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RESEARCH ARTICLE

Integration of proprioceptive signals and attentional capacity during postural control are impaired but subject to improvement in dyslexic children

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Abstract Children with developmental dyslexia suffer from delayed reading capabilities and may also exhibit attentional and sensori-motor deficits. The objective of this study was twofold. First, we aimed at investigating whether integration of proprioceptive signals in balance control was more impaired in dyslexic children when the attentional demand was varied. Secondly, we checked whether this effect was reduced significantly by using a specific treatment to improve eye control deficits and certain postural signs that are often linked to dyslexia (Quercia et al. in J Fr Ophtalmol 28:713–723, 2005, J Fr Ophtalmol 30:380–89, 2007). Thirty dyslexic and 51 treated dyslexic children (>3 months of treatment) were compared with 42 non-dyslexic children in several conditions (mean age: 136.2 ± 23.6, 132.2 ± 18.7 and 140.2 ± 25 months, respectively). Co-vibration of ankle muscles was effected in order to alter proprioceptive information originating from the ankle. In two vibration conditions, ankle muscles were either not vibrated or vibrated at 85 Hz without illusion of any movement. These two vibration conditions were combined with two attentional conditions. In the first such condition, children maintained balance while merely fixing their gaze on a point in front of them. In the second condition, they had to look for smaller or larger stars in a panel showing forty of each kind. Balance was assessed by means of a force plate. Results indicated that the mean velocity (i.e. the total length) of the center of pressure (CoP) displacement in the 85-Hz vibration condition increased significantly more (compared with no vibration) in the dyslexic and the treated dyslexic groups than in the control group, irrespective of the attention task. Interestingly, in the condition without vibration, the attentional performance of treated children was similar to that of the control group, whereas the attentional performance of the untreated dyslexic children was significantly impaired. Altogether, these results suggest that integration of proprioceptive signals in balance control and attentional capacity are impaired in dyslexic children. However, attention capacity during the control of stance could be improved significantly.

Keywords Dyslexia · Postural control · Proprioception · Vibration · Attention

Introduction

Children suffering from developmental dyslexia have a normal intelligence level but typically exhibit delayed reading capabilities and various deficits in the sensory and motor domains (Nicolson et al. 1999; Ramus 2003; Stein 2001). Classically, the etiology of dyslexia is traced to an impairment of the phonological loop (Lieberman et al. 1985; Ramus 2003). However, the range of symptoms observed in dyslexia has led some authors to suspect a cerebellar origin (Nicolson et al. 2001; Nicolson and Fawcett 2005, 2006, 2007). Dyslexic children show signs of cerebellar dysfunction, such as motor co-ordination impairment, reach and gaze overshoot or lack of balance (Nicolson et al. 1999). Subsequent authors have investigated the issue of motor and balance impairments in dyslexia, but with conflicting results. No effect of dyslexia on

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balance control was found or found only in some cases (Poblano et al. 2002; Ramus 2003; Stoodley et al. 2005), suggesting that impairments were not uniquely due to dyslexia but co-occurred with other developmental disorders (Rochelle and Talcott 2006). In contrast, other studies have emphasized a link between dyslexia and balance impairments (Fawcett et al. 1996; Fawcett and Nicolson 1999; Moe-Nilssen et al. 2003). Notably, Nicolson and Fawcett (1990) observed that balance was adversely affected by any secondary task, which served to distract attention from the primary motor one. They suggested that dyslexic children need to invest significant conscious resources in monitoring balance. More precisely, these authors voiced their suspicions that the cerebellum was involved in dyslexia, because dyslexic children were impaired in both the attentional and the motor tasks when the two were performed simultaneously. However, they were not impaired when the attentional task was performed in isolation. All the results mentioned above were obtained using a battery of motor balance tests. These results were reinforced in three more recent studies in which balance control was assessed using a force plate, allowing a more precise evaluation of the center of pressure displacement during normal and quiet upright standing (Pozzo et al. 2006; Kapoula and Bucci 2007; Vieira et al. 2009).

It is widely known that proprioceptive signals originating from the spino-cerebellar pathways are processed unconsciously in the cerebellum and are involved in the control of equilibrium (Sherrington 1906; Delmas 1981). It is possible to manipulate these proprioceptive signals by means of tendon vibration, which almost selectively activates muscle spindle primary endings and elicits a discharge in the fast-conducing large diameter group Ia afferent fibers. For instance, such vibration can induce oriented postural imbalance as well as direction-specific deviations (Eklund 1972; Kavounoudias et al. 1999; Roll et al. 1989). Although the muscles do not increase in length during vibration, the increased afferent activity from spindle primary endings induces illusory movement by simulating proprioceptive discharges, mimicking true muscle stretch. A simultaneous co-vibration applied around the same joint perturbs the proprioceptive signals sent via the ascending pathways. This procedure is of interest, especially to probe the manner in which proprioceptive signals are integrated and involved in the control of equilibrium.

