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Discriminant validity of spatial and temporal postural index in children with neurodevelopmental disorders

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ABSTRACT

Autism, learning disabilities and attention deficit/hyperactive disorder are often comorbid disorders. In order to try and find some markers that might be transnosographic, we hypothesized that abnormal postural sway profiles may discriminate children with neurodevelopmental disorders (NDDs) from typically developing chil-dren. The aim of our study was thus to compare spatial and temporal measures of the Center of Pressure in three distinct groups of children with NDDs (high functioning autism spectrum disorders, learning disabilities (dys-lexia) and attention deficit/hyperactive disorders) and in typically developing children. Postural performances were thus evaluated in 92 children (23 per group, sex-, age- and IQ-matched groups) by using the Multitest Equilibre platform (Framiral®). Two viewing conditions (eyes open and eyes closed) were tested on a stable and unstable platform.

Results reported similar poor postural instability for the three groups of children with NDDs with respect to the typically developing children, and this was observed for both spatial as well as temporal analysis of dis-placement of the center of pressure.

Such postural instability observed in children with NDDs could be due to impairment in using sensorial inputs to eliminate body sway, probably due to poor cerebellar integration.

ARTICLE INFO

Keywords:; Dyslexia ; Autistic spectrum disorder ADHD ; Children ; Cerebellum ; Postural control

1. Introduction

Postural stability is a complex process, which allows obtaining a coordinated relation of the various physical segments of the body. Muscle effectors involved in postural control are connected to various structures in the central nervous system, such as the basal ganglia, the brainstem, the cerebellum, and several cortical areas (Mergner and Rosemeier, 1998). Different inputs are also responsible for good postural control, including those transmitted through the proprioceptive, vestibular, and visual afferents (Brandt, 2003). The correct relationship between all of this information is necessary to reach an appropriate posture during everyday life in the natural environment. Thus, a deficit in one of these inputs may lead to an imbalance in other sensory inputs and consequently may lead to postural instability.

Several studies explored postural control in children with neurodevelopmental disorders as autism, dyslexia and hyperactivity; however, to our knowledge no study has compared at the same time these pathologies with respect to typically developing (TD) children.

Kohen-Raz et al. (1992) were the first, to record body stability of children with autism using a computerized posturographic procedure, and they showed that autistic children exhibited fewer age-related changes in postural performance and were significantly more unstable than control children. A synthesis and meta-analysis of deficits in motor control in autistic children was done by Downey and Rapport (2012). All studies exploring postural control in autistic children are in favor of the hypothesis that their poor postural stability could be due to a deficit in multimodal sensory integration, in other words to poor ability of autistic children at reweighting sensory inputs.

Similarly, dyslexic children have poor postural control. Frank and Levinson (1973) were the first to show poor postural capabilities in dyslexic children subjectively with the Romberg test. Afterwards, several studies were done by our group (Bucci et al., 2013a,b, 2014;

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Goulème et al., 2015a,b) and other researchers (Barela et al., 2011; Quercia et al., 2011; Vieira et al., 2013) during simple and/or dual postural tasks in dyslexic population, measuring body sway objectively with postural platforms. All these studies confirm the hypothesis that automaticity, via the cerebellum activity, is responsible for coordinating sensory and motor information, and that it could be impaired in dyslexic children, leading to poor postural stability.

Attention deficit hyperactivity disorder (ADHD) is associated with poor gross and fine motor control tasks (Piek et al., 1999; Wang et al., 2011; Papadopoulos et al., 2014). Several studies also reported postural instability in ADHD children compared to TD children (Zang et al., 2002; Wang et al., 2003; Buderath et al., 2009; Bucci et al., 2014, 2016). Interestingly, a study by Hove et al. (2015) reported for the first time a positive correlation between postural sway and cerebellar gray matter volume in adults with ADHD, providing additional support for cerebellar involvement in ADHD. Furthermore, as reported by Stoodley (2016) in a recent review, cerebellar deficiencies have been found in several developmental disorders (autism, dyslexia, ADHD); she sug-gested that deficits in different cerebellar subregions related to poor specific cerebro-cerebellar circuits could lead to the behavioral symp-toms at both motor and cognitive levels observed in these children.

Based on these findings, we aim to compare postural capabilities in children with autism, dyslexia and ADHD and in a group of typically developing children. We used the Multitest Equilibre from Framiral® (www.framiral.fr), which permits to analyze the Center of Pressure (CoP) both in the spatial and temporal domains. In particular, important information on the dynamic of the CoP may be reached by applying nonlinear analysis methods such as the wavelet transformation method. Indeed, a study by Ghulyan et al. (2005) demonstrated that a dynamic analysis of posture allows a better discrimination of the pathological effects on postural control.

2. Materials and methods

2.1. Subjects

Postural capabilities were explored in four different groups of twenty-three children sex-, IQ-and age-matched (Table 1): *Group 1*, children with high functioning Autism Spectrum Disorder (ASD); *Group 2*, dyslexic children; *Group 3*, children with ADHD and *Group 4*, typically developing children (TD).

Patients from *Groups 1, 2 and 3* were enrolled in the study at the Child and Adolescent Psychiatry Department, Robert Debré Hospital (Paris, France); they had a neurological exam in the normal range and were naïve of psychotropic treatment.

Children with ASD had been evaluated by the Expert Centre for High Functioning and diagnosis of ASD was based upon evaluation data from the ADI-R (Autism Diagnostic Interview-Revised, by Lord et al., 1994), the ADOS (Autism Diagnostic Observation Schedule, by Lord et al., 2000) and expert clinical judgment based on DSM-5 criteria.

