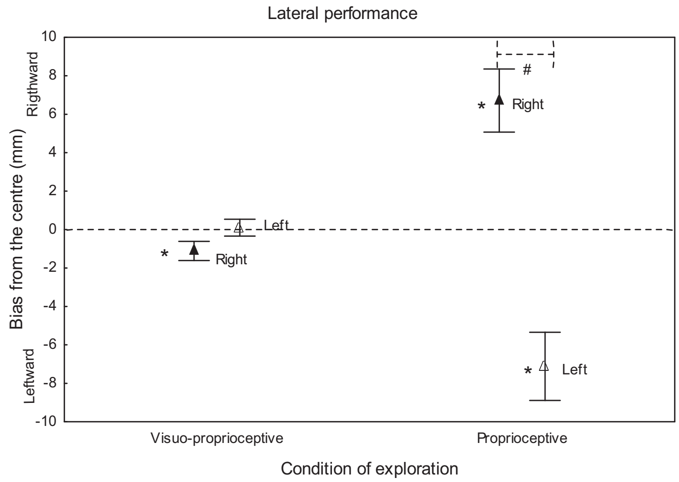

Fig. 2. Lateral performance for left- and right-sided starting positions in the circle centering in visuo-proprioceptive and proprioceptive conditions. Lateral performances (mean ± SE) are presented by black triangles for right-sided starting position and by white triangles for left-sided starting position. Leftward biases are indicated with a negative value and rightward biases with a positive value. The significant difference from zero is indicated by a star. The symbol # indicates post hoc significant difference.

3.2.2. Radial performance (Figs. 4 and 5)

ANOVA showed a significant main effect of sensory modality (visuo-proprioceptive/proprioceptive) ($F_{(1,30)} = 21.05$; $p < 0.001$). Fig. 4 showed a forward bias in visuo-proprioceptive condition and a more backward bias in proprioceptive condition. There was also a significant effect of the exploration way (clockwise/counterclockwise) ($F_{(1,30)} = 8.16$; $p < 0.01$) and a significant interaction between sensory modality and exploration way ($F_{(1,30)} = 8.05$; $p < 0.01$). Fig. 4 showed a forward bias in clockwise exploration compared to counterclockwise exploration in proprioceptive condition (post hoc, $p < 0.01$). Single-sample *t*-tests against zero showed a forward bias in visuo-proprioceptive condition with both clockwise and counterclockwise explorations ($p < 0.001$) and a backward bias in proprioceptive condition for counterclockwise exploration ($p < 0.05$). There was also a significant interaction between sensory modality, exploration way, and starting position ($F_{(1,30)} = 4.97$; $p < 0.05$) showing a significant difference between the accurate performance in clockwise exploration and the backward bias in counterclowise exploration in proprioceptive condition for left starting position ($p < 0.01$). There was also a significant interaction between group, exploration way and starting position ($F_{(1,30)} = 6.13$; $p < 0.05$). Fig. 5 showed the significant difference between the forward bias in clockwise exploration and the more accurate performance in counterclockwise exploration for left starting position in children with dyslexia ($p < 0.05$). In children with dyslexia, the forward bias for clockwise exploration from left starting position was significantly different from zero ($p < 0.02$).

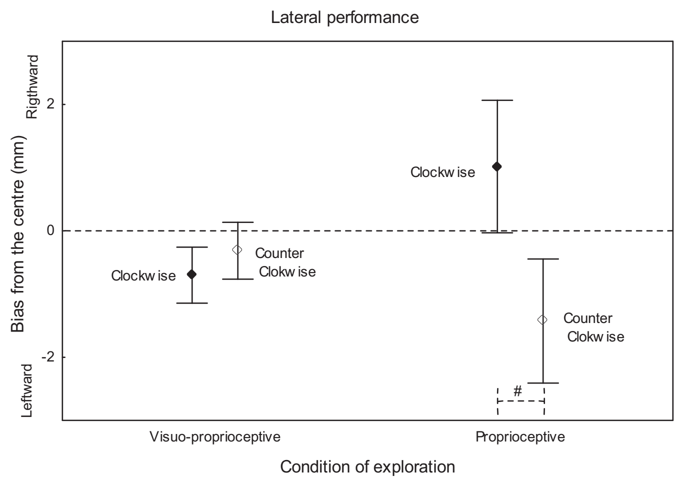

Fig. 3. Lateral performance for clockwise and counterclockwise explorations in the circle centering in visuo-proprioceptive and proprioceptive conditions. Lateral performances (mean ± SE) are presented by black diamonds for clockwise exploration and by white diamonds for counterclockwise exploration. Leftward biases are indicated with a negative value and rightward biases with a positive value. The symbol # indicates post hoc significant difference.