At the anatomical level, some recent studies have suggested that anomalies of the cerebellum may be an important candidate and the best biomarker of dyslexia (Rae et al. 2002; Laycock et al. 2008; Pernet et al. 2009). To further investigate this hypothesis at a functional level, we applied co-vibration on the ankle joint of both legs. We hypothesized that if the functioning of the cerebellum (as well as its anatomy) was pathological, we would observe more displacement of the CoP when both ankles were co-vibrated. Furthermore, we recently demonstrated that the displacement of the CoP in dyslexic children was more impaired when required to perform an additional attentional/cognitive task (Vieira et al. 2009). To further probe the cerebellar hypothesis of dyslexia and to further investigate whether sensory and attentional/cognitive deficits could interact in dyslexia, we designed an experiment in which co-vibration was applied or not to both ankles of dyslexic and normal children who had to remain as stable as possible on a force plate while either staring at a point or looking for and counting objects in a panel in front of them. We compared a group of dyslexic children with a group of control children. We also included a group of treated dyslexic children to determine whether certain deficits could be countered by following a specific treatment aimed at compensating for eye control deficits and certain postural signs linked to dyslexia (Quercia et al. 2005, 2007; Vieira et al. 2009).

Methods and materials

Participants

Three groups of children were tested as part of an experimental setup in conformity with the guidelines of the Declaration of Helsinski, after obtaining the informed consent of their parents. The experiment was conducted according to the guidelines of the clinical ethics committee of the University of Burgundy. The groups were, respectively, composed of 30 non-treated dyslexic children (mean age = 136.2 ± 23.6 months, range = [100;177]), 51 treated dyslexic children (mean age = 132.2 ± 18.7 months, range = [96;174] with the mean duration for the treatment = 16.9 ± 17.9 months, range = [3;60]), and 42 control children (mean age = 140.2 ± 25 months, range = [96;174]). In France, the diagnosis of dyslexia is made by a speech therapist. The inclusion criteria for the present study included school difficulties or literacy impairments in combination with a normal IQ (>85), documented diagnosis, and past speech therapy. We were unable to collect IQ data because the speech therapists refused to communicate this information on ethical grounds. However, they confirmed that the IQ measurements for all included children were normal. It is important to note that this diagnosis is not sufficient to determine whether the children in question suffer from a ‘pure’ form of dyslexia and that in many other countries, especially in the United Kingdom and the United States of America, they would be diagnosed as co-morbid Specific Language Impairment (SLI) and Dyslexia. This is important in the context of the claims formulated by Rochelle and Talcott (2006) that balance difficulties tend to be associated with co-morbid but not 'pure' dyslexia. In complement to the diagnosis, all groups were also given one additional test of language abilities to estimate impairments in word reading and spelling abilities (leximetric global validated test "TIME 3"). This test was performed after inclusion and was not fully representative of the initial diagnosis, given the intervention periods which ranged from 3 to 60 months. However, this test made it possible to estimate a reading age for each child, based on the time required to read a 265 word text, the number of errors, and their level of severity. Reading discrepancies (reading age–real age) were -31.1 ± 17.7 months (range = [−80;0]) in the dyslexic group, -25.4 ± 18.5 months (range = [−76;7]) in the treated dyslexic group, and 5 ± 28 months (range = [−54;68]) in the group of control children.