Dyslexic children were recruited from the Center for Language Disorders and Learning, to which they had been referred for a complete evaluation of their dyslexia, including an extensive examination of their phonological capabilities. For each child, the time required to read a text passage, text comprehension and the ability to read words and pseudo-words using the L2MA battery (oral Language, written Language, Memory, Attention, Chevrie-Muller et al., 1997) were measured. Inclusion criteria (more than two standard deviations from the mean) were scored on the L2MA.

The diagnosis of ADHD children was done according to DSM-5 criteria (APA, 2013) and it was carried out using the Kiddie-SADS semi-structured interview (Kiddie Schedule for Affective Disorders and Schizophrenia, Goldman et al., 1998). ADHD symptom severity was assessed using the ADHD Rating Scale-parental report (ADHD-RS). This scale is based on a large collection of normative data and has demonstrated reliability and discriminant validity in children and adolescents (DuPaul et al., 1998; Collett et al., 2003).

Patients with comorbid diagnosis such as developmental coordination disorder, ASD and ADHD (or ADHD and dyslexia) were not included in our study.

For each ASD, dyslexic and ADHD child the mean intelligence quotient (IQ) was evaluated using the WISC-IV (Wechsler Intelligence Scale for Children, fourth edition); for all subjects the WISC-IV was in the normal range (between 85 and 115). The WISC-IV is composed of four indexes: (1) Verbal Comprehension Index (VCI). This index is calculated from the performance to tests measuring verbal concept formation (including similarities, vocabulary, and comprehension). (2) Perceptual Reasoning Index (PRI). This index is calculated from the performance to tests measuring non-verbal and fluid reasoning (including block design, picture concepts, and matrix reasoning). This index may also be influenced by visual-spatial perception and visual perception-fine motor coordination, as well as planning ability. (3) Working Memory Index (WMI). This index is calculated from the performance to tests measuring working memory (including digit span and letter-number sequencing). (4) Processing Speed Index (PSI). This index is calculated from the performance to tests measuring speed of information processing (including coding and symbol search).

The IQ in typically developing children was estimated in two

Table 1
Clinical characteristics of the four groups of children tested (TD, typically developing children; ASD, children with autism spectrum disorders, DYS, Dyslexic children and ADHD, children with hyperactivity).

	TD (N = 23)	ASD (N = 23)	DYS (N = 23)	ADHD (N = 23)
Age (years)	10.2 ± 0.3	10.3 ± 0.4	10.2 ± 0.2	10.3 ± 0.3
ADHD-RS total score	5 ± 1	6 ± 2	5.8 ± 1.8	39.9 ± 1.5
Autism Diagnostic Interview-Revised (ADI-R) scores				
Social Reciprocal Interaction		18.8 ± 0.9		
Communication		12.2 ± 0.8		
Stereotyped Patterns of Behaviors		5.0 ± 0.3		
Autism Diagnostic Observation Schedule (ADOS) scores				
Social Reciprocal Interaction		8.3 ± 0.7		
Communication		3.9 ± 0.3		
Wechsler scale (WISC-IV) scores				
Verbal Comprehension subscale		101 ± 6	100 ± 5	101 ± 2
Perceptual Reasoning subscale		99 ± 4	98 ± 3	97 ± 2
Working Memory subscale		92 ± 3	90 ± 4	85 ± 4
Processing Speed subscale		89 ± 3	90 ± 5	91 ± 3
Similarity test	12.5 ± 2	12 ± 1	10 ± 2	11 ± 1
Matrix reasoning test	10.7 ± 1	11 ± 1	10.8 ± 1	10 ± 2

subtests, assessing verbal ability (the similarities test) and performance ability (matrix reasoning test).

The clinical characteristics of all four groups of children are summarized in Table 1.

The investigation adhered to the principles of the Declaration of Helsinki and was approved by our Institutional Human Experimentation Committee (Comité de Protection des Personnes CPP, Ile de France V, Hôpital Saint-Antoine). Written informed consent was obtained from the participants' parents after the nature of the procedure had been explained.

3. Postural recording procedure

Postural performance was evaluated using the Multitest Equilibre, also called Balance Quest, from Framiral®, with a static/dynamic platform by Micromedical Technologies (www.framiral.fr). The displacement of the CoP was sampled at 40 Hz. The child was placed on the Framiral® platform in a dark room and he/she was positioned with the feet aligned in parallel on the footprints, and the arms hanging along the body. Postural recording was performed on both a stable (S) and an unstable (U) platform, under two different visual conditions: eyes open (EO) and eyes closed (EC). The child was asked to stay as stable as possible. During the EO condition, child had to fixate a small red light at a distance of 2.5 m. The duration of each postural recording was 30 s, with a 15-s rest period between conditions to reduce the possible effects of tiredness. The order of the conditions varied randomly across children.

4. Data processing

Analysis in both spatial and temporal domains is described below.

4.1. Spatial domain analysis

The surface area covered by the displacement of the CoP (cm^2) and its mean velocity (mm/s) were analyzed. Recall that the surface area is an efficient measure of CoP spatial variability, corresponding to an ellipse including 90% of CoP excursions (Chiari et al., 2002). The mean velocity of the CoP is a good index of the amount of neuromuscular activity required to achieve postural control (Maki et al., 1990). The Romberg's Quotient (RQ) also was calculated, that is the ratio between the surface area of the CoP in the eyes closed condition and in the eyes open condition (Van Parys and Njiokiktjien, 1976). The RQ was compared in the two postural conditions (stable and unstable platform). The RQ allows evaluating the influence of weighting of visual input on postural stability.