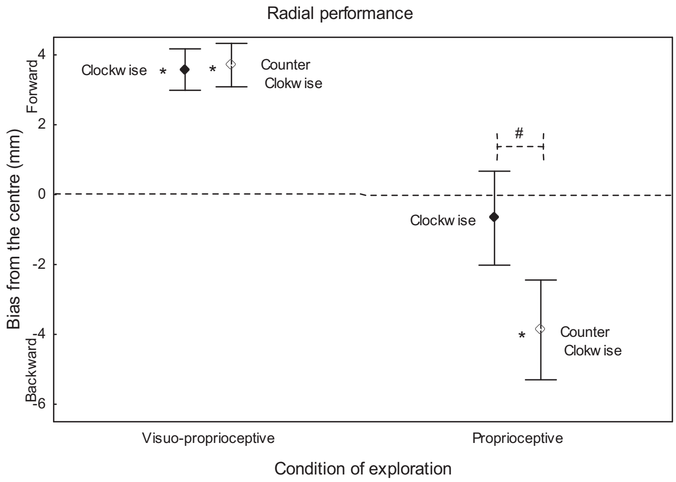

Fig. 4. Radial performance for clockwise and counterclockwise explorations in the circle centering in visuo-proprioceptive and proprioceptive conditions. Radial performances (mean ± SE) are presented by black diamonds for clockwise exploration and by white diamonds for counterclockwise exploration. Backward biases are indicated with a negative value and forward biases with a positive value. The significant difference from zero is indicated by a star. The symbol # indicates post hoc significant difference.

Bivariate correlations computed to examine the relationships between the reading discrepancies and the biases in circle centering (for the different sensory modalities, exploration ways, starting hand positions in both lateral and radial directions) were not significant ($ps > 0.11$, $|rs| < 0.41$).

4. Discussion

4.1. Line bisection tasks

4.1.1. Bisection with different space locations

In our experiment, children without dyslexia showed a modulation of space representation by space location similar to the modulation shown in adults (McCourt & Jewell, 1999; Milner et al., 1992). When children without dyslexia viewed lines in the left visual space they exhibited a significant leftward bias; when they viewed lines in the right visual space they exhibited a significant rightward bias. This effect of azimuthal spatial position is moreover consistent with the activation–orientation hypothesis (Bultitude & Aimola Davies, 2006; Reuter-Lorenz et al., 1990). The slight asymmetry in spatial attention seen in adults, has led to suggest that each hemisphere mediates the allocation of attention within the controlateral hemispace, but that the right hemisphere exerts a dominant role in the control of spatial attention (Heilman & Van Den Abell, 1979; Mesulam, 1981). Therefore increasing the involvement of the right hemisphere with a leftward spatial location shifts the bisection response to the left whereas increasing the involvement of the left hemisphere with a rightward spatial location shifts the bisection response to the right. In children with dyslexia, the present results showed a significant rightward bias for central lines which is in line with previous studies and may result from asymmetrical distribution of spatial attention in favour of the right space (e.g. Michel et al., 2011; Sireteanu et al., 2005; Waldie & Hausmann, 2010). Furthermore, when children viewed lines in the left visual space they exhibited a significant leftward bias; when they viewed lines in the right visual space they exhibited a significant rightward bias. These results argue in favour of the 'inverse pseudoneglect' hypothesis because the rightward bias for central lines reversed to become leftward in left-sided location as for children without dyslexia of the present experiment and for individuals without dyslexia in general (e.g. Milner et al., 1992). This behaviour testifies the preservation of the capacity to orient the spatial attention as previously shown with spatial cueing paradigm (Michel et al., 2011). Moreover, we could note that the spatial context processing was asymmetrically more efficient in the left space. The leftward displacement of the bisection mark was significant when the lines were placed in the left space compared to central space but the rightward displacement for right-sided location was not significant. It was as if spontaneous rightward orientation of attention in children reached almost this maximal level for central locations; therefore the displacement of the attention with right-sided lines had a minor effect on the attentional shift whereas left-sided location was more efficient. Moreover, because divided visual space paradigm contributes much to our understanding of functional asymmetries in hemispheric organization (Jewell & McCourt, 2000 for a review) it is likely that the present results in children with dyslexia may be linked to an altered or unstable hemispheric asymmetry as shown during linguistic (Spironelli, Penolazzi, & Angrilli, 2008; Penolazzi, Spironelli, Vio, & Angrilli, 2006), visual (Schulte-Korne, Bartling, Deimel, & Remschmidt, 1999) or dichotic (Koltuska & Grabowska, 1992) tasks.