The prismatic and postural treatment

Using a global approach to dyslexia, certain clinical studies have highlighted the possibility of a link between posture deficits and dyslexia (Quercia et al. 2005, 2007). Based on clinical signs (e.g. tonic asymmetry, pseudo-vertigo, perceptive deficits etc.) initially depicted by Da Cunha (1987), these studies revealed abnormalities of standing posture in 60 dyslexic children and suggested the possibility of improving postural signs and reading abilities. As some dyslexic children have unstable binocular movements (Stein et al. 1987), the proposed treatment was based on the assumption that clinical signs in dyslexia are caused, fully or partially, by faulty control of oblique muscles and especially the heterophoria. The fact that ocular proprioception can influence visual localization supports this hypothesis (Gauthier et al. 1990a, b; Roll et al. 1991). Interestingly, Kono et al. (2002) also demonstrated that vertical phoria adaptation was impaired in patients with cerebellar dysfunction. The idea was thus to compensate for the vertical and torsional heterophoria characteristic of dyslexic children by using oblique prisms with slight optical deviations (Quercia 2008). To determine whether there is a heterophoria, the principle is to dissociate vision of the two eyes while they fix on a single spot of light (Maddox test). For one eye, after interposing a panel with special optical characteristics, the spot of light becomes a line, whereas the other still perceives the real spot of light. Vertical discrepancies between relative positions of the line and of the light determine the positioning of the prisms. Their magnitude depends on asymmetries in the tonus of neck muscles and ranges between 2 and 3 dioptries (i.e. 1° to 1.5° of deviation). As heterophoria also has consequences on postural control (Matheron and Kapoula 2008), additional modes of rehabilitation were also undertaken: instruction to maintain certain specific postures when reading, specific respiratory training, and the wearing of proprioceptive soles to recalibrate the general posture (Quercia et al. 2007). In our study, there was no quantitative measure of heterophoria. Heterophoria was diagnosed using the Maddox test which is a clinical test. This test allowed us only to determine qualitatively whether (or not) there was a discrepancy between the visual spot seen by one eye and the horizontal visual line seen by the one behind the Maddox panel. This test has been shown to be reliable and reproducible (Matheron et al. 2005; Matheron and Kapoula 2008). Matheron and Kapoula (2008) were the only ones who quantitatively measured vertical heterophorias during balance control. They demonstrated that small vertical heterophorias could impair balance. However, the tools used to precisely measure vertical heterophorias and torsions of the eyes are difficult to find since they involve small prisms of less than 1° of optical deviation and are not common tools for most therapists. Before any treatment, all our dyslexic children reported heterophorias based on the Maddox test. It is the aim of the treatment to reduce them using the previously described procedure (please see above and Quercia 2008). There was no measure of heterophorias just before the present study. At this point, it is important to remark that prisms and soles were removed more than 5 min before initiating the experiment.

Setup and procedure

The center of pressure (CoP) displacement was recorded from a quiet standing posture on a force plate (Fusyo Medicaptors®, France) using a sampling frequency of 40 Hz for a duration of 30 s. Arms were relaxed on each side of the body. The feet were positioned apart (2 cm between the two heels and the feet axes forming a 30° angle). The children were instructed to remain as stable as possible in each of two attentional conditions. In the first condition, they had to fixate a point located in front of their eyes at a distance of 40 cm (control condition). In the second condition, the children had to visually explore (keeping the head immobile) an A4 sheet of paper on which 40 big stars (with a diameter of 1.5 cm) and 40 small stars (with a diameter of 0.8 cm) were randomly but uniformly distributed with the same density in each quadrant (attention condition). Children were not given a time limit or any information about the duration of the task, to prevent any effect of stress on the recordings of the CoP displacement. They were instructed to silently count the number of big or small stars. We recorded the performance on this task.

These two conditions requiring different levels of attention were combined with two conditions of vibration.

In the first condition, no vibration was applied to the ankle muscles (no vib), but participants were equipped with the vibrators (Techno-Concept VB115). In the second condition, an 85-Hz vibration was applied at the ankle level and simultaneously to the Achille's tendon and to the tendon of the tibialis of both legs in order to bias the proprioceptive afferences (85-Hz vib).

The 2 attention × 2 vibration conditions were performed in a random order. The attention task was thus performed two times for each child. A different sheet of paper with a different distribution of stars was presented each time. For the children in the treated dyslexic group, any equipment required for their treatment, namely prisms and soles, was removed several minutes (range = [5;10]-min) before testing began.

Force plate measurements and data analysis

Basic parameters of the CoP displacement were analyzed: surface of the 90% confidence ellipse, mean velocity (i.e. total length), and standard deviations along the medio-lateral and anterio-posterior axes. The 90% confidence ellipse represents the spatial distribution around the mean for 90% of the CoP (x, y) positions and excludes extreme data. Mean velocity is equivalent to the total length of the CoP displacement since it represents the total length of the CoP displacement divided by the number of temporal intervals. It should be noted that these two variables are not necessarily correlated: for instance, the CoP can vary greatly within a small area.

All postural dependent variables were thus submitted to 3 × 2 × 2 ANOVAs with group (Dyslexic, Treated Dyslexic and Control), vibration (no vib and 85-Hz vib), and attention conditions (fixation vs. attention) as factors with repeated measures on the three factors. Post hoc comparisons were performed using the Fisher least significant difference test (LSD).

Results

Age was identical for the three groups

Results of the one-way ANOVA showed that there was no age discrepancy between the three groups ($F(2,109) = 1.242$, $P = 0.3$).

Reading discrepancies

Results of the one-way ANOVA revealed a significant effect of group ($F(2,112) = 29.3$, $P \ll 0.01$). Post hoc comparisons showed that reading discrepancies were much lower in the control group than in the dyslexic and treated dyslexic group (P's $\ll 0.01$). Interestingly, a single tailed t-test applied to compare the dyslexic and the treated dyslexic group also revealed a tendency between these two latter groups with the treated dyslexic children showing less reading discrepancy ($t(79) = -1.71$, $P = 0.091$). This effect may be promising to the extent that it shows that some substantial improvements are possible in any case within a limited amount of time. However, it should be interpreted with caution and is not particularly striking given an intervention period that ranged from 3 to 60 months.