4.2. Temporal analysis

We applied wavelet analysis to study the frequency of CoP displacements. A wavelet non-linear analysis using Morlet waves was applied to CoP displacements in order to elaborate a time-frequency chart of body sways (Dumistrescu and Lacour, 2006; Bernard Demanze et al., 2009). This software (PosturoPro, Framiral, Cannes) provides a time-frequency chart of body sway and a 3D representation of body sway. This method gives access to the changes in the frequency components of body sway with time, the third dimension calculated as the decimal logarithm of the spectral power being given on the 3D map by a color code (see Lacour et al., 2008).

Such analysis allows revealing temporal fluctuations in the body sway spectrum. The time-frequency plane's main advantage is its double resolution (time and frequency). The wavelet analysis was applied on the antero-posterior and medio-lateral sway data by using the software PosturoPro. From this analysis, the spectral power index (PI) and the canceling time (CT) were extracted for three frequency bands (F1: 0.05–0.5 Hz; F2: 0.5–1.5 Hz; F3: > than 1.5 Hz). The spectral power index represents the amount of energy spent during a condition and is the integral of the surface of the CoP oscillations frequency at 0.05 Hz step width. The canceling time is the total time during which the spectral power of the body sway (for a specific frequency band) is canceled by the postural control mechanisms. Note that the use of the wavelet decomposition applied to the analysis of postural control allow to provide a three-dimensional description of the posturographic signal. In other words, it provides a dual frequency-time resolution with great precision of the variations of the frequencies throughout all postural recording period.

The postural instability index (PII), which quantifies the postural performance by taking into account the two precedent indices (PI and CT), was calculated as follows:

$$PII = \Sigma_x \Sigma_y PI\ (F1, F2, F3)/CT\ (F1, F2, F3)$$

where PI and CT are the spectral power index and cancellation time for each of the three frequency bands (F1, low; F2, medium; F3 high frequency band). The PII values were calculated from both the spectral power recorded in a given frequency range, and the total time during which the spectral power of the different body sway frequencies in this given frequency range tend to be canceled by the posture control mechanisms (Bernard-Demanze et al., 2014).

4.3. Statistical analysis

Statistical analysis was performed with the Statistica software using the GLM (Advanced Linear Models) with the four groups of children (ASD, dyslexic, ADHD and typically developing children) as inter-subject factor, and the RQ under stable and unstable condition and the other postural parameters in the different conditions (EO, and EC on static -S- and unstable -U- supports, respectively) as within-subject factor. Furthermore, in case of significant effects post-hoc comparisons were performed using Bonferroni correction for multiple comparisons. The effect of a factor was considered significant when the p-value was below 0.05.

4.4. Supplementary analysis

To determine whether certain cognitive domains (the four indexes of the WISC-IV: VCI, PRI, WMI and PSI) were associated to postural performance among children with a neurodevelopmental disorder, we performed a Structural Equation Model (SEM). In this SEM, we simultaneously examine the relationships between (*i*) the four indexes of the WISC-IV, the age of the children, the different conditions (EO-S, EC-S, EO-I, EC-I), and the three clinical groups of children (ASD, dyslexic, ADHD) and (*ii*) the postural surface area of the CoP, the mean velocity of the CoP and the postural instability index (PII). Because our approach was exploratory, statistical significance was evaluated using a two-sided design with alpha set a priori at 0.05. All analyses were conducted in Mplus Version 7.1 (Muthen and Muthen, 1998) using the Mplus defaults of delta parameterization and the Maximum Likelihood estimator. We used standardized data because they are less affected by the scales of measurement and can be used to evaluate the relative impact of each predictor (Kline, 2010).

5. Results

The surface area of the CoP (A) and its mean velocity (B) are reported in Fig. 1.

For the surface area of the CoP, the analysis of variance showed a significant group effect ($F(3,88) = 4.17$, $p < 0.008$) and the post-hoc comparisons reported that the three groups of children (ASD, dyslexic and ADHD) did not differ from each other for the surface area of the CoP, while all were different from the TD children group (all $p < 0.03$). Moreover, the analysis of variance showed a significant