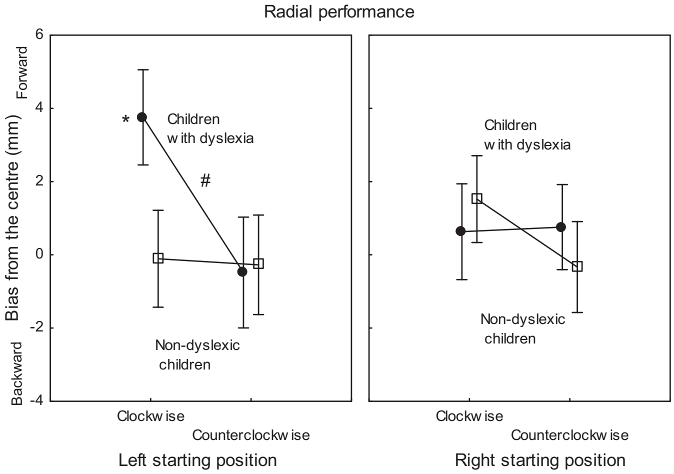

Fig. 5. Radial performance for clockwise and counterclockwise explorations for left and right starting positions in the circle centering in children with dyslexia and children without dyslexia. The black circles represent performance of children with dyslexia (mean ± SE) and the white squares represent the performance of children without dyslexia. The symbol * shows significant differences from zero and the symbol # shows significant post hoc difference.

4.1.2. Bisection with different line lengths

The use of different line lengths did not influence the amplitude of bisection response in children without dyslexia and children with dyslexia in the present study. Similar results were shown by Nichelli et al. (1989) where adults without dyslexia were presented with individual lines (8–24 cm) in different spatial locations (centred, left- and right-displaced) in pseudorandom order. In this study no significant bias was observed in central position. Altogether, a stimulus context-effect hypothesis may be proposed to account for such results. It has been shown that the introduction of lines of one length influences responses to lines of another length. The context of the figural series in which lines are placed exerts a strong effect upon the accuracy of judgments of the centre. For example, Marshall, Lazar, Krakauer, and Sharma (1998) showed that when lines of a second length were mixed into any uniform set of lines, bisection performance on the reference lines changed. For example, the classical rightward neglect bias was reversed when longer lines were added in the set of lines to bisect. Thus the perceived midpoint of a line is related not to absolute length but to the length of line relative to other lines with which it is presented. In the same way, errors in line length have been reported in participants without dyslexia by Werth and Poppel (1988). When participants were asked to estimate how far a previously viewed line would extend to the left or right of a given mark (indicating the end of the line) and then to bisect the estimated line, overestimation errors were made with greater frequency on shorter lines and underestimation errors made more frequently with longer lines. Authors interpreted these results in terms of adaptation processes where the midpoint of the shorter lines and the midpoint of the longer lines have been moved closer together. Therefore, in the present experiment the enlargement of the space of work by varying the length of the lines in a mixed set may lead to an underestimation of the line and therefore a reduced representational bias.

4.2. Circle centering

4.2.1. Why there was no difference on lateral performance between children without dyslexia and children with dyslexia in the present conditions of circle centering?