Co-vibration of the ankle muscles more clearly altered postural control in the dyslexic and treated dyslexic children than in the control group children

Effects on the surface of the 90% confidence ellipse

Figure 1 illustrates mean values ±95% CI for the surface of the 90% confidence ellipse of the CoP displacement for each group, in the 85-Hz vib and the no vib conditions, and for the fixation (left panel) and high attention conditions (right panel).

Results of the ANOVA showed a significant main effect of group ($F(2,107) = 3.5$, $P = 0.03$), a significant main effect of vibration ($F(1, 107) = 99.3$, $P \ll 0.01$), no significant group × vibration interaction ($F(2,107) = 0.6$, $P = 0.54$), no significant effect of the attentional task but rather a tendency ($F(1,107) = 3.2$, $P = 0.07$), no group × attention interaction ($F(2,107) = 1.2$, $P = 0.29$), a significant vibration × attention interaction ($F(1,107) = 7.1$, $P \ll 0.01$), and finally no significant interaction between group, vibration, and attention ($F(2,107) = 0.2$, $P = 0.84$).

Interestingly, the post hoc analysis revealed that the surface of the 90% confidence ellipse was smaller (indicating better stability) in the control group compared with the other two groups ($P < 0.05$).

A decomposition of the vibration × attention interaction revealed that as ankle muscles were co-vibrated, the surface increased more in the fixation condition than in the high attention condition, independently of the group.

Effects on the mean velocity of the CoP displacement

Figure 2 illustrates mean values ±95% CI for the mean velocity (i.e. total length) of the CoP displacement for each group, in the 85-Hz vib and the no vib conditions, for the fixation (left panel) and high attention conditions (right panel).

Results of the ANOVA showed a significant main effect of group ($F(2,107) = 3.1$, $P = 0.05$), a significant main effect of vibration ($F(1, 107) = 764$, $P \ll 0.01$), a significant group × vibration interaction ($F(2,107) = 3.4$, $P = 0.04$), a significant effect of the attentional task

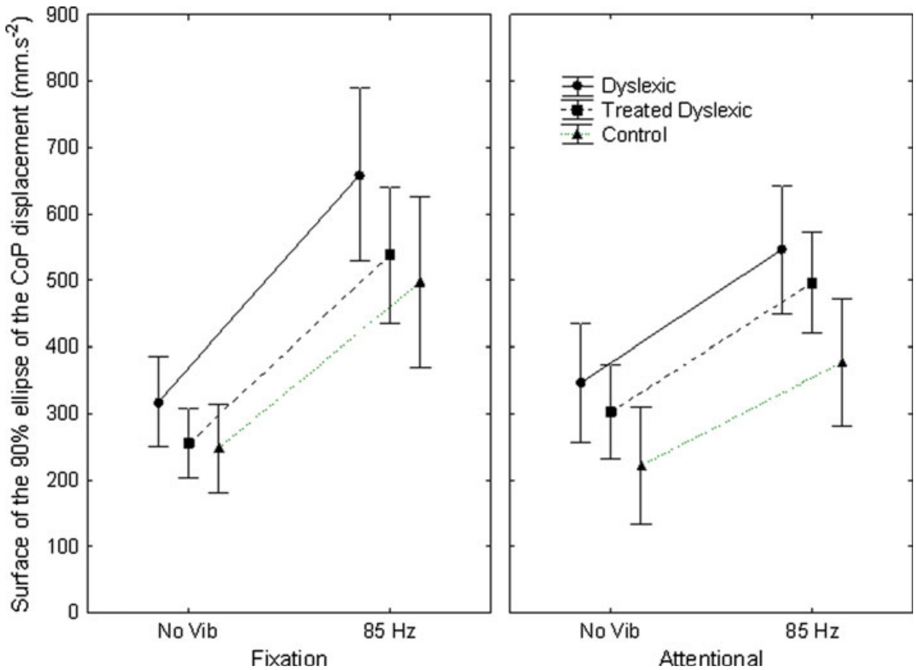

Fig. 1 Mean values ±95% CI for the surface of the 90% confidence ellipse of the displacement of the CoP for each group in the 2 vibration (no vib and 85 Hz) conditions × 2 attentional (fixation and high attention) conditions