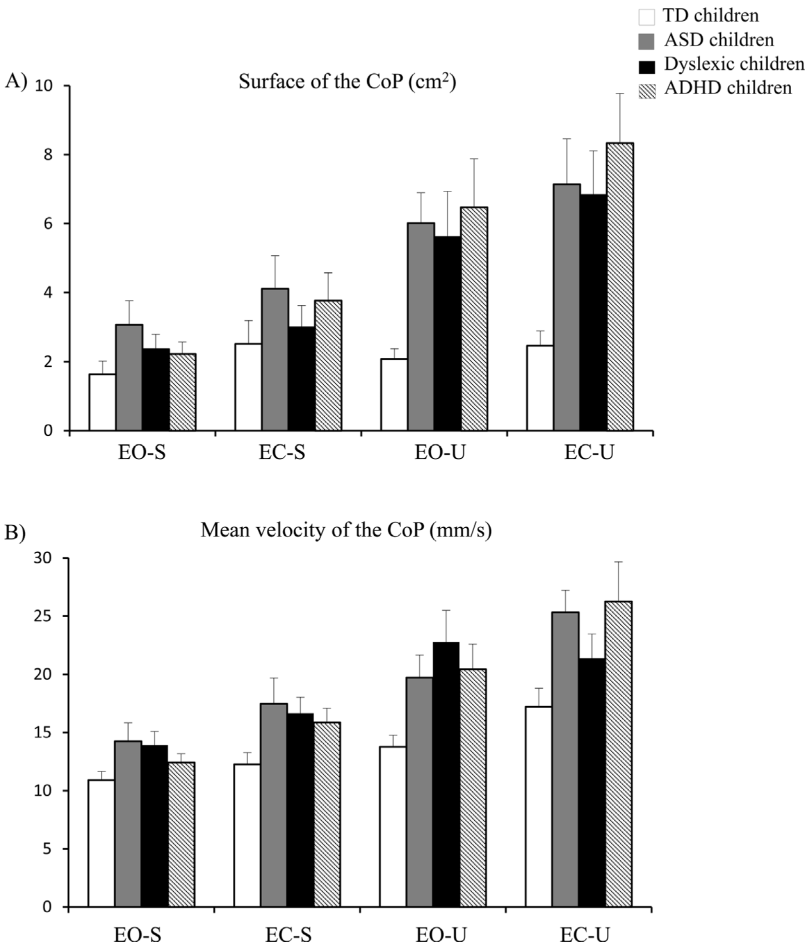

Fig. 1. Means and standard deviations of the surface area covered by the CoP (in cm^2) (A) and the mean velocity of the CoP (mm/s) (B) in the two visual conditions (eyes open: EO and eyes closed: EC) on a stable -S- or unstable -U- platform, in the four groups of children tested (TD, typically developing children; ASD, children with autism spectrum disorders, Dyslexic children and ADHD, children with hyperactivity).

effect of postural condition (F(1,88) = 34.66, $p < 0.0001$): the surface of the CoP was significantly smaller in stable than in unstable postural condition; and a significant effect of visual condition was observed (F (1,88) = 15.25, $p < 0.0001$): the surface of the CoP was significantly smaller in eyes open than in eyes closed condition. Finally, there was also a significant interaction between group and postural condition (F (3,88) = 3.99, $p < 0.01$): in the unstable postural condition, the surface area of the CoP for three groups of children (ASD, dyslexic and ADHD) was significantly larger than those observed in the TD children group (all $p < 0.02$).

The RQ was also measured for both stable and unstable conditions but the analysis of variance failed to show any significant difference (see Table 2).

For the mean velocity of the CoP, the analysis of variance also showed significant group effect (F(3,88) = 3.58, $p < 0.01$). Post-hoc comparisons reported that the three groups of children (ASD, dyslexic and ADHD) did not differ from each other for the mean velocity of the CoP, while all were different from the TD children group (all $p < 0.03$). There also was a significant postural condition effect (F (1,88) = 46.13, $p < 0.0001$): the mean velocity was greater in the unstable postural condition, and a significant visual condition effect (F (1,88) = 31.53, $p < 0.0001$) was noted, showing that the mean velocity of the CoP in the eyes open condition was lower than that reported in the eyes closed conditions. Finally, the analysis of variance reported also a significant interaction between group and visual condition (F(3,88) = 3.31, $p < 0.02$): in the eyes closed condition, the mean velocity measured in three groups of children (ASD, dyslexic and ADHD) was significantly greater than those reported in TD children group (all $p < 0.01$).

Table 2

Romberg Quotient (RQ) for the four groups of children tested (TD, typically developing children; ASD, children with autism spectrum disorders, DYS, Dyslexic children and ADHD, children with hyperactivity).

	RQ stable condition	RQ unstable condition
TD	1.1 ± 0.05	1.5 ± 0.13
ASD	1.3 ± 0.13	1.6 ± 0.16
DYS	1.4 ± 0.08	1.5 ± 0.08
ADHD	1.6 ± 0.11	1.6 ± 0.13

To summarize, children with ASD, dyslexia and ADHD have poor postural control that is worsened, in a dynamic environment and when visual information is absent.

Using wavelet transformation, the postural instability index (PII) was measured (see Fig. 2); the analysis of variance showed a significant group effect (F(3,88) = 8.84, $p < 0.0001$). Post-hoc comparisons reported that the PII was similar for the three groups of children (ASD, dyslexic and ADHD), while it was different from that of the TD children (all $p < 0.01$). There was also a significant postural condition effect (F (1,88) = 72.30, $p < 0.0001$): the PII was greater in the unstable postural condition, and a significant visual condition effect (F(1,88) = 35.89, $p < 0.0001$) was observed, showing that the PII in the eyes open condition was lower than that reported in the eyes closed condition.

In conclusion, both static and dynamic analyses of CoP displacement reveal differences in postural control between children with ASD, dyslexia and ADHD and normally developing children: postural stability in children with neurodevelopmental disorders is deficient with respect to that of control children.

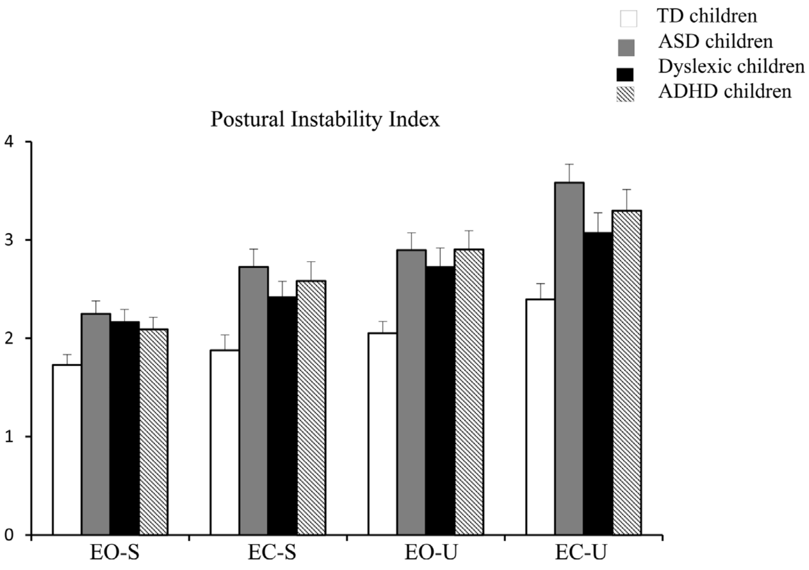

Fig. 2. Postural Instability Index in the two visual conditions (eyes open: EO and eyes closed: EC) on a stable -S- or unstable -U- platform, in the four groups of children tested (TD, typically developing children; ASD, children with autism spectrum disorders, Dyslexic children and ADHD, children with hyperactivity).