Both the lack of rightward bias in children with dyslexia and the lack of leftward bias in children without dyslexia were also unexpected in the present circle centering tasks. Three main hypotheses may be proposed to explain this lack of representational bias. First, the radial dimension to consider (20 cm) was shorter than previously used in circle centering task (30 cm) in adults without dyslexia (Girardi et al., 2004) and neglect patients (McIntosh et al., 2002) which may reduce the sensitivity of the test in this dimension as shown in line bisection (Halligan & Marshall, 1989) or other geometrical figures (Tegner & Levander, 1991). Second, even if the lateral dimension to consider was the same as the one used in line bisection by Michel et al. (2011), i.e. 20 cm, the sensitivity of the task could have been reduced by the geometrical configuration of the stimulus. Indeed it has been shown that geometrical constraints affect perceptual and attentional processes (Charras et al., 2012). The presentation of two dimensional figures provokes 'diffusion' of attention over the visual field. For example, patients with typical rightward bisection errors following right temporo-parietal lesion, bisected accurately or with leftward errors large circles and long white paper strips (Marshall & Halligan, 1991; Tegner & Levander, 1991). The same results were observed when patients have to estimate centre of squares or when they have to bisect the horizontal lines with vertical lines positioned to the right extremity (Halligan & Marshall, 1994). As figures of objectively equal length increase in height, their subjective length appears to decrease. Third, for a last hypothesis, a strategy of estimation from the apex of the figure could be envisaged. The topmost (highest) point of a circle can be detected and can be considered as a landmark of the centre of the circle in radial dimension. Performing this construction allows the centre to be marked correctly by getting around the difficulty of the perceptual estimation of the half of the circle.

4.2.2. Lateral performance in visuo-proprioceptive vs proprioceptive condition

The proprioceptive response was sensitive to where the hand movement started at the beginning of each trial following circle exploration: when the hand started from the left side of the circle, children erred to the left whereas they erred rightward when the hand started from the right. The proprioceptive modality allows the detection of the spatial configuration of the different body parts. This specialization produced a modality-specific attentional bias such that attention is preferentially oriented towards the arm during proprioceptive exploration. Therefore there would be an overrepresentation of the space crossed by the arm in proprioceptive condition in accordance with a spatio-motor cueing (Halligan, Manning, & Marshall, 1991). By contrast, the visual system is specialized for detecting distant stimuli. Therefore attention is distributed away from the body during visual exploration (Shelton et al., 1990) which could explain the more distant estimation of the circle centre in visuo-proprioceptive condition compared to proprioceptive condition. Furthermore because this task is not usual for the children, it may be possible that it favoured a larger visual exploration of the stimulus which has less restricted the attention around the hand compared to the proprioceptive condition. Similar attentional bias was observed towards portion of the space where participants are put in trouble such as experimental bisection paradigm with low contrast stimuli recruiting more attention and then magnified the stimulus perceived size (Bradshaw, Nathan, Nettleton, Wilson, & Pierson, 1987; McCourt & Jewell, 1999).

4.2.3. Radial bias in visuo-proprioceptive vs proprioceptive condition

The children showed a forward error for the estimation of the centre in visuo-proprioceptive condition and a more backward error in proprioceptive condition. These results can be compared to classically results in line bisection. The bisection bias of participants without dyslexia for lines oriented along the radial axis (intersection of the axial or transverse and sagittal planes) appears consistent, with line bisected farther than the true midpoint (Chewning, Adair, Heilman, & Heilman, 1998; Geldmacher & Heilman, 1994; Halligan & Marshall, 1993; Shelton et al., 1990). Shelton et al. (1990) attributed this bias to perceptual/attentional factors. During visual exploration attention is preferentially distributed away from the body since the visual system is tuned to detect distant stimuli. This model represents a spatial (spatiotopic) processing scheme (Geldmacher & Heilman, 1994). It has also been proposed that the visual attention processes are organized with respect to visual hemifield (retinotopic) boundaries (Hughes & Zimba, 1985, 1987) including specialization of the upper visual field for visual attention (Previc, 1990). Because both spatiotopic and retinotopic influences coincide when the stimuli were below the eye level (Geldmacher & Heilman, 1994), they may contribute to the distant estimation of the centre of the circle. By contrast the proprioceptive exploration of the circle restricted the space perception more proximally and oriented preferentially the attention towards the body as shown in line bisection by Shelton et al. (1990).

4.2.4. The influence of the clockwise and counterclockwise explorations

The influence of the exploration way is observed only in proprioceptive condition. In lateral dimension the clockwise exploration produced a rightward error whereas a counterclockwise exploration produced a leftward error. The error seems to be constrained by the direction of the movement in the distant (far from the body) half of the circle. In radial dimension the clockwise exploration produced a forward error whereas the counterclockwise exploration produced a backward error. The error seems to be constrained by the direction of the movement in the left half of the circle. One possible explanation which could account for both lateral and radial biases might propose that when making movements with the right hand, there is a slight tendency for the movement to describe an arc in distant and left parts, since it is natural for the right forearm to rotate around the elbow. This movement realized in the distant part (or left part) of the circle during the exploration might then consecutively "contaminate" the response bias in lateral (or radial) dimension. In radial dimension this effect is more pronounced in children with dyslexia. For left starting movement exploration, they showed a forward bias in clockwise exploration and a more accurate performance in counterclockwise exploration. The 'contaminate' effect of the exploration way in the left part of the circle described above may be all the more pronounced in children with dyslexia than they expressed a leftward asymmetrical spatial processing as shown in the line bisection for left-sided location.