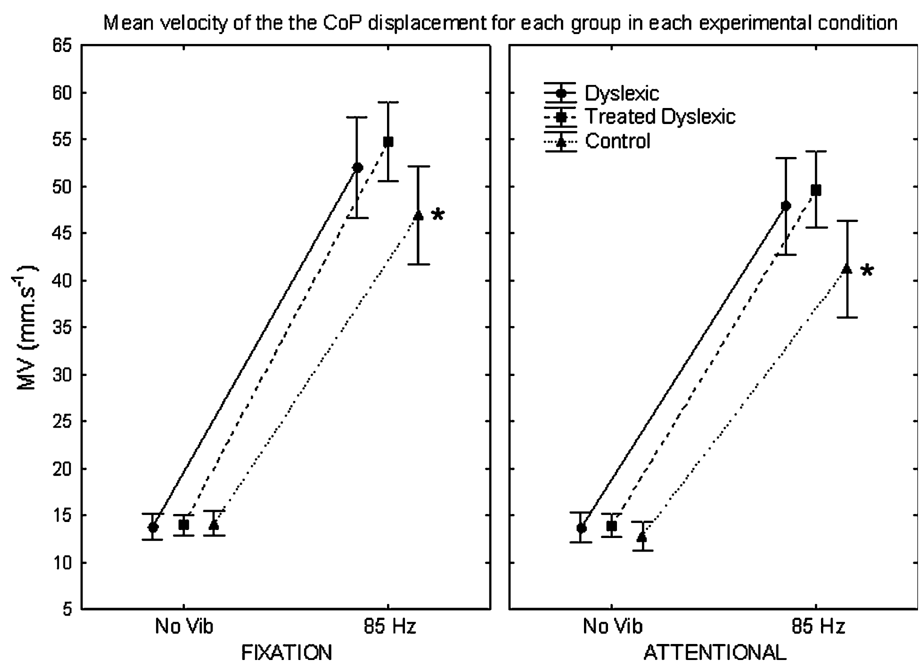

Fig. 2 Mean values ±95% CI for the mean velocity displacement of the CoP for each group in the 2 vibration (no vib and 85 Hz) × 2 attentional (fixation and high attention) conditions

($F(1,107) = 29$, $P \ll 0.01$), no group × attention interaction ($F(2,107) = 0.6$, $P = 0.5$), a significant vibration × attention interaction ($F(1,107) = 15.8$, $P \ll 0.01$), and finally no significant interaction between group, vibration, and attention ($F(2,107) = 0.1$, $P = 0.9$).

A decomposition of the group × vibration interaction revealed that the mean velocity (i.e. the total length) of the CoP displacement was smaller for the control group children in the 85 Hz vib condition in comparison with the dyslexic and treated dyslexic groups ($P = 0.046$ and $P = 0.002$, respectively) in both the fixation and high attention conditions. There was no significant difference between the dyslexic and the treated dyslexic group ($P = 0.4$). As such, the destabilizing effects of the vibration only and CoP oscillations were more pronounced in an identical fashion in both the dyslexic and treated dyslexic groups. The attentional task did not induce different effects between groups. Similarly to observations previously reported concerning the surface of the 90% confidence ellipse, the vibration × attention interaction revealed that as ankle muscles were co-vibrated, the mean velocity of the CoP displacement increased more in the fixation condition than in the high attention condition, independently of the group.

Effects on the x-std and y-std

In terms of the *x*-std, results of the ANOVA showed no significant main effect of group ($F(1,107) = 1.97$, $P = 0.14$), a significant main effect of vibration ($F(1,107) = 81.9$, $P \ll 0.01$), no significant group × vibration interaction ($F(2,107) = 0.21$, $P = 0.80$), no significant effect of the attentional task ($F(1,107) = 1.1$, $P = 0.3$), no group × attention interaction ($F(2,107) = 1.7$, $P = 0.18$), a significant vibration × attention interaction ($F(1,107) = 15.6$, $P \ll 0.01$), and finally no significant interaction between group, vibration, and attention ($F(2,107) = 0.02$, $P = 0.98$).

A decomposition of the vibration × attention interaction revealed that as the frequency of vibration increased, the *x*-std increased more in the fixation condition than in the high attention condition, independently of the group. This finding mirrored those previously observed for the two parameters reported and confirmed that children in all groups oscillated less in the high attention than in the fixation condition.

Turning now to the *y*-std, results of the ANOVA showed a significant main effect of group ($F(2,107) = 3.7$, $P = 0.03$), a significant main effect of vibration ($F(1,107) = 65.5$, $P \ll 0.01$), no significant group × vibration interaction ($F(2,107) = 0.4$, $P = 0.68$), a significant main effect of the attentional task ($F(1,107) = 9.1$, $P \ll 0.01$), no group × attention interaction ($F(2,107) = 0.9$, $P = 0.39$), no significant vibration × attention interaction ($F(1,107) = 0.05$, $P = 0.81$), and finally no significant interaction between group, vibration, and attention ($F(2,107) = 0.15$, $P = 0.86$).

Altogether, the profiles of the results and the curves for these two parameters mirrored those observed for the surface of the ellipse. Consequently, for the sake of clarity, graphs are not presented here as they do not add further significant information to the main results (Table 1).