5.1. *Supplementary analysis*

In our SEM (Fig. 3), we did not find differences in postural performance between the three clinical groups (ASD, dyslexic, ADHD), but we did find differences with regards to the four conditions (EO-S, EC-S, EO-I, EC-I; β not indicated on the figure). Two WISC-IV indexes were negatively associated to postural performances: PRI was associated to postural instability index (PII) (β standardized = −0.20 (SD = 0.07); p-value = 0.004) and WMI was associated to the postural surface area of the CoP (β standardized = −0.15 (SD = 0.06); p-value = 0.015).

6. Discussion

The present study reported poor postural control in children with neurodevelopmental disorders with respect to typically developing children; we also reported that such postural deficit is greater when sensory inputs are not available, and that some cognitive domains (working memory and visual perception – *i.e.* fine motor coordination) were negatively associated with some of the postural parameters measured. These findings are discussed below.

This study is the first one comparing postural capabilities in a group of children with autism, dyslexia and hyperactivity with respect to a group of typically developing children. The result of this study is in line with previous studies (see Introduction) showing poor postural control for children with neurodevelopmental disorders; however we reported here that autism, dyslexia and hyperactivity lead to a similar instability and a common postural pattern. Indeed, it is well known that healthy children use both visual and somatosensory information to control their postural stability (Gouleme et al., 2014) and that in conditions where vision is not present anymore and/or somaesthetic information are misled (as is the case in eyes closed condition on an unstable platform) both the surface area and the mean velocity of the CoP increase significantly, suggesting the important role of sensorial inputs for controlling posture, as already established in previous studies (Shumway-Cook and Woollacott, 1985; Hirabayashi and Iwasaki, 1995). This also occurs in children with neurodevelopmental disorders; however such increase in postural parameters as the surface area and the mean velocity of the CoP is significantly larger to that reported in healthy children. This finding suggests that, differently from healthy subjects (Assländer and Peterka, 2014), compensatory mechanisms and reweighing of sensorial inputs to obtain a good postural control does not easily occur in children with neurodevelopmental disorders. This

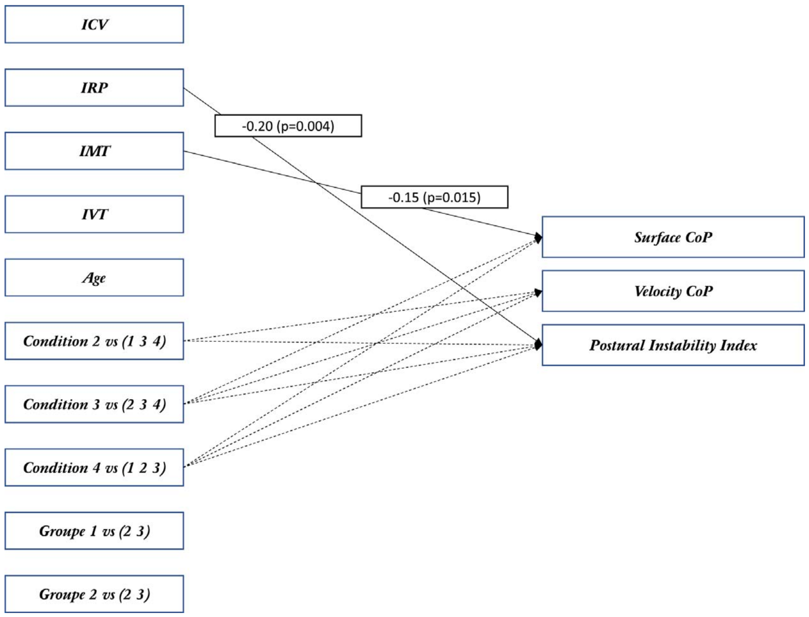

Fig. 3. Structural Equation Model (SEM) in which we examined the relationships between the four indexes of the WISC-IV, the age of children, the different conditions (EO-S, EC-S, EO-U, EC-U), and the three clinical groups of children (ASD, dyslexic, ADHD) and the postural surface area of the CoP, the mean velocity of the CoP and the postural instability index (PII).

finding is also corroborated by the temporal analysis of the CoP displacement; indeed the Postural Instability Indices are larger, particularly when vision is not present on an unstable platform.