4.2.5. Anatomical origin of the lack of lateral representational bias in circle centering task?

Both the lack of rightward bias in children with dyslexia and the lack of leftward bias in children without dyslexia in circle centering may have an anatomical origin. A double neuropsychological dissociation has been shown between the estimation of the centre of two-dimensional figures and one-dimensional line. First, in the field of neurology neglect patients with typical line bisection errors following right temporo-parietal lesions may show normal performance when they have to mark the centre of circle or square (Marshall & Halligan, 1991; Tegner & Levander, 1991). Conversely patient with damage to a range of right posterior cortex region, including occipito-temporal cortex, but without neglect, are seriously impaired at judging whether a dot is situated in the centre of a square (Warrington & James, 1988). Second, it has been shown in participants without dyslexia that line centre judgements activated right parietal cortex (Billingsley, Simos, Sarkari, Fletcher, & Papanicolaou, 2004; Fink, Marshall, Shah, et al., 2000; Fink et al., 2001, 2002; Foxe et al., 2003), while square centre judgements differentially activated the lingual gyrus bilaterally (Fink, Marshall, Weiss, et al., 2000). Taken together these results suggest that position discrimination in one- and two-dimensional space involves partially distinct neural mechanisms. The ventral visuoperceptive route ('what' system) assumes more responsibility for assessing position within the two dimensional object. Because stimulus-configuration thus appears to interact with the nature of the judgement itself in determining the principal cerebral loci implicated in task performance, it is likely that the ventral stream may be preserved in children with dyslexia because they exhibited the same performance as children without dyslexia in circle centering task. This interpretation of the preservation of the ventral stream in dyslexia seems in accordance with previous studies on visuo-spatial tasks (Buchholz & McKone, 2004; Vidyasagar & Pammer, 1999).

5. Conclusion

This study was conducted to explore the distinctive characteristics of the space representation in children with dyslexia by comparison to children without dyslexia. More precisely the present work was aimed to clarify (1) the behavioural performance of children with dyslexia in line bisection. We wanted also to investigate (2) whether the representational bias in dyslexia was restricted to visual modality or extended to a supramodal level of space representation by using proprioceptive circle centering task and (3) explored the space representation in both horizontal and radial dimensions. The main contribution of our work to the already existing body of research in this area was to show that the behaviour of both children without dyslexia and children with dyslexia differed according to the task. The rightward bias characteristic of children with dyslexia may be sensitive to experimental paradigms known to modulate the spatial orientation of attention as the use of different line locations (present study) or spatial cueing (Michel et al., 2011). On the contrary, the use of different line lengths seems to reduce the sensitivity of the task and to mask the representation bias. In similar vein, circle centering tasks failed to reproduce a lateral representational bias. One plausible explanation is that the widening of the space of work by different experimental devices (as the use of two dimensions geometrical stimulus or variable size) may decrease the sensitivity of the test and therefore mask the attentional/representational bias. Finally, we showed for the first time the orientation of the spatial attention far from the body when vision was allowed during stimulus exploration and near form the body when only proprioception was allowed in children. Children with dyslexia showed a forward bias in clockwise exploration and a more accurate performance in counterclockwise exploration for left starting position in accordance with their leftward asymmetry for spatial processing in line bisection. Therefore, the sensitivity of the line bisection with different space locations, spatial cueing (Michel et al., 2011) and/or the radial estimation of proprioceptive circle centering seem to be appropriate tools to explore space representation in children with dyslexia which could be used for clinicians, researchers, and/or caregivers.

Moreover, further investigations could help us to understand the possible link between our results concerning space representation and writing techniques and the spatial characteristics which the written symbols have. Furthermore complementary investigations could led us to consider representational bias as an early indicator of dyslexia as already shown for psychomotor ability, motor, neuro-physiological development, phonological awareness, prereading and prewriting skills (Fawcett & Nicholson, 1995; Kujala & Näätänen, 2001; Rouse & Fantuzzo, 2006; Temple et al., 2003; Zakopoulou et al., 2011).

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