The dyslexic group performed less well than the treated dyslexic and the control groups in the high attention task performed in the no vib condition

We computed the absolute error of the number of stars that were counted in order to assess the level of performance in the high attention task performed in the condition without vibration. Results of the one-way ANOVA showed that the dyslexic group made more errors than the treated dyslexic and the control groups ($F(2,108) = 4.12$, $P = 0.019$). There was no difference between the treated dyslexic and the control groups ($P > 0.05$). This finding is illustrated in Fig. 3. The same tendency was observed in the two other vibration conditions but without significant differences. The attentional performance was not correlated with any postural parameters in any group ($|rs| < 0.12$). As a whole, attentional performance was inferior in the dyslexic group only but remained similar in the treated dyslexic and control groups.

Combined balance and attentional performances

In order to combine balance and attentional performance, we converted raw data into *z* scores with respect to the mean and the standard deviation of the control group. For each individual and each condition in which the attention task was performed, we thus obtained a *z* score relative to the balance performance and a *z* score relative to the attentional performance. These two *z* scores were added, and separate ANOVAs were performed.

It is important to note here that the condition with vibration and that without vibration were not normalized with the same mean and standard deviation. In consequence, the no vib and the 85-Hz vib conditions cannot be compared here, and two different one-way ANOVAs with group as a factor were performed. We first used the surface of the 90% CE as an index of balance performance.

Figure 4 illustrates mean values ±95% CI for the combined *z* scores of balance and attentional performances for each group, in the no vib condition. Results of the first ANOVA performed for the no vib condition showed a significant main effect of the group ($F(2,108) = 4.8$, $P = 0.01$). A post hoc analysis revealed that the combined

Table 1 Results for standard deviations along the medio-lateral (*x*-std) and antero-posterior (*y*-std) axes. Mean (±std) for each group in each condition

Group	*x*-std fixation no vib	*x*-std attentional no vib	*x*-std fixation 85 Hz	*x*-std attentional 85 Hz	*y*-std fixation no vib	*y*-std attentional no vib	*y*-std fixation 85 Hz	*y*-std attentional 85 Hz
Dyslexic	3.6 ± 1.7	4 ± 1.4	5.2 ± 1.6	4.8 ± 1.3	5.9 ± 2.4	5.7 ± 2.9	8.3 ± 3.1	7.8 ± 2.9
Treated dyslexic	3.1 ± 1.2	3.9 ± 1.8	4.7 ± 1.4	4.7 ± 1.3	5.6 ± 2.7	5.1 ± 2.9	7.5 ± 2.6	7.2 ± 2.4
Control	3.2 ± 0.96	3.5 ± 0.94	4.6 ± 1.6	4.2 ± 1.1	5.4 ± 2.3	4.4 ± 1.9	7.1 ± 2.4	6 ± 2.1

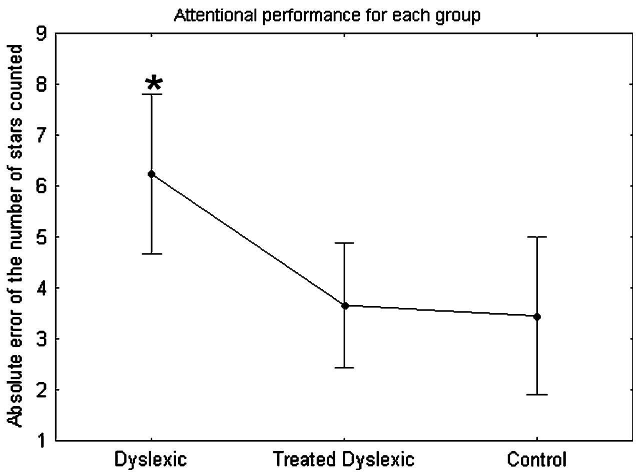

Fig. 3 Mean values ±95% CI for the attentional performance of each group in the no vib condition

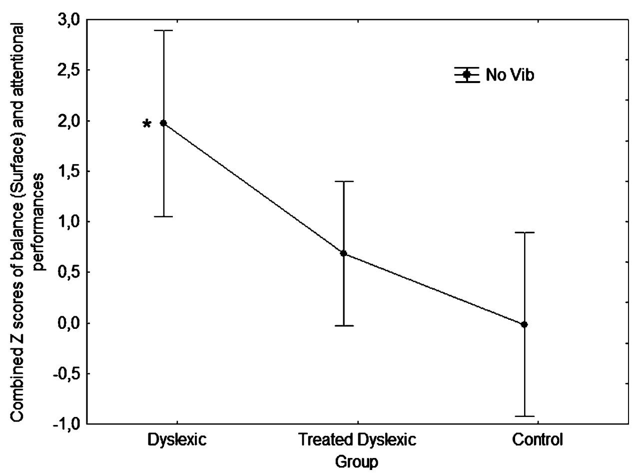

Fig. 4 Mean values ±95% CI for the combined *z* scores of balance (surface of the 90% confidence ellipse of the CoP displacement) and attentional performances for each group in the no vib condition

balance and attentional performance was lower in the dyslexic group than in the two others. Results of the second ANOVA performed for the 85-Hz vib condition showed no significant main effect of the group ($F(2,108) = 0.5$, $P = 0.5$).