It is well known that human balance is controlled by vestibular, visual, and somatosensory inputs to the brainstem and cerebellum (Peterka and Loughlin, 2004) and vestibular inputs are particularly important to control body's stability in unstable conditions (Bacsi and Colebatch, 2005). Since sensorimotor integration and balance regulation rely on the cerebellum, our results could suggest that poor balance in children with NDD could stem from suboptimal cerebellar function. Recall that the cerebellum is involved in motor learning and motor control, and patients with cerebellar tumors showed large instability with respect to healthy subjects, particularly in deprived sensory conditions (Konczak et al., 2005; Buderath et al., 2009). It has also been reported that cerebellar activity increases during standing posture (Ouchi et al., 1999; Jahn et al., 2008) and a recent study by Inukai et al. (2016), using a transcranial direct current stimulation applied over the cerebellum, also showed a direct effect of the cerebellum on postural control. Based on these findings and on Stoodley's report (2016), already cited in the introduction, we suggest that the poor postural control observed in children with autism, dyslexia and hyperactivity could be due to cerebellar impairment and deficiencies in cerebro-cortical network, leading to abnormal instability.

Adaptive mechanisms in the cerebellum had been reported and few studies in patients exist showing cerebellar plasticity after postural training. Burciu et al. (2013) observed that in 20 patients with cerebellar degeneration, two weeks of sensorimotor training lead to both an improvement in postural performances and an increase of gray matter volume in the cerebellum; in a group of patients with Parkinson's disease, Sehm et al. (2014) reported a change of grey matter in the right cerebellum, together with an improvement in postural stability after postural training on movable support. Recently, Drijkoningen et al. (2015) examined the effect of eight weeks of balance training program in a group of 29 children with traumatic brain injury and they found that the changes in balance control were associated with alterations in the cerebellar white matter microstructure. Finally, our group (Goulème et al., 2015a,b) reported in a small group of dyslexic children an improvement in postural stability after 3 min of postural training in deprived sensory conditions only (eyes closed on an unstable platform), suggesting an improvement in sensory input processing, most likely due to a better cerebellar integration. Future research on postural training in children with neurodevelopmental disorders combined with imaging studies for measuring the cortico-cerebellar activity could be useful to gain more insight on such issue.

Finally, Fawcett et al. (2001) examined the association of postural control with IQ among dyslexic children. However, to our knowledge, no study had previously examined whether certain cognitive domains were particularly associated to postural performance among children with a neurodevelopmental disorder. In our study, some cognitive domains (working memory and visual perception – fine motor coordination) were negatively associated with some of the postural parameters measured (postural surface area of the CoP and postural instability index (PII), respectively). These results suggest that working memory skills may be involved in the postural control of children with neurodevelopmental disorders. Such hypothesis has been put forward by several studies on dual task performances (*i.e.*, how postural control is affected by the simultaneous realization of a cognitive task) among patients with major depressive disorders (Doumas et al., 2012), degenerative cerebellar disorders (Jacobi et al., 2015) or Parkinson's disease (Marchese et al., 2003). In our study, the Perceptual Reasoning Index (PRI) of the WISC-IV was found to be associated to the postural instability index. As previously mentioned, the PRI is influenced by visual-spatial perception and visual perception-fine motor coordination, as well as planning ability. Children with neurodevelopmental disorders are well known to manifest difficulties in these cognitive skills (Kadesjö and Gillberg, 1999). Further studies on a large population of children with NDDs are needed to gain insight on the relationship between neuropsychological tests and postural sway and on their use as transnosographic markers for such children population.

7. Conclusion

This study reported similar postural impairment in children with autism, dyslexia and hyperactivity with respect to typically developing children. Both spatial and temporal analysis of the center of pressure suggests poor use of sensory inputs to compensate natural body perturbation, most likely due to cerebellar deficiencies.

Conflict of interests

The authors have no financial relationships relevant to this article to disclose.

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References

Diagnostic and Statistical Manual of Mental Disorders. In: American Psychiatric Association (Ed.), 5th ed. .

Assländer, L., Peterka, R.J., 2014. Sensory reweighting dynamics in human postural control. J. Neurophysiol. 111, 1852–1864. http://dx.doi.org/10.1152/jn.00669.2013.

Bacsi, A.M., Colebatch, J.G., 2005. Evidence for reflex and perceptual vestibular contributions to postural control. Exp. Brain Res. 160 (1), 22–28.

Barela, J.A., Dias, J.L., Godoi, D., Viana, A.R., de Freitas, P.B., 2011. Postural control and automaticity in dyslexic children: the relationship between visual information and body sway. Res. Dev. Disabil. 32 (5), 1814–1821.

Bernard Demanze, L., Dumitrescu, M., Jimeno, P., Borel, L., Lacour, M., 2009. Age-related changes in posture control are differentially affected by postural and cognitive task complexity. Curr. Aging Sci. 2 (2), 139–149.

Bernard-Demanze, L., Léonard, J., Dumitrescu, M., Meller, R., Magnan, J., Lacour, M., 2014. Static and dynamic posture control in postlingual cochlear implanted patients: effects of dual-tasking, visual and auditory inputs suppression. Front. Integr. Neurosci. 7 (111). http://dx.doi.org/10.3389/fnint.2013.00111.

Brandt, T., 2003. Vertigo: Its Multisensory Syndromes. Springer, New York.

Bucci, M.P., Bui-Quoc, E., Gerard, C.-L., 2013a. The effect of a Stroop-like task on postural control in dyslexic children. PLoS One 8 (10), e77920.

Bucci, M.P., Gerard, C.-L., Bui-Quoc, E., 2013b. The effect of a cognitive task on the postural control of dyslexic children. Res. Dev. Disabil. 34 (11), 3727–3735.

Bucci, M.P., Seassau, M., Larger, S., Bui-Quoc, E., Gerard, C.L., 2014. Effect of visual attention on postural control in children with attention-deficit/hyperactivity disorder. Res. Dev. Disabil. 35, 1292–1300.

Bucci, M.P., Stordeur, C., Acquaviva, E., Peyre, H., Delorme, R., 2016. Postural instability in children with ADHD is improved by methylphenidate. Front. Child Neurodev. Psychiatry 10 (163) eCollection.

Buderath, P., Gartner, K., Frings, M., Christiansen, H., Schoch, B., Konczak, J., et al., 2009. Postural and gait performance in children with attentiondeficit/hyperactivity disorder. Gait Posture 29, 249–254. http://dx.doi.org/10.1016/j.gaitpost.2008.08.016.

Burciu, R.G., Fritsche, N., Granert, O., Schmitz, L., Sponemann, N., Konczak, J., et al., 2013. Brain changes associated with postural training in patients with cerebellar degeneration: a voxel-based morphometry study. J. Neurosci. 33 (10), 4594–4604.

Chevrie-Muller, C., Simon, A.M., Fournier, S., 1997. Batterie langage oral écrit. Memoire Attention (L2MA). Editions du Centre de Psychologie appliquée, Paris.

Chiari, L., Rocchi, L., Capello, A., 2002. Stabilometric parameters are affected by anthropometry and foot placement. Clin. Biomech. 17 (9–10), 666–677.

Collett, B.R., Ohan, J.L., Myers, K.M., 2003. Ten-year review of rating scales. V: scales assessing attention-deficit/hyperactivity disorder. J. Am. Acad. Child Adolesc. Psychiatry 42, 1015–1037. http://dx.doi.org/10.1097/01.CHI.0000070245.24125.B6.

Doumas, M., Smolders, C., Brunfaut, E., Bouckaert, F., Krampe, R.T., 2012. Dual task performance of working memory and postural control in major depressive disorder.

Neuropsychology 26 (1), 110–118.

Downey, R., Rapport, M.J., 2012. Motor activity in children with autism: a review of current literature. Pediatr. Phys. Ther. 24 (1), 2–20.

Drijkoningen, D., Leunissen, I., Caeyenberghs, K., Hoogkamer, W., Sunaert, S., Duysens, J., Swinnen, S.P., 2015. Regional volumes in brain stem and cerebellum are associated with postural impairments in young brain-injured patients. Hum. Brain Mapp. 36 (12), 4897–4909. http://dx.doi.org/10.1002/hbm.22958.

DuPaul, G.J., Power, T.J., Anastopoulos, A.D., Reid, R., 1998. Norms and Clinical Interpretation. Guilford, NewYork, NY.

Dumistrescu, M., Lacour, M., 2006. Nouveaux critères quantitatifs d'analyse du contrôle postural. In: Pérennou, D., Lacour, M. (Eds.), Efficience et déficiences du contrôle postural. Solal éditeur, Marseille.

Fawcett, A.J., Nicolson, R.I., Maclagan, F., 2001. Cerebellar tests differentiate between groups of poor readers with and without IQ discrepancy. J. Learn. Disabil. 34 (2), 119–135.

Frank, J., Levinson, H., 1973. Dysmetric dyslexia and dyspraxia: hypothesis and study. J. Am. Acad. Child Psychiatry 12 (4), 690–701.

Ghulyan, V., Paolino, M., Lopez, C., Dumitrescu, M., Lacour, M., 2005. A new translational platform for evaluating aging or pathology-related postural disorders. Acta Otolaryngol. (Stockh.) 125, 607–617. http://dx.doi.org/10.1080/00016480510026908.

Goldman, L.S., Genel, M., Bezman, R.J., Slanets, P.J., 1998. Diagnosis and treatment of attention-deficit/hyperactivity disorder in children and adolescents. JAMA 279, 1100–1107. http://dx.doi.org/10.1001/jama.279.14.1100.

Goulème, N., Gérard, C.L., Bucci, M.P., 2015a. The effect of training on postural control in dyslexic children. PLoS One 10 (7), e0130196. http://dx.doi.org/10.1371/journal.pone.0130196.

Goulème, N., Gerard, C.L., Bui-Quoc, E., Bucci, M.P., 2015b. Spatial and temporal postural analysis in dyslexic children. Clin. Neurophysiol. 126 (7), 1370–1377.

Gouleme, N., Ezane, M.D., Wiener-Vacher, S., Bucci, M.P., 2014. Spatial and temporal postural analysis: a developmental study in healthy children. Int. J. Dev. Neurosci. 38, 169–177. http://dx.doi.org/10.1016/j.ijdevneu.2014.08.011. PubMed PMID: 25196999.

Hirabayashi, S.I., Iwasaki, Y., 1995. Developmental perspective of sensory organization on postural control. Brain Dev. 17 (2), 111–113.

Hove, M.J., Zeffiro, T.A., Biederman, J., Li, Z., Schmahmann, J., Valera, E.M., 2015. Postural sway and regional cerebellar volume in adults with attention-deficit/hyperactivity disorder. Neuroimage Clin. 8, 422–428. http://dx.doi.org/10.1016/j.nicl.2015.05.005.

Inukai, Y., Saito, K., Sasaki, R., Kotan, S., Nakagawa, M., Onishi, H., 2016. Influence of transcranial direct current stimulation to the cerebellum on standing posture control. Front. Hum. Neurosci. 10, 325. http://dx.doi.org/10.3389/fnhum.2016.00325. eCollection.

Jacobi, H., Alfes, J., Minnerop, M., Konczak, J., Klockgether, T., Timmann, D., 2015. Dual task effect on postural control in patients with degenerative cerebellar disorders. Cereb. Ataxias 2, 6. http://dx.doi.org/10.1186/s40673-015-0025-z.