We repeated this analysis using the mean velocity of the CoP displacement as an index of balance performance. Results mirrored those previously obtained.

Figure 5 illustrates mean values ± 95% CI for the combined *z* scores of balance and attentional performance for each group in the no vib condition.

Results of the first ANOVA performed for the no vib condition showed a significant main effect of the group ($F(2,108) = 5.7$, $P = 0.04$). A post hoc analysis revealed that the combined balance and attentional performance was lower in the dyslexic group than in the two others. Results

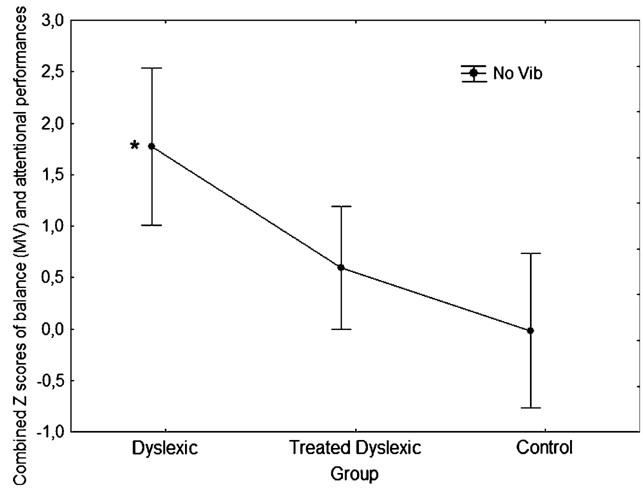

Fig. 5 Mean values ±95% CI for the combined *z* scores of balance (mean velocity CoP displacement) and attentional performances for each group in the no vib condition

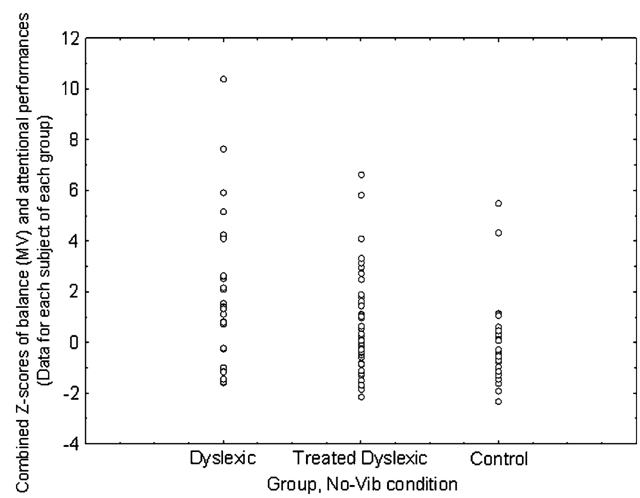

Fig. 6 Combined *z* scores of balance (mean velocity CoP displacement) and attentional performances for each subject in all groups in the no vib condition

of the second ANOVA performed for the 85-Hz vib condition showed no significant main effect of the group ($F(2,108) = 2.1$, $P = 0.12$). Figure 6 shows combined balance (mean velocity of the CoP displacement) and attentional performances for each subject in each group in the no vib condition, which was the most discriminative index and condition between the three groups. This figure confirms the more markedly distributed behavior observed in the dyslexic group compared with the other two. Interestingly, this widespread behavior was homogeneous and not limited to a few outliers. In the treated dyslexic group, this distribution tended to be normalized and to resemble that of the control group.

Discussion

The objective of this study was twofold. First, we aimed at investigating whether integration of proprioceptive signals in postural control was more impaired in dyslexic children when the level of attentional demand was manipulated. Secondly, we checked whether this potential effect could be significantly reduced by the use of a specific treatment aimed at improving eye control deficits and certain postural signs that are likely to be linked to dyslexia (Quercia et al. 2005, 2007).

Results clearly demonstrated that co-vibrating ankle muscles more markedly impaired balance control in dyslexic and treated dyslexic children compared with children in the control group. This finding suggests that the integration of proprioceptive signals is deficient in these children. This effect was not correlated with their reading discrepancies. It is widely known that the cerebellum plays an important role during the unconscious integration of proprioceptive signals during balance. This result thus fits well with the idea that the cerebellum of dyslexic children is impaired, especially in regard to procedural learning and automaticity in learning tasks (Nicolson and Fawcett 2007).

The dyslexic and the treated dyslexic groups were identically impaired, suggesting that the prismatic and postural treatments did not directly influence the integration and the processing of proprioceptive signals. Interestingly however, attentional performance was significantly improved during the condition without vibration of the ankle muscles in the treated dyslexic group, resulting in measures similar to those noted for the control group. This suggests that their treatment did improve these children's attentional capacity while maintaining balance. This effect was persistent, given that the treated children were not equipped with their prisms and soles when performing the tests. This finding provides support for the hypothesis that attention capacity may be improved by means of prisms (Pestalozzi 1992, 1993, Quercia 2005, 2007). Pestalozzi (1992, 1993) reported a positive influence of prisms on the attentional reading capacities of dyslexic children. He stated that in 71% of patients ($n = 370$), "[…] prismatic corrections may save energy [i.e. less attentional resources are used] as the patients no longer have to compensate for their heterophoria themselves. Thus they dispose of more energy e.g. for understanding the text they are reading [or the scene they are looking at]". z scores revealed that when balance and attentional performances were combined, the dyslexic group was clearly impaired in the no vib condition. This finding confirmed that the prismatic treatment does not directly improve the integration of proprioceptive signals in dyslexic children. However, using the present experimental setup, we were unable to distinguish whether the prismatic treatment could improve attentional resources or rather improve the automatic control of stance, thus allowing more resources to be allocated to the attentional task.

Several limitations should be mentioned so as to avoid over-interpreting the effects of treatment. First, the present study is not a double-blind study, as such we cannot totally exclude the possibility that the observed effect on the treated dyslexic children may be a placebo effect, despite the fact that the exercises were not performed just before the tests (at least several hours before) and that glasses and soles were removed between 5 and 10 min before the tests (please see the "Methods and materials" section). Nevertheless, the measures recorded in the treated group are important in their suggestion that it is possible to improve the attentional capacities of dyslexic children. Moreover, results obtained from this group also demonstrated that the processing of proprioception is also impaired during balance control, suggesting that the treatment does not directly recalibrate the processing of proprioceptive information by the cerebellum during balance control.

In addition, one may speculate that higher IQ or a higher level of attentional capacities in the treated dyslexic group may explain higher attentional performances compared with the dyslexic group (Wimmer et al. 1999). This could not be fully controlled in our experiment. However, the dyslexic and treated dyslexic participants were recruited using the same random procedure (they come on their own, on a voluntary basis to be treated), limiting the recruitment bias. Given that the ages of the two groups were the same despite an intervention period that ranged from 3 to 60 months in the treated group, it would seem that children in the treated group were diagnosed earlier and included at a younger age in the treatment process than those in the dyslexic group. Conversely, it may be that learning difficulties appeared earlier in this latter group, which was less capable of compensating for their learning disabilities, rather suggesting lower IQs and less attentional capacity in the treated group. This possible scenario would in fact play against our hypothesis.

As mentioned in the introduction, balance difficulties have been an enduring feature of dyslexia research despite inconsistent results. Very recently, Brookes et al. (2010) suggested that between-study heterogeneity may be influenced by various factors such as balance tasks, balance measurement, participant age, and inclusion of co-morbid disorders and especially ADHD. We have no measurements of ADHD and thus cannot judge whether there were greater attentional deficits in the treated group than in the untreated dyslexic group in the first instance, which thus led to their earlier identification. However, Brookes et al. (2010) clearly confirmed that there is a significant incidence of balance difficulties in children and adults with dyslexia, even for those without co-morbid attention deficit.

In a previous study, we demonstrated that when dyslexic children were required to simultaneously maintain balance and perform a simple silent reading task, balance control was impaired in these children, and not in the groups of control or treated children. In this particular task, children only had to find a simple 'target' word, i.e. the name of a color written in another color (e.g. "green" written in red etc.) among several other color names and to count how many times this word was written. In the present study, we did not find that the dyslexic group was more impaired in its balance performance during the attentional task. This may be due to the fact that the attentional cost engaged in the present task is lower than that engaged during a silent reading task. Behaviorally, these two tasks share certain common features, as children had to visually explore a panel and determine how many times an object was present in a scene. However, when children are required to find a word, they probably invest more attention and more cognitive resources in relation to the semantic goal of the task. In fine, this increase in the attentional/cognitive cost may result in more interference with balance control.

In conclusion, these results suggest that both integration of proprioceptive signals in balance control and attentional capacity are impaired in dyslexic children. However, this latter difficulty could be reduced significantly. In addition, combined z scores of balance and attentional performances allowed for a clearer differentiation among groups and seemed to be an interesting tool to simultaneously consider various aspects of dyslexia that may interact. More extensive research is needed to investigate these phenomena and to explore the possible causality between the many sensori-motor and cognitive impairments that characterize developmental dyslexia.

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