Jahn, K., Deutschländer, A., Stephan, T., Kalla, R., Wiesmann, M., Strupp, M., Brandt, T., 2008. Imaging human supraspinal locomotor centers in brainstem and cerebellum. Neuroimage 39 (2), 786–792.

Kadesjö, B., Gillberg, C., 1999. Developmental coordination disorder in Swedish 7-year-old children. J. Am. Acad. Child Adolesc. Psychiatry 38 (7), 820–828 PubMed PMID: 10405499.

Kline, R.B., 2010. Principles and Practice of Structural Equation Modeling, 3rd ed. The Guilford Press, New York.

Kohen-Raz, R., Volkmar, F.R., Cohen, D.J., 1992. Postural control in children with autism. J. Autism Dev. Disord. 22 (3), 419–432.

Konczak, J., Schoch, B., Dimitrova, A., Gizewski, E., Timmann, D., 2005. Functional recovery of children and adolescents after cerebellar tumour resection. Brain 128, 1428–1441.

Lacour, M., Bernard-Demanze, L., Dumitrescu, M., 2008. Posture control, aging, and attention resources: models and posture-analysis methods. Neurophysiol. Clin. 2008 (38), 375–389. http://dx.doi.org/10.1016/j.neucli.2008.09.005.

Lord, C., Rutter, M., Le Couteur, A., 1994. Autism Diagnostic Interview-Revised: a revised version of a diagnostic interview for caregivers of individuals with possible pervasive developmental disorders. J. Autism Dev. Disord. 24 (5), 659–685.

Lord, C., Risi, S., Lambrecht, L., et al., 2000. The autism diagnostic observation schedule-generic: a standard measure of social and communication deficits associated with the spectrum of autism. J. Autism Dev. Disord. 30 (3), 205–223.

Maki, B., Holliday, P., Fernie, G., 1990. Aging and postural control: a comparison of spontaneous and induced way balance tests. J. Am. Geriatr. Soc. 38 (1), 1–9.

Marchese, R., Bove, M., Abbruzzese, G., 2003. Effect of cognitive and motor tasks on postural stability in Parkinson's disease: a posturographic study. Mov. Disord. 18 (6), 652–658.

Mergner, T., Rosemeier, T., 1998. Interaction of vestibular, somatosensory and visual signals for postural control and motion perception under terrestrial and microgravity conditions-a conceptual model. Brain Res. Rev. 28, 118–135.

Muthen, L.K., Muthen, B.O., 1998. Mplus User's Guide, 1th ed. Muthén & Muthén, Los Angeles, CA.

Ouchi, Y., Okada, H., Yoshikawa, E., Nobezawa, S., Futatsubashi, M., 1999. Brain activation during maintenance of standing postures in humans. Brain 122, 329–338. http://dx.doi.org/10.1093/brain/122.2.329.

Papadopoulos, N., McGinley, J.L., Bradshaw, J.L., Rinehart, N.J., 2014. An investigation of gait in children with Attention Deficit Hyperactivity Disorder: a case controlled study. Psychiatry Res. 218, 319–323. http://dx.doi.org/10.1016/j.psychres.2014.04.037.

Peterka, R.J., Loughlin, P.J., 2004. Dynamic regulation of sensorimotor integration in human postural control. J. Neurophysiol. 91 (1), 410–423.

Piek, J.P., Pitcher, T.M., Hay, D.A., 1999. Motor coordination and kinaesthesis in boys with attention deficit-hyperactivity disorder. Dev. Med. Child Neurol. 41, 159–165. http://dx.doi.org/10.1017/S00121622990. 00341.

Quercia, P., Demougeot, L., Dos Santos, M., Bonnetblanc, F., 2011. Integration of proprioceptive signals and attentional capacity during postural control are impaired but subject to improvement in dyslexic children. Exp. Brain Res. 209 (4), 599–608. http://dx.doi.org/10.1007/s00221-011-2593-3.

Sehm, B., Tauberta, M., Conde, V., Weise, D., Classen, J., Dukart, J., et al., 2014. Structural brain plasticity in Parkinson's disease induced by balance training. Neurobiol. Aging 232–239.

Shumway-Cook, A., Woollacott, M.H., 1985. The growth of stability: postural control from a development perspective. J. Mot. Behav. 17 (2), 131–147.

Stoodley, C.J., 2016. The cerebellum and neurodevelopmental disorders. Cerebellum 15 (1), 34–37. http://dx.doi.org/10.1007/s12311-015-0715-3.

Van Parys, J.A., Njiokiktjien, C.J., 1976. Romberg's sign expressed in a quotient. Agressologie 17. SPECNO 95–99.

Vieira, S., Quercia, P., Bonnetblanc, F., Michel, C., 2013. Space representation in children with dyslexia and children without dyslexia: contribution of line bisection and circle centering tasks. Res. Dev. Disabil. 34 (11), 3997–4008. http://dx.doi.org/10.1016/j.ridd.2013.08.031.

Wang, J., Wang, Y., Ren, Y., 2003. A case control study on balance function of attention deficit hyperactivity disorder (ADHD) children. J. Peking Univ. Health Sci. 35, 280–283.

Wang, H.Y., Huang, T.H., Lo, S.K., 2011. Motor ability and adaptive function in children with attention deficit hyperactivity disorder. Kaohsiung J. Med. Sci. 27, 446–452. http://dx.doi.org/10.1016/j.kjms.2011.06.004.

Zang, Y., Gu, B., Qian, Q., Wang, Y., 2002. Objective measurement of the balance dysfunction in attention deficit hyperactivity disorder children. Chin. J. Clin. Med. 6, 1372–1374.